Oceanography and Marine Biology: An Annual Review, 2023, **61**, 3-34
© S. J. Hawkins, P. A. Todd, B. D. Russell, A. J. Lemasson, A. L. Allcock, M. Byrne, L. B. Firth, C. H. Lucas, E. M. Marzinelli, P. J. Mumby, J. Sharples, I. P. Smith, and S. E. Swearer, Editors
Taylor & Francis

ONE HUNDRED YEARS OF DAILY SEA-SURFACE TEMPERATURE FROM THE HOPKINS MARINE STATION IN PACIFIC GROVE, CALIFORNIA: A REVIEW OF THE HISTORY, ACQUISITION, AND SIGNIFICANCE OF THE RECORD

LAURENCE C. BREAKER[1] & LUKE P. MILLER[2]

[1]*Moss Landing Marine Laboratories, Moss Landing, CA 95039-9647, United States*
[2]*Coastal and Marine Institute Laboratory & Department of Biology, San Diego State University, San Diego, CA 92182, United States*

Abstract The 100-year record of daily sea-surface temperature (SST) acquired at the Hopkins Marine Station (HMS) in Pacific Grove, California, is one of the longest oceanographic records in existence. It is exceeded in length by the record at Scripps Pier by only 3 years. The history of the record at HMS, the methods used to gather the data, the problems that were encountered, and finally, the scientific significance of this record are presented.

Reconstructing a complete version of the 100-year time series record was not straightforward. Two major gaps had to be filled using data from another site, and variation in the time of day for sample collection was addressed to better standardise the SST values presented.

The observations were first examined for their oceanographic content based on the relevant timescales involved that ranged from daily to the record length, i.e., centennial. The major sources of variability included the El Niño phenomenon, the Pacific Decadal Oscillation, and the Marine Heat Wave (MHW) that began in 2014. The impact of the MHW cannot be overstated, and it was well represented in the data from the HMS. The use of the historical temperature record for studies of long-term changes in species and communities in the biological literature is highlighted.

Finally, a set of conclusions is presented highlighting the important contributions of the SST dataset that are only possible through dedicated long-term environmental monitoring programmes such as the one reported here.

Keywords: Daily Sea-Surface Temperature; Hopkins Marine Station; Monterey Bay; 100-Year Record; Physical Oceanography; Marine Biology; North Pacific Marine Heat Wave; Coastal Upwelling; El Nino Episodes

Introduction

Sea-surface temperatures (SSTs) in the coastal zone are increasing at rates that often exceed global ocean warming trends by 50%–150% (Lima & Wethey 2012) and the impact of urbanisation in its many aspects may increase warming rates near urban centres by up to an order of magnitude (Amos et al. 2015). These trends, coupled with other anthropogenic impacts in the coastal zone, have important implications for coastal climate change (Halpern et al. 2008). The trends in warming near shore are often less representative of the data that are being acquired further offshore and beyond the coastal zone. As a result, the importance of data collection in these nearshore regions, rather

DOI: 10.1201/9781003363873-2

than being considered as unrepresentative of the regions further offshore, might deserve greater consideration because they are the regions that are experiencing the greatest change.

Unlike the Permanent Service for Mean Sea Level (PSMSL) which provides a global database for sea level, we have no such centralised database for long-term nearshore or shoreline SST. The establishment and maintenance of nearshore SST monitoring programmes has been undertaken by various individual research and government agencies, and in some cases, in more recent decades, these efforts have been coordinated on a national level by organisations such as the British Oceanographic Data Center (BODC), the National Oceanographic Data Center, and the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). Continuous records of SST at fixed locations of at least 50 years or more are uncommon and most of the coastal data during the past century have come from ship reports, and more recently, from coastal buoys and satellites, which add greatly to the spatial and temporal coverage of the surface temperature field. The many benefits of oceanographic time series were enumerated as part of the Global Ocean Observing System Programme in a report published by Send et al. (2001).

In the late nineteenth and early twentieth centuries, several sites worldwide began regularly sampling SST at permanent observing sites along the coastal boundary or at the water's edge. A record that stands out is the time series from Port Erin on the Isle of Man in the Irish Sea in the United Kingdom. This record was started in 1904 and is continuing till this day with observations made twice daily. Significant gaps occur only during each of the two world wars.

Several groups have generated long-term records of SST for the eastern coast of North America. Nixon et al. (2004) compiled what was believed to be the longest 'coherent' record of SST in North America (as of 2002). It extended from 1886 through 2002 for a record length of 117 years. According to the authors, the near-surface measurements were obtained almost daily with just a few gaps at Great Harbor, Woods Hole, Massachusetts. Overall, there was no significant trend for the first 60 years after which some cooling during the 1960s was observed followed by warming at a rate of +0.04°C/year since 1970. Shearman and Lentz (2010) compiled a composite dataset consisting of monthly averaged observations from lighthouses, lightships, coastal buoys, and shore-based observations which included 128 sites from Eastport, Maine, to Dry Tortugas, Florida. This dataset spanned the period from 1875 to 2007. Of these, 46 sites had more than 25 years of observations, 15 sites had more than 50 years of observations, and four sites more than 75 years of observations off the U.S. east coast. A total of 30 time series were chosen for length and completeness over the last century to estimate the long-term trends. Due to two world wars and a significant number of major hurricanes, it was not possible to construct complete records at most locations. Thus, a patchwork quilt of observations along the east coast was required to perform the final analysis. Maul et al. (2001) examined seven records of SST from adjacent tide gauges during the twentieth century from Boston to Key West that varied in length from 49 to 80 years. The data were monthly averaged and contained significant gaps. Such gaps in SST data occur throughout Europe and along the U.S. east coast.

Since 1910, the Korean National Fisheries Research and Development Institute has collected oceanographic and meteorological data along the coast of the Korean Peninsula. These observations included SST, but data collection was interrupted during the Korean War (1950–1953). In total, the observational network includes some 40 observing sites. Jo et al. (2014) used the daily SSTs from three locations along the eastern coast of Korea for the period from 1966 through 2004 to examine long-term changes in water temperature off the eastern coast of South Korea. Although this analysis only included a 38-year period, the data collection programme, as it is presently understood, is still in operation with its primary goals unchanged.

Daily observations of SST have been acquired at several locations along the coast of British Columbia (BC) since the early years of the twentieth century with most having served as light stations (i.e., former lighthouses). The data were obtained starting in 1914 at the Pacific Biological Station in Departure Bay, BC, and have essentially been in continuous operation since 1914, i.e., with no significant gaps (Amos et al. 2015). Several stations have been added since that time although the number has varied somewhat since the programme began. This programme is referred to as the British Columbia Shore Station Oceanographic Program (BCSOP) with 12 stations participating at this time. The sampling used in this programme to obtain the daily observations corresponds to the stage of the tide which has been chosen to be at or near the time of high tide. This sampling strategy differs from most programmes which employ a fixed time of day for data collection.

Along the coast of New Zealand, regular observations of daily SST have been collected at the Portobello Marine Station, University of Otago, since 1953, and at the Leigh Marine Station, University of Auckland, since 1967 (Greig et al. 1988).

In addition to the individual and combined records of SST that have been described above, it would be remiss of the authors not to mention the work of Shears and Bowen (2017) who have compiled half a century of coastal temperatures using three separate records to study warming trends in the South-west Pacific boundary current region. In a similar vein, we reference the work of Morris et al. (2018) who reported on over 10 million seawater temperature records over the continental shelf of the United Kingdom between 1880 and 2014. This truly monumental effort brings together a vast collection of observations over a 130-year period from many sources.

The concept of monitoring SST along the California coast on a continuous basis appears to have originated at the Scripps Institution of Oceanography (SIO) in San Diego with a measurement programme that started in 1916. The record of daily SSTs from Scripps Pier in La Jolla, California, which began in 1916 is, as of this writing, now 106 years long and essentially complete. This record has recently been documented in Rasmussen et al. (2020). The programme that emerged at SIO was soon followed by the establishment of a similar programme 3 years later in January 1919 at Hopkins Marine Station in Pacific Grove, California, located at the southern end of Monterey Bay (Figure 1). The Pacific Grove record measured at Hopkins serves as a companion piece for the record at Scripps since they were, in part, inspired and coordinated by the same people. The names 'Hopkins Marine Station', 'Hopkins', 'HMS', and 'Pacific Grove' are used interchangeably here and should be taken to represent the same location in all cases.

The importance for acquiring continuous records over time was apparently recognised from the outset of these measurement programmes. Although data archiving is not discussed in this report, this important task has been the responsibility of the Shore Stations Program at Scripps over many years and they have continued to perform this duty with excellence. Despite the efforts of the record keepers, in some cases, records went missing, necessitating the reconstruction of a complete record using data from other sources. In addition, changes in the methodology, particularly with regard to the time of day (TOD) of sample collection, have introduced potential variation in the record that warrants attention.

The Pacific Grove historical temperature record has found use among students and scientists in two primary groups, the oceanography and marine biological communities. It is estimated that the number of published and unpublished reports utilising the long-term SST record from Pacific Grove approaches 100. The bibliography alone contains almost 50 reports that have appeared in the literature.

This review is organised as follows. The history of the programme is followed by a brief description of the measurement site which, in turn, is then followed by a description of the procedures that were and are, for the most part, still in use today in acquiring the data. There is a discussion of some of the problems that transpired, as indicated above, and the steps taken to fix those issues in the record. The observations of SST themselves and what they represent are then summarised and discussed in terms of physical oceanography. The use of the HMS time series in a variety of biological studies is summarised, including its use in historical ecology work, biophysical modelling, and fisheries studies. In the final section, a discussion of the results and a number of conclusions regarding the data that have been acquired at the Hopkins Marine Station in Pacific Grove over the past century are presented.

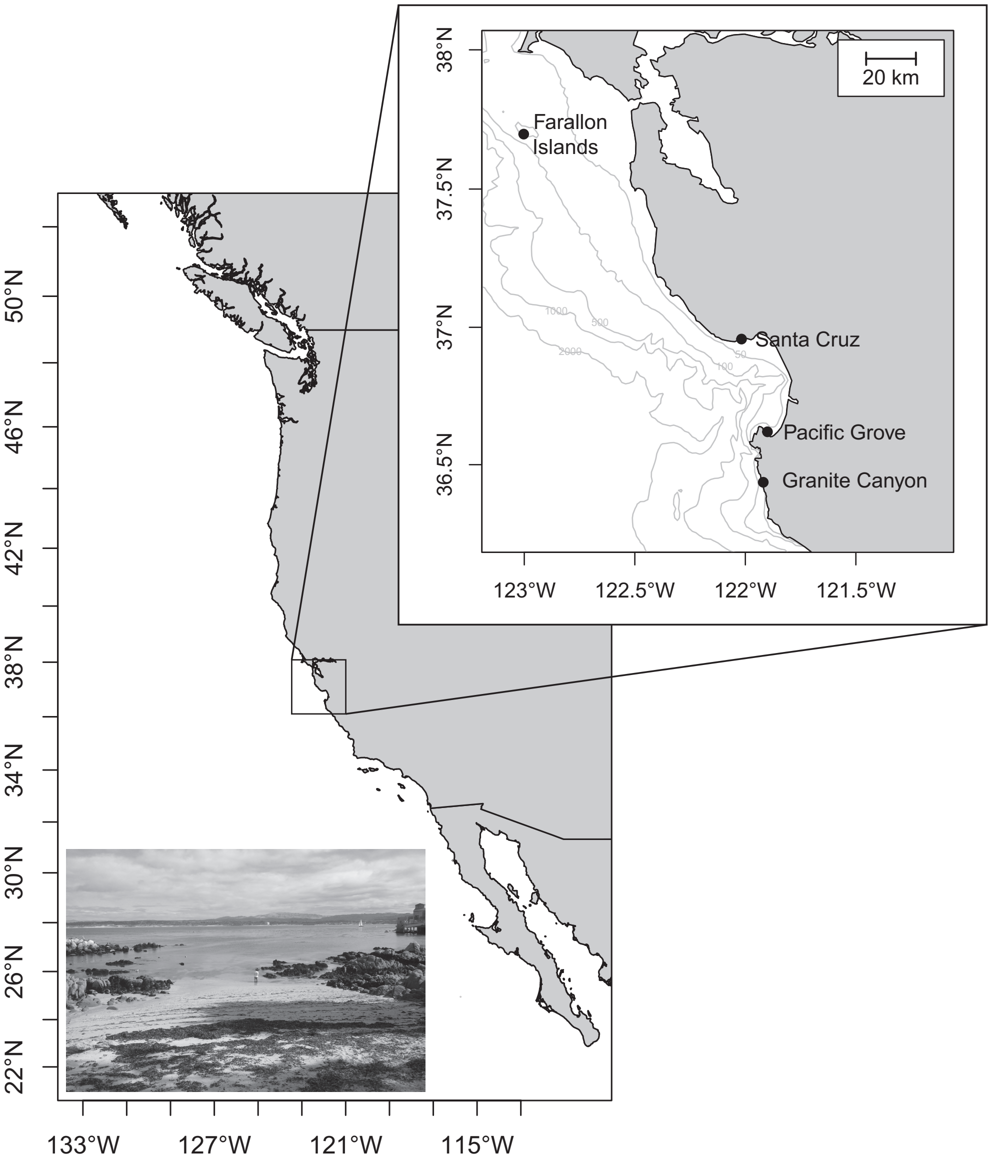

Figure 1 Map of the west coast of North America from Canada to Mexico. Monterey Bay is located in central California. Inset map: the long-term sea-surface temperature record has been collected at Hopkins Marine Station, located in the city of Pacific Grove at the southern end of the Monterey Bay. The Farallon Islands, Santa Cruz, and Granite Canyon, additional sites with shorter historical sea-surface temperature records discussed here, are also indicated. The photo at the lower left shows a view of the Agassiz Beach sampling site at low tide, looking east. Water samples were generally collected near the rocky area on the right.

History of the programme

The Shore Stations Program for the U.S. west coast started at the SIO in 1916 for the purpose of collecting SST data at a single location along the coast of southern California (Rasmussen et al. 2020). The programme was expanded in 1919 when the Hopkins Marine Station in Pacific Grove on the coast of southern Monterey Bay became the second measurement site.

A key player during the early days was Dr. George F. McEwen at SIO, whose name frequently appears in the various communications that were exchanged between SIO and Hopkins (i.e., HMS). A set of similar but distinct procedures were adopted and have been followed at both institutions. This is primarily due to the fact that Scripps Pier itself served as the actual measurement site at SIO, necessitating the manual lowering of containers into the water. In contrast, the measurement site at HMS has been on the beach near the main laboratory where bucket samples of seawater are taken within the swash zone.

Daily observations of SST were first acquired on 20 January 1919 at Hopkins. The observations have been made on a continuous basis up to the present time except for the year 1940 and for several smaller gaps of at least a month. These gaps have been filled using standard methods of regression and interpolation in order to create a continuous record to enable taking advantage of some of the methods that are used in time series analysis. Of the most serious problems that were encountered, however, were variations in the TOD when the observations were acquired. A similar problem was encountered at SIO (Rasmussen et al. 2020). SSTs and similar data from other locations along the U.S. West Coast are collected and archived by the Shore Stations Program at SIO (https://shorestations.ucsd.edu/data-pacific-grove/). Finally, since its inception, the programme has continued to grow as more stations along the coast have started to collect data and report their results, totalling 10 active stations in California in 2021. These stations from North to South along the coast are Trinidad Bay, Trinidad Beach, Farallon Islands, Pacific Grove, Granite Canyon, Santa Barbara, Point Dume/Zuma Beach, Newport Beach/Balboa Pier, San Clemente, and La Jolla/Scripps Pier.

Location

The observing site at Hopkins Marine Station is located on Agassiz Beach on the eastern side of Point Cabrillo just east of the main laboratory (Figure 1). This location has an excellent exposure to the incoming waves and swell from the north-west as it passes Point Pinos, providing waters that are generally well-mixed and thus representative of conditions at the southern end of Monterey Bay (e.g., W. Nirenberg 1975).

Procedures

The instruments that have been and are being used in the data collection over the course of the time series have been as follows. High-grade mercury-filled glass thermometers similar to those used at Scripps Pier were almost certainly used at Hopkins since the observations were first acquired in 1919. These instruments were considered to be the scientific standard at the time and were used for at least several decades thereafter (Rasmussen et al. 2020). Since the early 2000s, NIST-traceable alcohol-based thermometers were used when SIO transitioned away from mercury thermometers after mercury was banned in California, although the initial date of the transition is unknown. The alcohol thermometers were used until 2008, when calibrated digital thermometers became the standard.

A bucket is used at Hopkins to collect a water sample at the shore line in the swash zone. The temperature of the water sample is measured immediately and then recorded according to the instructions given for the particular instrument that is used. This temperature has been considered to represent the upper ~30 cm (approximately 1 foot) of the water column (Surface Water Temperatures, U.S. Coast and Geodetic Survey, Pacific Coast, Washington, DC, 1945). The precision of the mercury and alcohol thermometers from 1956 onwards was generally taken to be 0.1°C, and the precision of the current digital thermometers is taken to be 0.01°C, though the usual practice is to round the temperatures to the nearest 0.1°C. According to SIO Report 81-30 (1981), the final temperatures are recorded either manually or by an automated device with an accepted accuracy ±0.2°C. To illustrate the accuracy of these instruments based on a sample of readings obtained several years ago by comparing two instruments at different times, the differences between them ranged from 0.04°C to 0.1°C. Correspondence between Scripps and Hopkins indicates that the thermometers in recent years were often calibrated at least once a year and may be calibrated as often as every 6 months.

The temperature time series

From 1916 at Scripps Pier and then 3 years later at Hopkins, daily SSTs were being acquired for the first time on the Pacific coast of North America, producing time series with daily resolution where the information content is greatly increased and patterns emerge that might otherwise be missed. One of the benefits of employing coastal observations at a set location is that they may be of slightly higher quality than data that are obtained from models where spatial and/or temporal interpolation is required to obtain values from the nearest grid point. Estimated values from these models obtained from such geographically based grid systems are inherently low-pass filtered (i.e., smoothed), and therefore they could actually be of slightly lower quality.

The degree to which the measurements of SST and other parameters at various locations along the coast are independent is a different matter. Their independence depends on both their correlation timescales and their correlation length scales. It is not difficult to estimate the correlation timescale by simply calculating the autocorrelation function (ACF) of the daily observations and observing the rate of decay once any long-term trends in the data have been removed. Breaker, Lewis and Orav (1983) calculated the ACF from SST along the central coast of California at Granite Canyon just north of Pt. Sur and observed an e-folding decay timescale of approximately 1 week. Calculating representative length scales presents similar problems, but are more difficult to estimate because the problem is essentially 2-dimensional if considering the correlation length scales in both the alongshore and cross-shore directions.

Investigations of methodology

When the programme began at Hopkins, the observers were instructed to collect the data at 8:00 am local time (UTC-8:00) each day of the week except on Sunday (Dr. G.F. McEwen, 1919). The records show that data collection on Sundays was first introduced on 25 November 1928.

A potential problem developed over the reason for a relatively abrupt and significant increase in SST (~1°C) that occurred in May 1929 where colder temperatures had prevailed for the previous 10 years. Figures 2 and 3 show the dramatic increase in temperature that apparently occurred at that time. Could it have been due to an observational or instrumental error, or was it due to natural causes? Several possible explanations arose. As one possibility, the original data collection site could have been moved to a different location. To address this question and others, Dr. Mark Denny of Hopkins compared the daily observations from the current sampling location on Agassiz Beach at HMS with those acquired from a shoreline site approximately 250 metres away on the north-west side of Cabrillo Point, adjacent to an older HMS seawater pump house. These data were acquired between August 2007 and January 2008 for a period of almost 6 months. The two datasets turned out to be almost identical with a mean difference of less than 0.1°C. Not surprisingly, it was concluded that the measurement site had probably not been moved, and furthermore, that it did not matter anyway. Two points supporting the possibility of a natural shift in temperatures are worth noting. First, corroborating data from Skogsberg (1936) was found and his results are discussed in the section that follows in this review (*Daily and short-term variability*). Second, significant increases in SST were observed elsewhere around the world during the 1920s and 1930s (e.g., Kaplan et al. 1998, Enfield and Mestas-Nunez 2001, Hawkins et al. 2003, Southward et al. 2004, Philippart et al. 2011). It may come as a surprise that such a change would occur so rapidly, but perhaps the most significant aspect of this event was the degree to which it appears to have been sustained.

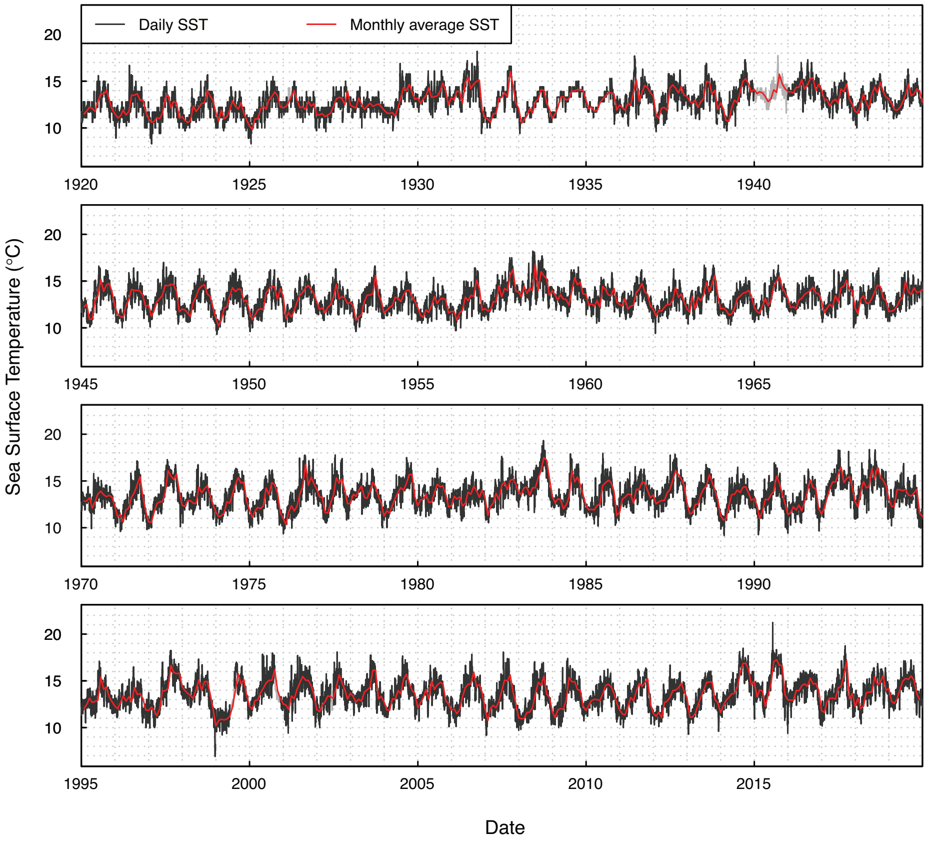

Figure 2 One hundred years of reconstructed temperature time series from Pacific Grove, CA, from 1920 to the end of 2019. Daily values are shown in black, and monthly average temperatures shown in red. The light grey period in 1940 represents 1 year of missing data that had to be imputed based on a regression against SST data from South Farallon Island.

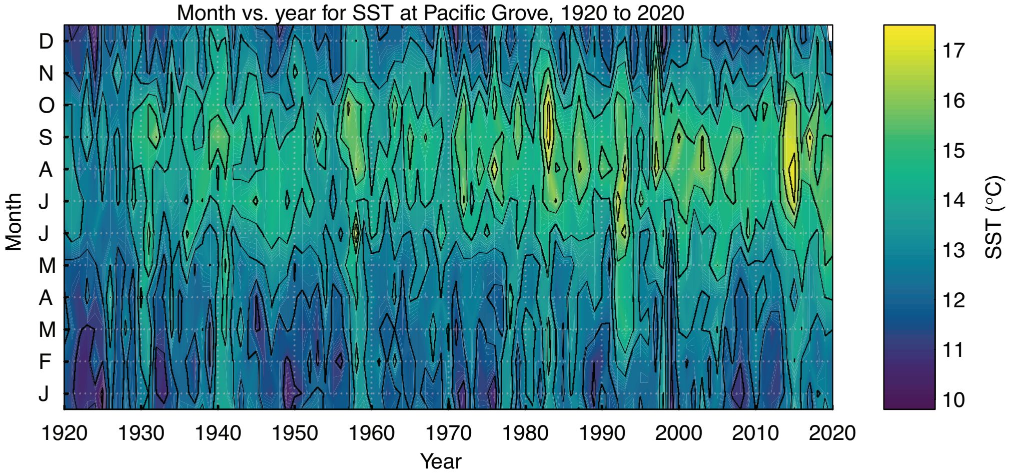

Figure 3 The complete 100-year record of monthly averaged SSTs is shown as a two-way layout by month along the ordinate and the year along the abscissa. Black isolines represent 1°C intervals.

In 2006, Breaker, Broenkow, and Denny (2006) published a report entitled “Reconstructing an 83-year time series of daily SST at Pacific Grove, California”. In this report, a number of problems with the record were brought to light which were addressed or at least partially addressed. These problems included gaps in the record, possible outliers, variations in precision, and variations in the TOD when the observations were taken. The problem of possible outliers was not serious and only affected a small number of observations. Variations in precision, i.e., the number of decimal places to which the observations were recorded, were also a relatively minor problem. As a result, these problems are only mentioned in passing (for further details, see Breaker et al. 2006).

At HMS, the intended time at which the observations were collected, to the best of anyone’s knowledge, was 08:00 am Pacific Standard Time (PST, UTC – 08:00); however, over the years, observation times may have varied, in some cases, significantly. For the early portion of the Pacific Grove record, more than one source has recalled that most of the observations were collected at, or at least near, 08:00 am because a single person, a Mr. Ted Balesteri, was in charge of collecting the data from 1919 to almost 1950. In later years, graduate students living in the caretaker’s cottage were employed in the data collection process. Although conjecture enters the picture at this point, one test was applied to the data to see if temperatures tended to be higher on weekends than during the week since students are often known to rise later in the day on weekends. Later observing times would of course be expected to produce higher temperatures on average if such a pattern could be established. Although it was somewhat surprising, the pattern that was anticipated to indicate later observation times was not found (Breaker et al. 2006). Although this period is uncertain, the goal of achieving an 08:00 am observing time was almost certainly maintained, but the degree to which it was actually adhered to is less certain. Since the early 2000s, Dr. Joe Wible, the head librarian for 22 years at Hopkins, strongly encouraged students to adhere to the 08:00 am observation time in order to help maintain the quality of the record, particularly after one period with a student caretaker known to frequently have difficulty rising before noon.

Although the targeted sampling time was 8:00 am Pacific Standard Time (UTC – 8:00), the implementation of ‘War Time’ from 1942 to 1945 and the subsequent observance of ‘Daylight Saving Time’ starting regularly in California in 1954 introduced the likelihood that sampling times may have shifted by 1 hour, to Pacific Daylight Time (UTC – 7:00), during spring, summer, and fall, for many years of the record.

TOD corrections have been applied for observations acquired since 1 January 1969, but it has not been possible to apply these corrections prior to 1969 because the log sheets that contained this information were lost. The earlier records that contained the TOD information may have been lost during the move to the new building (personal communication, Alan Baldridge) at Hopkins in 1989 as a result of the construction of a new library and shift in location. In any case, since 1969, it has been possible to apply approximate corrections for variations in the TOD, including shifts in sampling time due to the seasonal change from Pacific Standard Time to Pacific Daylight Time. An examination of the available log sheets from 1969 onwards shows no evidence that data collectors adhered to Pacific Standard Time (UTC – 8:00) when the time zone shifted to Pacific Daylight Time in the spring each year, but instead collected samples based on the adjusted time on their watch.

The diurnal variation in SST is due to a number of factors that include cloud cover, incoming solar radiation, turbulent mixing due to the wind, the latitude, and the time of the year (Roll 1965). Cloud cover can reduce the diurnal range in SST by up to 0.5°C depending on the time of year (ibid.). In addition to the TOD, information on cloud cover is also available since 1969. A cloud covered sky is present in Monterey Bay much of the time particularly during the morning hours and in the summer. However, the cloud cover often dissipates later in the day. Thus, these conditions may not have prevailed for a significant portion of the day. As a result, because of the ephemeral nature of the cloud cover in Monterey Bay, this information could not be incorporated within the framework of the model that was initially adopted. To address this problem, an effective method of stratifying the data to reduce the scatter was needed. It was found that by binning the observations by month as well as TOD, a slightly modified version of the model could be used to obtain a TOD correction. This model can be expressed as follows:

$$T_i(t) = A_i \cos(2\pi t / P) + B_i \sin(2\pi t / P), \text{ for } 0.0 < t \leq 24.0 \text{ and } i = 1, \ldots, 12 \tag{1}$$

where $T_i(t)$ represents the predicted temperature as a function of time and t is in hours, i is the month of the year, and $P=24$ hours. A_i and B_i are estimated by the method of least squares (Bloomfield 1976). Since the diurnal cycle varies in a generally cyclic manner, the selection of harmonic basis functions was a natural choice.

The results indicate that the diurnal cycle clearly increases during the summer, as expected, and has a maximum range that approaches or may even exceed 2°C. The magnitude of the diurnal range in this case is almost twice that is predicted for the open ocean (Monin et al. 1977). It was also found that the rate of increase in temperature during the summer is at its maximum between 08:00 and 12:00 hours with rates of increase that approach 0.4°C/hour. Finally, because the observations when they were not collected at 08:00 am were usually collected later in the day, the final corrected values are in most cases lower than the values that were usually recorded. In conclusion, the awareness of the sampling problem and the importance of collecting the observations at the same time each day has apparently been a gradual learning process. Almost certainly in the early days of the programme, there was little awareness of how large the diurnal signal actually was. The TOD issue also appears to have been the most significant problem encountered in evaluating the 100-year record of SST at Scripps Pier (Rasmussen et al. 2020).

Gaps in the record which required filling if a complete record was to be produced, albeit a partial proxy, are finally discussed. The gaps varied in length from 1 day to one entire year. The year was 1940. According to Alan Baldridge who was the chief librarian at HMS for many years in the decades that followed, it is most likely that the observations during that year were acquired but misplaced during the archiving process. Consistent with this argument is the fact that the observations that were missing were very close to 1 year in length.

To fill the 1-year gap, the first option that was considered was to use the mean annual cycle (MAC) as the basis. The problems with using the MAC were two-fold. First, during the year 1940, two maxima in SST occurred, the first of which was the major 1940–1941 El Niño and the second was a maximum in the Pacific Decadal Oscillation. Figures 2 and 3 clearly show a major maximum approximately centred on 1940 in the record that has since been recreated (although the year 1940 is missing from our record, there were several other records including the Farallon Islands and Scripps Pier that were examined during the period in question and clearly supported our interpretation). However, to distinguish between these two events, the reader is referred to Breaker and Carroll (2019) who used Empirical Mode Decomposition to separate them based on timescale differences. Thus, in the first case, the MAC would not have served as a representative proxy. In the second case, since the MAC produces an inherently smoothed version of the desired product, much of the smaller-scale variability would be sacrificed in the averaging process.

Because SST measurements have also been acquired at the Farallon Islands since 1925 (Figure 1), the possibility of using this record as a proxy for the year in question arose. Using the Farallon Islands as a proxy assumed there was a significant relationship between the two records. Work by Robinson (1960) and Roden (1961) suggested that this was the case at least on seasonal and annual timescales. As a result, a lagged linear regression was used as the basis for establishing this relationship following standard procedures given in Thomson and Emery (2001). The results of the lagged regression between Hopkins and the Farallons revealed an overall lag between the two records of 1 day for the 1925–1943 period and a lag of zero days for the 1955-onward period (a gap exists in the Farallons record from 1943 to 1955). The infilling procedures that were employed depended on timescale and are described in detail in Breaker et al. (2006). Several smaller gaps of slightly less than a month were also filled using this relationship. At shorter timescales from 1 day to 16 days, linear interpolation was used after testing several more sophisticated methods of interpolation only to find that linear interpolation worked equally well or better than other common methods, consistent with the findings of Weedon (2003). Finally, the complete record that incorporates all of the corrections described above is shown in Figure 2 as a time series and Figure 3 as a two-way layout by month and year.

Scientific contributions

Although a number of topics could be addressed based on the observational database that resides at Hopkins, most of what follows has been devoted to the subjects of physical oceanography and marine biology. We provide examples of biological studies that utilise the Hopkins record to show the importance of such time series for diverse disciplines, including addressing emerging concerns about individual species' and community responses to climate change.

A number of studies have been conducted that were based primarily or at least in part on the Hopkins time series where physical oceanography was the primary focus. First, the daily observations are examined which in turn is followed by an examination of the longer timescales of variability. The importance of the diurnal influence in the early years may have been underestimated in part because its variability off the coast, where more data had been collected, was often found to be relatively small. In the early 1900s, oceanography was still a 'blue water' science and observations along the coast were less common.

Daily and short-term variability

To illustrate the importance of the daily samples, the spring transition to coastal upwelling was first reported by Huyer et al. (1979) off the coast of Oregon, an event that was preceded by a major reversal in wind direction with a corresponding oceanic response that occurred over a period of approximately a week. Typically, the spring transition takes a week or longer with significant decreases in temperature often observed on a daily basis. The coastal wind is a major driving force during the spring transition, and although its speed and direction are often poorly defined and variable at the outset, as the event progresses over the course of several days, the winds change direction, now coming consistently from the North-west with speeds that approach or even exceed 8 m/s (e.g., Hayes et al. 1984). The upper panel of Figure 4 shows daily SST at three locations in March 1980: Pacific Grove, Granite Canyon, and Santa Cruz (upper and lower panels taken from Breaker 2005). The greatest change occurs at Granite Canyon (>3°C) on the open coast where it occurs first. The transition is delayed by at least 5 days at Pacific Grove and the decrease in temperature is closer to 2°C. According to Gunter Seckel, the director of the National Marine Fisheries Service Laboratory in Pacific Grove during the 1980s (personal communication), he could often tell the exact day when the spring transition first arrived from his office overlooking Monterey Bay based on shifts in the wind and currents.

An autumn transition was observed in 1956 at Pacific Grove (lower panel of Figure 4) which in most years is less pronounced than the transition to coastal upwelling. In this case, the decrease in temperature at Pacific Grove is at least 3°C and it occurs over a period of approximately 2 days. The fall transition represents a major seasonal change that usually signals the arrival of the poleward flowing Davidson Current. It would be impossible to interpret these events without daily observations. With monthly or even weekly sampling, these events would almost certainly be overlooked. To further summarise, the observations at Hopkins (as in many cases) played an important role in contributing in our ability to interpret these data with greater certainty.

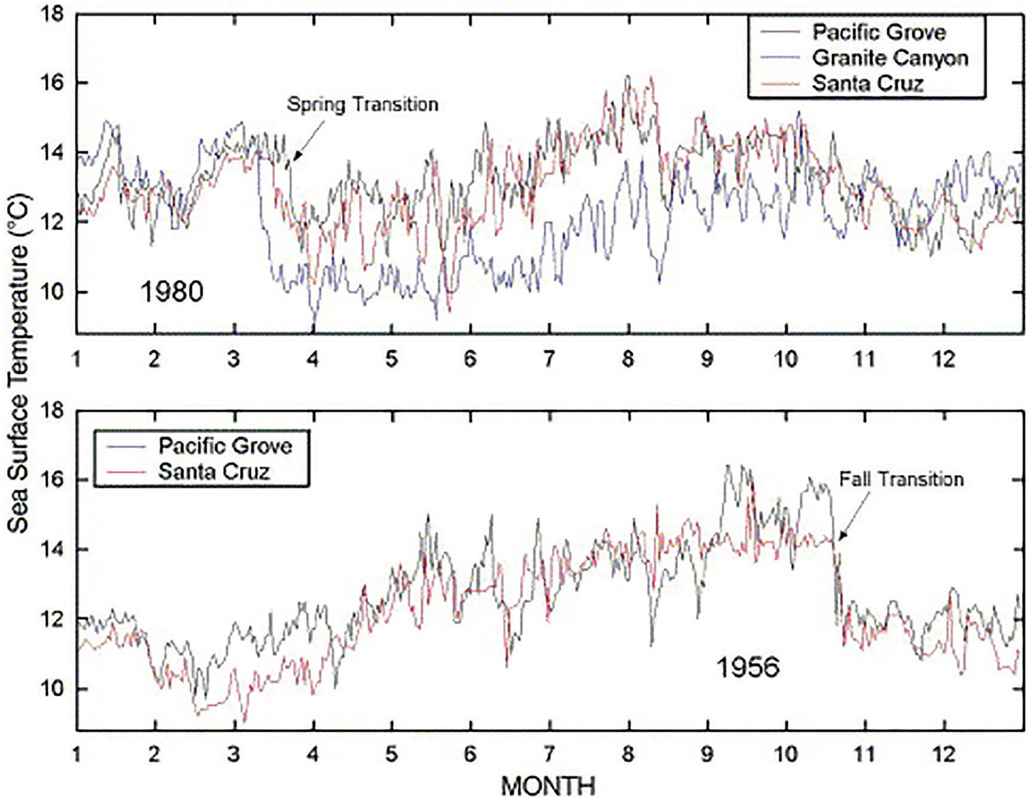

Figure 4 The upper panel shows the daily SSTs for the year 1980 for three locations: Pacific Grove (black), Granite Canyon (light blue), and Santa Cruz (red) (see Figure 1 for the locations). Our primary focus is on March because that is when the spring transition to coastal upwelling occurred. The lower panel shows the daily SSTs for the year 1956 from Pacific Grove and Santa Cruz, a year when the fall transition was particularly evident at these locations. It occurred during the month of October. (Taken from Breaker 2005.)

Let us now return to the rapid long-term increase in SST that occurred in 1929. Figure 5 shows the monthly averaged data from 1920 to 2020 with mean values plotted in red for the periods from 1920 to 1929 and from 1930 to 2020. The actual date of this abrupt increase was in mid-May 1929. It took place in just 2 or 3 days based on the daily observations. Separate calculations show that the overall sustained increase was almost 1°C between the periods before and after this event.

Skogsberg (1936) acquired observations of SST aboard ship in southern Monterey Bay over the 5-year period from 1929 to 1933 within approximately 10 km of HMS that provide additional insight into the event in 1929. According to Skogsberg, "These data again demonstrate that during the first five months of 1929, the temperatures at the surface by and large were subnormal. From June, 1929, until August, 1931, inclusive, they were generally speaking above normal." Several points are relevant. First, further in-depth analysis of Skogsberg's data also indicates that temperatures actually began to increase in May 1929, and second, that subsurface temperatures down to at least 100 m were increasing in unison with the data at the surface.

This event was also searched for in the data from Scripps Pier; although a significant increase in temperature was found in early April 1929, a subsequent sustained long-term increase in SST as far south as Scripps Pier could not be identified. This observation is consistent with that of Parrish et al. (2000) who found extensive cooling off the coast of northern California between 1908 and 1930, but that these anonymously cool waters did not extend as far south as southern California.

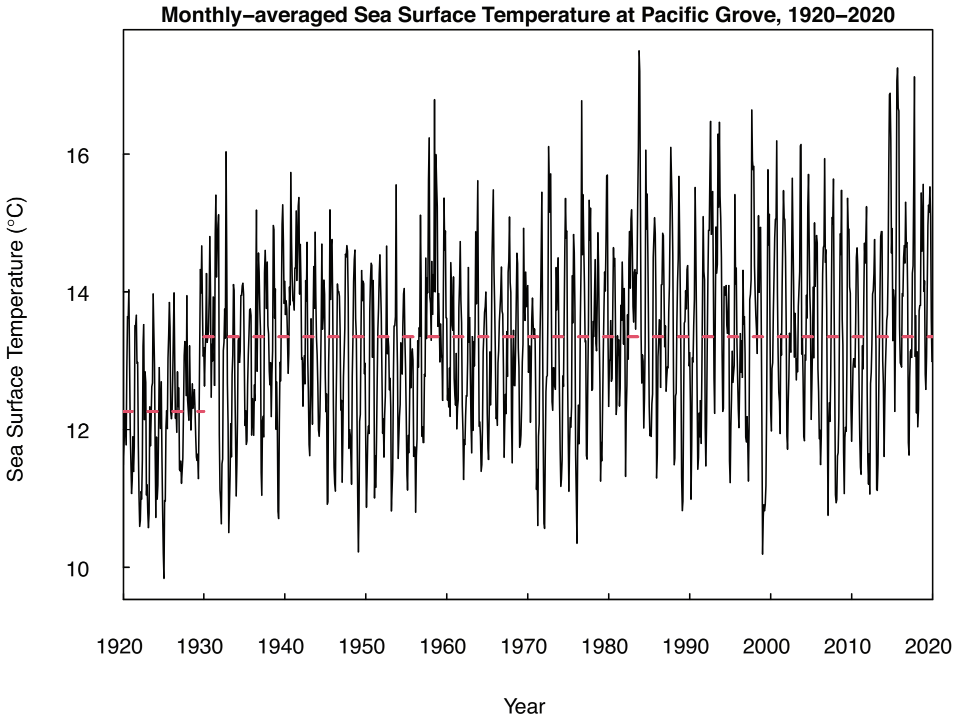

Figure 5 Monthly averaged SSTs from 1920 to 2020 with the mean values included for the periods from 1920 to 1929 and from 1930 to 2020 (dashed red lines).

It is important to emphasise that although no short-term increases in SST along the coast of southern California could be found that were necessarily consistent with the event that was observed at Hopkins, long-term increases in SST did occur off southern California during the 1920s and 1930s that are well-documented based on independent data including data that were obtained from planktonic foraminifera (e.g., Field et al. 2006).

As an aside, it was stated in Breaker (2006) that the event observed in the Hopkins time series in 1929 was a regime shift, even though it is now almost certain that it was not. Regime shifts almost by definition correspond to significant changes in the climate system that often affect both the physical and biological properties of the ocean. More specifically, regime shifts usually correspond to changes in the phase of the Pacific Decadal Oscillation (e.g., Newman et al. 2016). The results of Breaker (2007) indicate that several regime shifts have occurred between 1920 and 2000, but that they did not include a regime shift in 1929 because the timescales associated with regime shifts range from roughly 4 to 9 months, which are far too long to match the abruptness of the event that occurred in May 1929, which appears to have taken place in just a few days or less. Also, regime shifts do not exhibit any obvious surface manifestations, whereas the primary manifestation of this event may well have been its surface signature – the step-like increase in temperature of almost 1°C. Although the cause of this event is unknown, because it appears to have been sustained, perhaps indefinitely, it may represent a significant shift in the state of the ocean or climate system.

Extreme values

Next, the highest values in temperature that have been observed are indicated based on daily observations during the period between 1920 and 2020. Before the Marine Heat Wave (MHW) starting in 2014, the highest value was 19.0°C, which was recorded on 26 September 1983 during the 1982–1983 El Niño, widely regarded as one of the strongest events of the past century (e.g., Quinn et al. 1978). The highest overall temperature in the 100-year record occurred during the MHW in 2015 where a raw value of 21.02°C was observed at 8:10 am PDT (adjusted in the 100-year dataset presented here to 21.24°C at 8:00 am Pacific Standard Time) on 20 July during a period of calm seas.

Record low temperatures, based on the entire record, of 6.9°C were recorded on 23 and 24 December 1998 (adjusted from observed values of 7.0°C at 9:20 am and 9:30 am PST). Each of these events can be easily identified in Figure 2. These low temperatures corresponded to record low air temperatures over the Monterey Peninsula which matched the coldest temperatures on record during the past 50 years as of December 1998 (Renard 1999).

Hopkins and its relationship to the open coast

The closest neighbour to Hopkins is Granite Canyon located approximately 30 km south of Monterey Bay along the open coast (Figure 1). Granite Canyon started collecting daily observations of SST in 1971 and so has a relatively short history. Recent work has addressed the nature of the relationship between Granite Canyon and Pacific Grove in more detail. When events such as the spring transition occur, a significant correlation is found in the data with an average delay of approximately 5 days for the signal to reach Pacific Grove. During these infrequent periods, coastal trapped waves may be generated that contribute to the higher correlations that are observed. In any case, it can be inferred that the path is most likely indirect since a signal entrained in steady uniform flow with a speed of 15 cm/sec would take at most 3 days to travel between the two locations. The findings indicate that, in most cases, the primary sources of variability along the open coast tend to act independently of those well inside the bay at least at these locations because there is a lack of correlation between these sites.

In contrast to the results above, it has been found that when the records at Granite Canyon and Pacific Grove were compared at longer timescales, i.e., decadal and longer, that estimates of long-range persistence or correlation at the two sites were almost identical, suggesting that the lack of similarity between the records discussed above is clearly a scale-dependent issue (see subsequent section on Long-range persistence).

Seasonal and intraseasonal variability

Next, seasonal and intraseasonal variability are examined. First, a power spectrum of the Hopkins data taken from Breaker and Lewis (1988) as of 1983 (Figure 6) is shown. Before addressing the annual cycle, note the source of intraseasonal variability that has a period of approximately 47 days. The central frequency of this oscillation is not fixed but varies within about ± 10% of this value. A weaker indication of its influence appears as the second harmonic at a period of 23.3 days. This oscillation whose source lies in the tropical atmosphere is often referred to as the Madden–Julian Oscillation (Madden and Julian 1971) or simply the 40–50-day oscillation. Its influence is transmitted from the tropics to mid-latitudes primarily via atmospheric teleconnections although there is an oceanic component as well (e.g., Anderson and Rosen 1983). The 40–50-day oscillation is most likely connected to the ENSO cycle and it may, in fact, contribute to its onset (e.g., Zhang et al. 2001). This work and that of Spillane et al. (1987) were the first to report the presence of this oscillation along the central California coast. However, List and Koh (1976) in an earlier study analysed SST data from a number of locations along the California coast including the record from Pacific Grove, observing eight or so distinct temperature cycles each year during the 5-year period from 1966 to 1971. It is almost certain that they had discovered the 40–50-day oscillation but were unaware of its origin or significance.

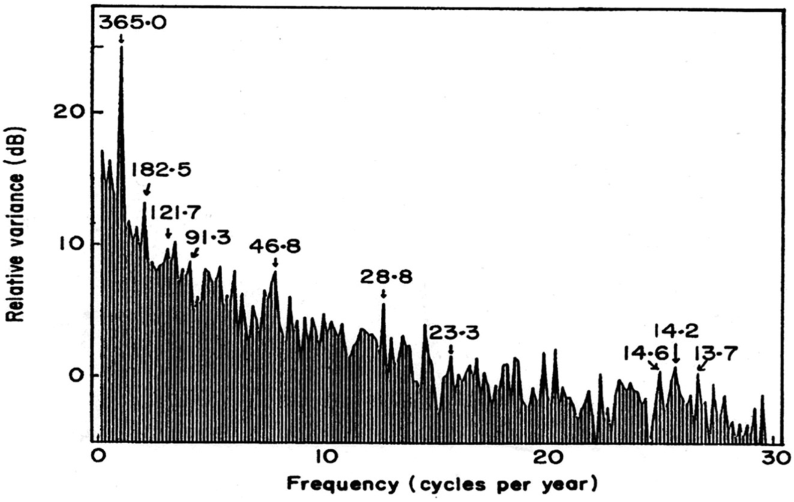

Figure 6 The power spectrum of daily SST from Pacific Grove from 1920 to 1983. The vertical axis is 10Log_{10} of the relative variance expressed in dB and the horizontal axis is in cycles per year (cpy). The numbers shown above selected peaks indicate the corresponding periods in days. Beyond 10 cpy, the peaks are primarily related to the tides and harmonics associated with peaks in the lower part of the spectrum. (Taken from Breaker and Lewis 1988.)

The annual cycle

Next, we consider the annual cycle with a period of 365 days (i.e., 1.0 cycle per year or cpy) where its importance is apparent, and even its second harmonic is noteworthy with a frequency of 2.0 cpy (182.5 days) (Figure 6). A third harmonic can be detected as well with a period of 121.7 days. Breaker (2006) shows that these oscillations are indeed harmonically related to the annual cycle and thus do not arise independently. In essence, they show the departure of the annual cycle from a purely sinusoidal wave form.

The mean annual cycles for Pacific Grove, Granite Canyon, and Santa Cruz are shown in Figure 7 together with unsmoothed versions. The annual cycle at Pacific Grove has a relatively small amplitude with a minimum in January of just under 12°C and a maximum in September of about 14.3°C. This reduction in amplitude is characteristic of regions strongly influenced by coastal upwelling, where temperatures in the summer are significantly lower than temperatures off the coast at similar latitudes. This limited range of temperature is further reduced by the relatively warm waters that flow northwards along the California coast between November and February due to the Davidson Current whose origins lie at lower latitudes.

In slightly more detail, the data from Hopkins also show that the annual cycle is asymmetric with seasonal warming that begins as early as in April and continues through most of September with seasonal cooling that starts in October. Based on model results, this asymmetry is primarily due to the net surface heat exchange which is positive for most of the year, and to a smaller extent, the influence of colder upwelled waters that enter the bay through advective processes during the spring and summer (Breaker 2005).

The dominant feature of the mean annual cycle (MAC) at Granite Canyon is the minimum that occurs in April and May due to the proximity of upwelled waters from the Pt. Sur upwelling centre located just to the south (e.g., Traganza et al. 1981). The MACs at Pacific Grove and Santa Cruz are similar, but greater warming occurs at Santa Cruz during July, August, and September, which may be primarily due to reduced cloud cover at the north end of Monterey Bay.

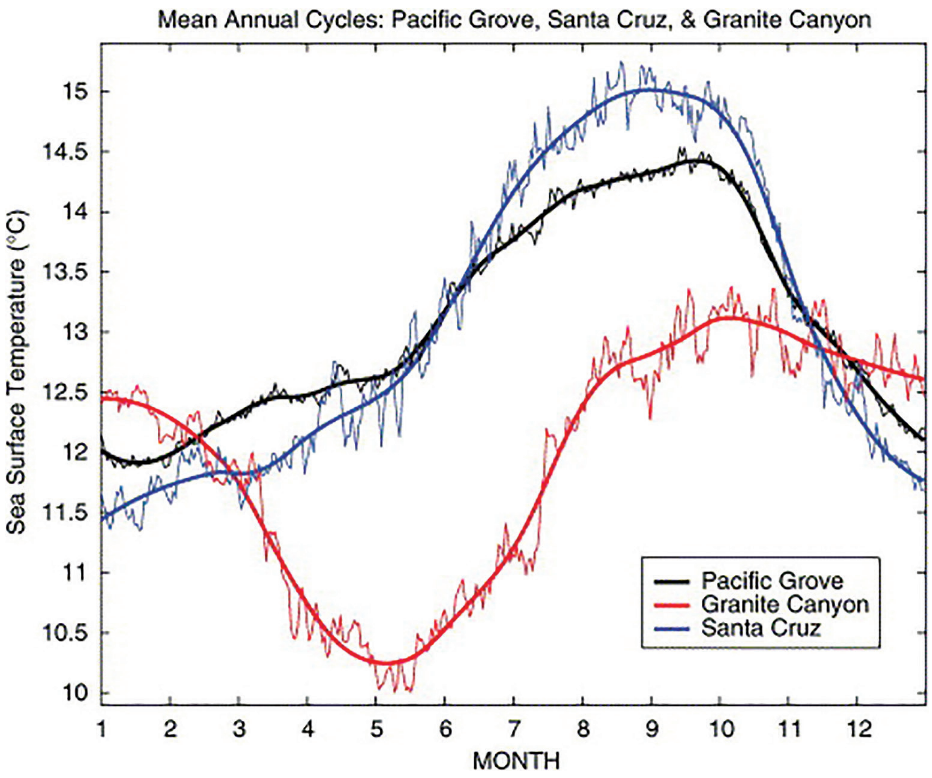

Figure 7 Smoothed and unsmoothed versions of the annual cycles for Pacific Grove, Granite Canyon, and Santa Cruz. The data for Pacific Grove are for the period from 1920 to 2001, for Granite Canyon from 1972 to 1991, and for Santa Cruz from 1955 to 1968. (Taken from Breaker 2005.)

El Niño and interannual variability

On interannual timescales, El Niño episodes are a dominant source of variability along the central coast of California. These events occur on average every 3–7 years and can last from roughly 6 months to up to 2 years (e.g., Talley et al. 2011). All of the major and a number of the lesser El Niño episodes that have occurred during the past and present centuries are shown in Figures 2 and 3. It may not be clear as to how many events should be expected during this period, but, according to Quinn et al. (1978) and other sources, if weak, moderate, and strong events are included, there have been 19 separate episodes during the period from 1920 to 2020, or, on average, one almost every 5 years. With the exception of the annual cycle, El Niño episodes are the largest source of variability in the data accounting for approximately 18% of the total variance (Breaker 2005). Using a threshold of 0.5°C above the mean value for each month, this upper limit was exceeded 27% of the time over the period from 1920 to 2002 thus implying the presence of El Niño conditions.

Decadal and interdecadal variability

Based on the record at Hopkins, Denny and Paine (1998) applied spectral analysis to the Hopkins record and found a maximum in the spectrum at 18.6 years, consistent with the lunar nodal tide, and that the temperature of the nearshore waters was shown to vary with the lunar oscillation. It is argued that *at least* two complete cycles of this tidal component would be required for a positive identification. Thus, without a record that was at least ~40 years long, it might be impossible to identify the lunar nodal tide and further points to the value of relatively long records.

On interdecadal timescales with periods generally in the range of 20–30 years, the Pacific Decadal Oscillation (PDO) is the single largest source of variability in the record and accounts for about 6% of the total variance (Breaker 2005). More recent results from Breaker (2019) indicate that the amplitude of the PDO is almost twice as large inside Monterey Bay as it is outside the bay and that this is most likely due to the fact that the bay is partially enclosed. Thus, the bay may serve as a reservoir of energy for the PDO.

Regime shifts

It may not be surprising that the timescales associated with regime shifts are similar to that of the PDO, i.e., 20–30 years. However, the timescale associated with a single regime shift per se is far shorter. Based on SSTs from Hopkins and several other locations, it has been possible to determine the times of occurrence of a number of regime shifts during the past century, observe how they evolve, and estimate their duration. Their durations range from about 4 to 9 months (Breaker 2007). Based primarily on SSTs, although several other variables were examined, the times of occurrence, how the process evolves or changes over time, and the duration of the entire event, once complete, were identified and estimated. The method of cumulative sums was employed which represents the summation of a sequence of values that is continually refreshed after each new value is added to the sequence (e.g., Hawkins and Olwell 1998). A cumulative sum or CUSUM as they are often referred to enhances the detection process particularly when changes in the mean value of the process occur.

Figure 8 shows the CUSUMs for Hopkins (red) and Scripps Pier (black) during the 1976–1977 regime shift. The CUSUM trajectories for each location are similar suggesting that the magnitude of this event was about the same in each case. The duration of this event was estimated to be about 7 months at each measurement site. Since the CUSUM also serves as a low-pass filter, it may show at a deeper level how similar, in fact, these two records are.

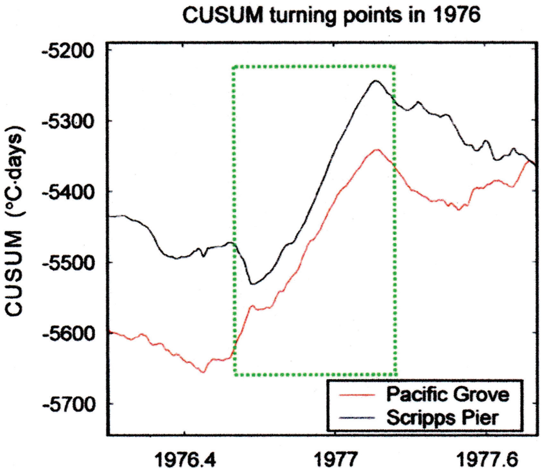

Figure 8 Cumulative sum trajectories for Pacific Grove and Scripps Pier during the 1976–1977 regime shift. The green box indicates the approximate duration of this event which was about 7 months. See text for further details. (Taken and adapted from Breaker 2007.)

Long-range persistence

Long-range persistence (LRP) or long-range correlation as it is often called, since it implies greater correlation at the longer and longest timescales, is a property that is frequently observed in geophysical time series such as hydrology and oceanography (e.g., Pelletier and Turcotte 1997). When we consider the correlation that is expressed in a time series, we usually consider values that are relatively closely spaced in time or adjacent, but LRP essentially represents the degree of correlation that may occur between distant neighbours (e.g., Blender & Fraedrich 2003). LRP in SST was recently estimated at three locations along the central California coast: Pacific Grove (i.e., Hopkins), Granite Canyon, and the Farallon Islands (Breaker 2019). Measures of LRP are obtained by calculating the Hurst exponent (Hurst 1951), which has frequently been used in hydrology, the atmospheric sciences and, to a lesser extent, in oceanography. In the coastal ocean, it provides information on how the influence of coastal waters tends to decrease as the distance between coastal and oceanic waters increases. It also provides information on long-term memory in relation to the global climate (e.g., Zhu et al. 2010). Although only 20-year segments of these records were used in the analysis, the differences in the scaling exponents obtained showed that LRP increased by almost 15% at the Farallons, located almost 20 miles offshore, compared to Pacific Grove (i.e., Hopkins) and Granite Canyon, both of which are located along the coast where similar values were obtained. These results are consistent with the few values that have been reported elsewhere in the north Pacific (e.g., Fraedrich & Blender 2003).

Using power law scaling and SST data from Hopkins and Scripps Pier, Breaker and Carroll (2019) found that the scaling behaviour changed significantly during the ~30-year period between regime shifts that occurred in 1945–1946 and 1976–1977, concomitant with changes in the winds and SSTs along the California coast.

Long-term trends

At the longest timescales, previous work is reviewed in estimating long-term trends in the data from Hopkins. However, as stated by Liebmann et al. (2010), long-term trends can be difficult to estimate because different time periods from the same record can lead to different results. In any case, several estimates of long-term trends have been made starting with the work of Barry et al. (1995) who studied climate-related, long-term faunal changes in the intertidal community at the southern end of Monterey Bay at Hopkins. In a 60-year period between 1931 and 1993 (the exact dates are uncertain), they employed SSTs from the record at Hopkins (1921–1993) from which they obtained an annual mean warming rate of +0.013°C/year (endnote 19 in Barry et al. 1995). They concluded that global climate change was primarily responsible for the results they obtained. In a similar study, Sagarin et al. (1999) for the same location and time period, i.e., ~60 years, used Hopkins SST data from 1920 to 1995 to calculate a warming rate of +0.0125°C/year for the time period, which is close to the value obtained by Barry et al. (1995). They concluded that although climate change was primarily responsible for the observed warming, other factors could have been involved.

Breaker (2005) also calculated long-term trends from the Hopkins data but employed slightly different periods, first from 1920 to 2001 (82 years) and second from 1930 to 2001 (72 years), each including the 1997–1998 El Niño warming event, which occurred after the Barry et al. (1995) and Sagarin et al. (1999) periods of analysis. For the first period, Breaker obtained a rate of +0.0105°C/year. As stated earlier, the second period was employed to examine the influence of the cold period from 1920 until 1929 just before the cold period ended. According to Parrish et al. (2000), the cold period off northern California actually began in 1908 and ended ca. 1930. Based on the two periods, the slope decreased from +0.0105°C/year to +0.0042°C/year. This reduction in the slope was over 50%, and in the first case (the full 82 years), the slope was statistically significant with a confidence

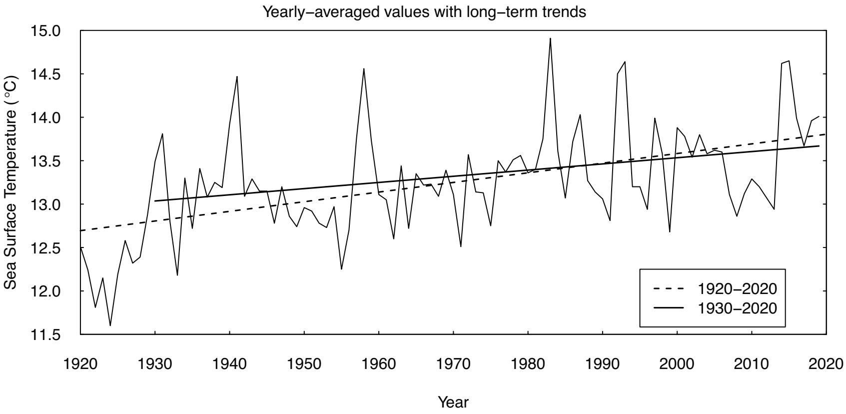

Figure 9 Yearly averaged temperatures at Hopkins with linear trends included. The dashed line shows the entire period from 1920 to 2020 and the solid line shows the period from 1930 to 2020.

level of 95%, but in the second case (72 years), the slope was not statistically significant at the same level. We repeated the same analysis here with the 100-year dataset, comparing the effect of including the first decade of data (1920–1929) versus excluding it. With the inclusion of 20 more years of data through the end of 2019, the slope for the full 100 years was 0.0111°C/year ($R^2 = 0.27$), and when the colder period from 1920 to 1929 was excluded, the slope decreased to 0.0071°C/year ($R^2 = 0.12$), though both versions of the regression were now significant ($P < 0.001$).

The two trends are shown in Figure 9 making it a simple matter to see the impact of the first 10 years. It comes as no surprise that the location of the cold period is crucial to its impact on the slope. If, for example, the cold period had occurred at a more central location within the record, its impact could have been minimal.

To summarise, the results of Breaker (2005) are generally similar to those obtained at Scripps regarding the long-term trends. Rasmussen et al. (2020) state that trends for records longer than a few decades are positive during the twentieth century and that trends for more recent records acquired since ca.1950 are not only positive but also strongly positive. Supporting these results, the more recent results from Checkley & Lindegren (2014) also concur with the warming patterns observed earlier. Regarding the results from HMS, if the cold period during the 1920s is included, then the long-term trends are positive and on the order of +1.0°C/100 years. Although the trends are still positive, they are weaker for records that do not include the cold period during the 1920s. Also, our results over the long term are consistent with those obtained at SIO except for the cold period observed prior to 1930. Finally, the impact of the MHW, which started in 2014 and is discussed in the next section, has been compelling at both Hopkins and Scripps Pier. This impact takes the form of an increase in temperature that is due to several factors. First, it is due to the overall magnitude of the sustained increase in temperature which has been reported to be from 2.0°C to 2.5°C; second, the duration of the MHW which has been at least 5 years (and may still be ongoing); and third, due to its location within the record (at the tail end), it will undoubtedly have a major impact on the long-term *linear* trend.

The marine heat wave since 2014

The final section has been reserved for what has occurred since 2014, which are considered highly unusual and unexpected oceanographic conditions along the west coast of California and Monterey Bay. A brief overview of what has transpired off the west coast since 2014 is presented and then the data from Hopkins is examined to see if any evidence can be found to support the larger-scale picture. The year 2013 is included as a point of reference since it serves to separate the most recent period of unusually high temperatures from the past 93 years, which have generally been more quiescent aside from a number of El Niño episodes.

Starting in the winter of 2013–2014, a large thermal anomaly formed in the north-eastern Pacific. By the summer and fall of 2014, the warming had reached the Pacific coast, and by the end of 2015, the anomaly extended from the Gulf of Alaska to Baja California essentially encompassing the entire coast of California (e.g., Di Lorenzo & Mantua 2016).

During 2014 and 2015, much higher SSTs were observed off the west coast and warm conditions prevailed in the North-east Pacific. This major warming event is called the North Pacific Marine Heat Wave (MHW). The term is attributed to the fact that 2014–2016 was the warmest 3-year period on record at Scripps Pier (Frölicher & Laufkötter 2018 and Frolicher et al. 2018). It is important to note that the processes leading up to this event, its persistence, and its decay are poorly understood.

By 2015, SSTs had decreased slightly along the west coast but were still well above average. Along the coast, SST anomalies in some cases exceeded 2.5°C during this period (CalCOFI Report 2016). Also, during this period, not only was the MHW in effect but also an El Niño occurred that started in the winter of 2015. The effects of this El Niño, i.e., the El Niño of 2015–2016, contributed to the overall observed warming, but its impact according to the same CalCOFI Report was significantly less than the impact of the 1997–1998 event.

Following the MHW that arrived along the central California coast in 2014 and lasted until 2016, oceanographic conditions north of Pt. Conception during the period from mid-2017 to mid-2018 gradually approached those more typical of the region. SSTs were close to expected values along most of the California coast but warmed to record levels by the summer of 2018 off southern California (CalCOFI Report 2018). Overall, north of Pt. Conception, the California Current System (CCS) by mid-2018 had returned to an approximately normal state, although 'remnants' of the MHW could still be detected further north (ibid.).

According to Thompson et al. (2012), the CCS has largely been in a warm state since 2014. A mild El Niño started in late 2018 further continuing the prevalence of relatively warm waters along the coast of California and further north well into 2019. Finally, to complete the year, although temperatures along the coast of California remained near normal or slightly cooler than normal during the spring and early summer of 2019 (https://www.ncdc.noaa.gov/oisst), another MHW formed off the Gulf of Alaska in May, and by August, its impact had been observed as far south as central California (Amaya et al. 2020).

Since 2014, significantly higher SSTs have been observed off central California. Specifically, higher SSTs were first observed in early 2014 at HMS and have persisted throughout the remainder of the record. Figures 2 and 3 show the period from 2014 to at least 2017 with the highest monthly averaged temperatures ever observed at Hopkins. Figure 10 shows the 7-year period for the daily values from 2013 to 2020. Figure 10 in the upper panel shows these observations together with the MAC and in the lower panel shows the SST anomaly or difference between the observations and the MAC. As indicated earlier, the year 2013 is included to provide a link to the past and shows close agreement with the MAC, the only year that does so from that point on.

The observations from Hopkins reveal temperatures during 2014 and 2015 that were often as much as 3°C higher than expected values with the extremes occurring primarily during the summer and fall months. In addition to the MHW, as mentioned, a moderate El Niño developed during the 2015–2016 time frame that may well also have contributed to the observed warming. Some cooling had occurred by 2016 as indicated in Figure 10 (upper panel), but temperatures were still almost 2°C higher than normal for most of the year excluding the last 2 months. Although temperatures generally indicated a return to near normal conditions along the coast of California by 2017, SSTs reached values of 18°C or higher in September at Hopkins. According to Wells et al. (2017), areas of warmer-than-average hot spots were detected during the year in the northern CCS, but a more detailed explanation for the unusually high values observed

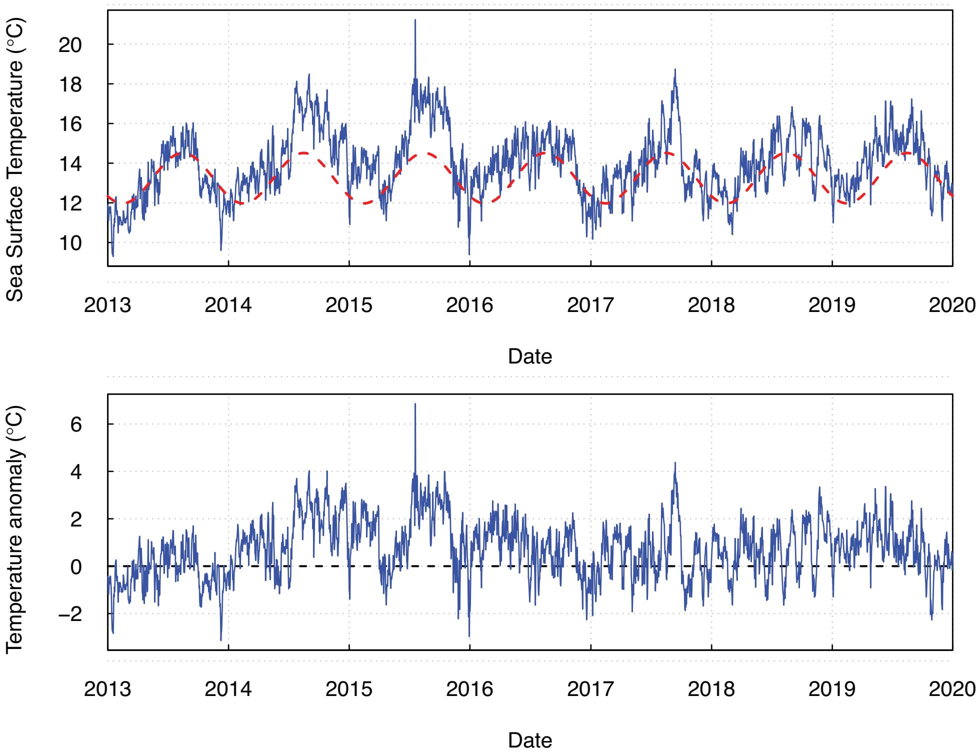

Figure 10 The upper panel shows SST for the period of daily observations from 2013 to 2019 with the mean annual cycle (MAC) included (dashed in red). The lower panel shows the difference between the original data and the MAC, or the anomaly. Note the strong positive bias in the anomaly starting in 2014.

in southern Monterey Bay during this period would be preferable. Higher-than-expected temperatures in southern Monterey Bay were recorded during 2018 as well, but the mild El Niño of 2018–2019 may have also contributed to these higher values. Although temperatures were close to normal along the coast of California starting in 2019, in southern Monterey Bay, they were clearly higher than average between the months of April and September. After September, temperatures decreased sharply, but by the end of the year, it is possible that the first signs of a second MHW were detected (CalCOFI Report 2019).

Returning to the lower panel in Figure 10, from 2014 through 2019, the anomaly, which is based on the full 100 years of data, is strongly biased towards positive values. Typically, the anomaly is expected to be centred approximately on zero as it appears to be in 2013. However, the average anomaly is almost +1.39°C during the years of 2014 and 2015. And for the entire period of 2014–2019, almost 67% of the anomalies are positive. Thus, this period is truly unique making it difficult at best to compare it with any other period of significant duration in the entire record.

Evidence for an increase in non-stationary behaviour since 2013 in the Hopkins record is apparent and suggests that significant changes in the processes involved (both oceanic and atmospheric) are at work. Changes in the mean value are observed that are readily apparent from inspection, but more specifically, from the sign and magnitude of the anomaly which is based on the entire record. Although not shown, changes in the variance or second moment have occurred as well. Also, the tendency towards increased peakedness, most apparent in 2014 and 2015 and in 2017, is consistent with increases in the variance and in non-linear behaviour (e.g., Kantz and Schreiber 2004).

The period from 2014 to 2020 based on the record from Hopkins represents a period of change that appears to be unprecedented. In this regard, 2013 serves as a link that connects essentially different oceanic regimes whose properties and processes most likely differ to a significant degree. Whether oceanic conditions gradually return to pre-MHW conditions or this change represents a permanent reset to a new initial state may take years to determine.

Non-linear behaviour

The topic of non-linear behaviour could have been introduced at almost any point earlier in this section since the timescales associated with non-linearity are highly variable. Perhaps one of the best questions one could ask about non-linearity is why does it matter? When the system under study changes from one that is essentially linear to one that is non-linear (or vice versa), it often indicates that the oceanic process or processes that govern the system have changed significantly. Also, a number of the methods that are used in statistics and spectral analysis assume that the data are linear or at least approximately linear.

Breaker (2006) found indications of non-linear behaviour in the Hopkins record from relatively large, rapid increases in temperature that corresponded to intrusions of warm water into Monterey Bay that lasted for periods as short as several days. It is also most likely that many of the major peaks in SST that occurred in 2014 and 2015 during the MHW (and in years following) are non-linear as well.

El Niño warming episodes have also been shown to exhibit non-linear behaviour during the periods of higher-than-average temperature. Because El Niño warming is a rather frequent occurrence, we must assume that non-linearity, although not necessarily a constant companion, is a common occurrence as well. Finally, the question was addressed of whether or not the annual cycle and the semi-annual cycle which usually accompanies the annual cycle are harmonically related? It was found that these two cycles are indeed harmonically related, and thus, the semi-annual cycle does not arise from a separate source. In Figure 6, a third harmonic can also be observed at a period of approximately 121.7 days. These harmonics essentially represent the degree to which the annual cycle departs from a linear basis.

Biological studies utilising the temperature time series

The utility of the long-term record of daily SST at Hopkins Marine Station for studies of the biological community at the station and surrounding areas has been illustrated in several groups of studies. Within the first decade of its establishment, the HMS temperature record was being held up as an exemplar of the types of long-term environmental records that would be useful in tracking changes in fisheries and biological communities (Hubbs & Schultz 1929). Hubbs and Schultz were primarily reporting on the occurrences of southern warm water species such as *Mola mola* sunfish, *Velella velella* Portuguese man-o'-war, and *Atherinopsis californiensis californiensis* jack smelt in the waters of Oregon, Washington, and BC during the 1925–1926 El Niño. They lamented the fact that there was no historical record of SSTs in those regions similar to what was available for the Monterey Bay at the time. In more recent years, the SST record has been used in a number of studies that are grouped broadly here into historical ecology studies, fisheries and life-history studies, and biophysical studies.

Historical ecology

The work of Barry et al. (1995) and Sagarin et al. (1999) was previously discussed as well-known examples of 'historical ecology' studies that attempt to discern patterns in community change over long time intervals based on revisiting the sites of earlier community surveys. The study first detailed in Barry et al. (1995) was initiated as an undergraduate research project to reoccupy and resurvey a fixed transect located in the intertidal zone at HMS. The transect was originally established in 1930 by a Stanford graduate student, W.G. Hewatt, who carried out detailed counts of animal species (and some algae community observations) from 1931 to 1933 through the high, mid, and low intertidal zones. In his original publication, Hewatt (1937) included a time series of water temperature data from the HMS record and remarked on the potential effect that water temperature, in addition to other factors such as emersion time and weather conditions, might have on the identity and abundance of organisms found in the survey site. After an approximately 60-year interval, Barry and co-authors found that several species of invertebrates with range centres predominantly in southern California had become more abundant at HMS, while species with northerly range centres had declined compared to Hewatt's 1930s baseline. They hypothesised that those changes might be linked to the increases in minimum, mean, and maximum water temperatures found in the HMS temperature record.

Denny and Paine (1998) noted that the surveys carried out by Barry et al. (1995) in the years 1993–1995 coincided with a minimum in the 18.6-year lunar inclination cycle, while Hewatt's original surveys occurred around the time of a maximum in the 18.6-year cycle, which could have influenced the makeup of the intertidal community due to changes in emersion time and associated changes in water temperatures on the shore. In more recent years, Micheli et al. (2020) have continued re-surveying the Hewatt transect and found evidence that the abundances of southern species present in the 1990s had declined in the intervening two decades (1995–2015). Species with more cosmopolitan coastwide distributions also declined for much of that time, but the more recent warm period (2014–2019) saw an uptick in those wide-ranging species. These continuing surveys will rely on the long-term water temperature record to assess the potential for climate change-related impacts on the shoreline flora and fauna.

Additional historical ecology studies have similarly made use of the Hopkins temperature record to investigate the role of water temperature in affecting species distributions, body size, and abundance on the shore. Hopkins graduate student L.J.H. Hunt (2006) used historical photographs to identify shifts in the upper shore limit of the algae *Endocladia muricata* on the Hopkins shoreline, where it creates a highly visible dark band against the native granite bedrock's light tan colour. Among these historical photographs were images taken in the 1960s by P. Glynn while working on his own graduate thesis (Glynn 1965) on the *Endocladia* and barnacle zone interface. Both Glynn in the 1960s and Hunt in the 2000s relied on the Hopkins water temperature record to determine whether shifts in the algae or barnacle distributions might be linked to water temperature. The historical reconstruction of *Endocladia* shore height distributions by Hunt indicated that relatively sudden shifts in the upper limit were likely driven by a combination of recruitment pulses and subsequent cooler local weather conditions that relaxed desiccation and temperature stress at low tide, with water temperature perhaps playing a less direct role.

Elahi et al. (2020) carried out re-surveys of snail and limpet body sizes, abundances, and shore height distributions on the Hopkins shoreline, again making use of older studies and the long-term water temperature and weather records to evaluate hypotheses regarding the role of climate warming. Body size distributions for three intertidal gastropod species generally trended downwards between initial samples taken in the 1940s, 1950s, and early 1960s, compared to re-surveys done in the 2014–2015 time frame. The observed trend was consistent with the temperature-size rule for ectotherms (Atkinson 1994), although the authors indicate that a variety of other environmental and biological influences could potentially be operating in this system.

Fisheries and life-history studies

The long-term temperature records have also been used in the analysis of Monterey fisheries trends. Brady (2008) found significant correlations between market squid (*Loligo opalescens*) body sizes and SST and upwelling dating back to the 1940s. Smaller body sizes were associated with warmer temperatures at the time of capture and also for the period of 7–11 months prior to capture, which could be tied to temperature and upwelling conditions around the time of egg deposition or hatching in this short-lived species. Dalton (2001) compared the Hopkins SST data against historical fisheries catch reports from 1981 to 1999 for albacore tuna (*Thunnus alalunga*), Chinook salmon (*Oncorhynchus tshawytscha*), sablefish (*Anoplopoma fimbria*), and market squid in Monterey Bay. Periods of warmer water temperatures associated with the 1983–1984 and 1997–1998 ENSO events were associated with a temporary increase in albacore tuna landings but a decrease in other species.

The daily SST dataset has also served as evidence of upwelling periods, which have been linked to abundance and growth rate changes in several species around the Monterey Peninsula. Larval fish abundance offshore of Monterey was associated with colder water temperatures linked to seasonal upwelling and a reduction in abundance during the anomalously warm 1983 ENSO event (Wallace 1988). Giant kelp (*Macrocystis pyrifera*) cover and productivity increased after periods of high water movement, followed by upwelling of cold water and nutrients to support high growth rates (Gerard 1976). Densities of several species of intertidal and subtidal spider crabs increased with increasing water temperatures and reduced ocean swell during the summer and autumn seasons (Hines 1982). For each of these examples, temperature alone was likely not the sole or primary driver of the changes in abundance or productivity, but the Hopkins temperature record served as a record of probable upwelling events until more direct measures such as ocean buoys and satellite ocean colour data could be brought to bear on the problem of documenting coastal upwelling.

Biophysical studies

The Hopkins daily SST dataset has also proved useful in a variety of biophysical studies that attempt to reconstruct time series of intertidal organism temperatures (Johnson 1975, Denny et al. 2006, Harley et al. 2009, Miller et al. 2009, Miller & Denny 2011, LaScala-Gruenewald & Denny 2020). These studies use heat-budget modelling methods to estimate temperature fluxes into and out of the rock surface or the animals or algae themselves, and rely on a variety of environmental parameters, including SST. Heat-budget modelling can operate from gridded environmental data interpolated from ground stations or remote sensing sources (Mislan & Wethey 2011), but environmental data measured in situ, particularly at daily or shorter time intervals, are often desirable for these methods. In a similar vein to the hindcasts of organismal body temperatures, the HMS water temperature record has also been incorporated into statistical approaches to forecast the frequency and intensity of future extreme temperature conditions on the shore and how those might impact organismal survival (Gaines & Denny 1993, Denny et al. 2009, Denny & Dowd 2012).

Discussion

The record of daily SST at the Hopkins Marine Station in Pacific Grove, California, has now passed the 100-year mark, a record that started in January 1919. It has only been surpassed along the U.S. West Coast by the record of SST acquired at Scripps Pier in La Jolla, California, a programme that started 3 years earlier (1916). Based on the information that is available, it would be fair to say that the programme at Hopkins was 'modelled' after the one at Scripps allowing for small differences in the procedures that have been used in the data collection process.

In a record of daily observations that has grown to be 100 years long, it is almost inevitable that problems in data acquisition would arise. Two problems arose in data quality that were highly significant and they were discussed earlier in the text. Briefly stated, the first problem was due to variations in the TOD when the observations were acquired although the intention had always been to collect the data at 08:00 am PST each day. Problems of a similar nature were also encountered with respect to observation times at SIO (Rasmussen et al. 2020).

The second problem was due to missing data or gaps that occurred in the record. One gap spanned the entire year of 1940. With respect to this gap, it appears that there was no intent to discontinue data collection at that time but rather the data for that year were simply lost. As discussed earlier, approximate solutions for these problems were found. In the future, one solution for the TOD problem would be to implement an automated data collection system, but SIO and Hopkins have, to date, not done so. Noteworthy is the obvious fact that existing procedures are basic and simple to perform in practice, and as a result, it may be more reliable.

The possibility of using satellite data in support of the analyses that have been presented was considered particularly with regard to the missing year of data from 1940. If we could have used satellite data as a proxy for the missing year, it would have been very helpful. The primary source would have been satellite-derived SSTs using daily observations from the AVHRR (Advanced High Resolution Radiometer). Unfortunately, there were several factors that weighed in heavily against this possibility. First, no satellite data with application to the ocean existed prior to the mid-1970s off the west coast of the U.S., and of course, the year we were missing was 1940. Second, because the temperature data are acquired at the shoreline, the spatial resolution of most satellite instruments has not been high enough (~1 km) to separate the water from the adjacent land at the water's edge. Satellite instruments in operation today, however, may have sufficient resolution to address this problem depending on the nearshore gradients in SST.

With regard to uncertainties in data quality, the periods of greater uncertainty are generally known as well as the nature of the uncertainties (random or biased). Clearly, the uncertainty is greater during the periods of missing data, but the uncertainties associated with the TOD problem are less clear. It was suggested that, in the earlier years of the record without available TOD information, the data might show a bias towards higher temperatures on the weekends due to later observation times, but that hypothesis was subsequently disproved. As a result, this gave greater confidence in the quality of the observations that were acquired during the week. Overall, however, uncertainty in the data due to the TOD problem, to the degree that it does exist, will, for the most part, contribute to positive biases because the data tend to be collected later rather than earlier in the day.

Finally, what climate-related questions can or cannot be adequately addressed or will be adversely affected by variations in data quality perhaps similar in nature to those we have already encountered? Estimating the magnitudes of major events should be largely unaffected, such as El Niño, which includes their beginning and end times. However, some smaller-scale events might be more problematic in nature. Estimating the timing and the relative impact of regime shifts as well as detecting and identifying them should not be a problem. Also problems are not anticipated in identifying change points such as the one observed in May 1929. Though not necessarily due to problems in data quality per se, the issue of weaker signals and delayed arrival times at Hopkins, as discussed earlier, may make it more difficult to identify the spring and fall transitions. There should be minimal impact on periodic phenomena such as the annual cycle and the 40–50-day oscillation. Likewise, there should be little or no impact in the ability to identify and characterise the Pacific Decadal Oscillation. Thus, the problem of data quality should have at most a minimal impact on detecting and describing major events regardless of timescale in most cases.

At least one exception occurs when one attempts to identify precise values of temperature to obtain the highest and lowest values in the record. If there had been a significant bias (or random error) in temperature for either of the two dates in question, then, of course, there would be a serious problem. In this case, an analyst has to rely heavily on neighbouring values for support. In each case, such support was observed but still there is a question on the validity of the exact values that are quoted. Also, further problems could arise when comparing different time periods, estimating rates of change such as long-term and local trends, and using derived parameters where small errors can be magnified. Overall, however, for the applications that are anticipated in the future, data quality is not expected to be a limiting factor. This will be due, at least in part, to what is hoped to be an increased awareness of such problems that have occurred in the past.

Next, the question arises as to why longer records are of greater value? It might be argued that the value of a record is in direct proportion to its length, but this may be an oversimplification depending on the nature of the processes involved. Longer records, however, do allow one to identify or resolve processes that might otherwise be unknown. It also helps to distinguish between processes that are basically oscillatory in nature from those that are trend-like. Longer records also help to identify stationary versus non-stationary processes. Another benefit from longer records is that it allows one to put various processes in perspective so that their frequency of occurrence, their repeatability, and their uniqueness can be examined. The El Niño phenomenon is a primary example of the latter.

Next, consideration is given to the location of the observation site at Hopkins. Oceanic signals tend to be delayed in time and reduced in amplitude at Hopkins located inside the bay, compared to Granite Canyon and elsewhere along the central California coast. Correlations between Granite Canyon and Hopkins, for example, are generally low as stated earlier and so the question of representativeness can be raised. Perhaps the better question, however, is what should be expected of observations that are acquired well inside the bay in this regard? Again, timescales are important. It is clear that the degree of representativeness should increase as the timescales increase. Looking back at the choice of monitoring sites, a location along the open coast might have been preferable to one located along the coast of southern Monterey Bay. However, it is important to note that it is perhaps only since the 1940s or later that we have gained sufficient knowledge to make such informed decisions.

Next, the question of similarity between the records at Hopkins and Scripps Pier arises. There are indeed major similarities between these records. First, the long-term trends are both positive and of the same order (i.e., ~+1.0°C/100 years). Also, although the amplitude of the annual cycle at Scripps Pier far exceeds the annual cycle at Hopkins, when both annual cycles are removed, the scaling properties that are indicative of long-range persistence and correlation are very similar (Breaker and Carroll 2019). Further evidence for the underlying similarity between the two records can be found in Figure 8 where the cumulative sum profiles are almost identical with respect to the impact of the 1976–1977 regime shift, even with a separation distance between the locations of almost 700 km.

The long-term time series has been used in a variety of marine biological studies, including those examining the potential link between seawater temperatures and species or community changes through time. Some of these studies (e.g., Barry et al. 1995, Sagarin et al. 1999) were the first to describe biological responses to rapid anthropogenic climate change, and they would not have been possible without the temperature time series at Hopkins. Elsewhere, similar groundbreaking studies on ecological responses to natural climate fluctuations and distinguishing them from those driven by anthropogenic climate change (e.g., work in the English Channel: Southward 1991, Southward et al. 1995, Southward et al. 2004; Hawkins et al. 2003; Genner et al. 2004) also heavily drew on temperature time series at fixed nearshore or inshore stations.

The existence of the Hopkins SST time series makes it relatively straightforward to incorporate seawater temperature into statistical or mechanistic models, but authors have rarely been able to identify seawater temperature alone as the main cause of observed changes or trends in the biological system. The historical ecology studies described here rely on observational data, since controlled manipulations of seawater temperature in natural settings are difficult to achieve, thus limiting the ability to make causative links between seawater temperature and species abundances and distributions. Besides the direct effects on organismal performance via changes in metabolic or behavioural shifts in response to changing water temperature, there are myriad of other indirect effects of shifting water temperature that may be hypothesised to cause changes in species abundance and diversity. For instance, local seawater temperatures may influence weather conditions including fog (and thus solar irradiance and heating) or humidity (and thus desiccation rates). Warming or cooling water temperatures could potentially cause indirect effects through trophic webs, and seawater temperature changes may be correlated with other changing physical variables that often have far less data available, such as dissolved oxygen, pH, alkalinity, and even salinity. The power to directly link SST to community changes will continue to be limited by the complexity of the interacting physical and biological systems and the relative difficulty of performing controlled manipulative trials of the sort necessary to recreate the observed changes in field conditions, but SST can potentially serve as an important indicator for these multiple pathways that could affect biological communities.

In closing, as stated earlier, since 2014, there has been a period of change that is unprecedented along the coast of California, and this is further supported by the Hopkins data. An important question that arises at this point is whether or not the changes that have occurred since 2014 are essentially transient in nature and will return to pre-MHW conditions similar to those observed in the past, or whether they could represent a permanent change or reset in the climate system?

Conclusions

1. The record of daily SSTs that have been acquired at the Hopkins Marine Station in Pacific Grove, California, is one of the longest oceanographic records in existence. It began in January 1919 and has continued ever since. It is exceeded in length by the record at Scripps Pier by only 3 years.
2. A number of problems arose during the acquisition of the data at Hopkins, two of which affected the integrity and quality of the record. The first problem was due to variations in the TOD when the data were collected although the intention had always been to collect the data at 08:00 am PST each day. Many times, but not always, solutions to this problem were found. The second problem was due to missing data or gaps in the record. Several gap-filling procedures were used depending on the nature of the gap, but the primary goal was to maintain continuity in the record. Thus, it is concluded that uncertainties in data quality do exist and that greater confidence in the results should not be expected than the data permit.
3. Although serious problems were encountered during the acquisition of the record at Hopkins, data quality should not be a limiting factor to answering most climate-related questions.
4. Oceanic signals travelling northwards along the central coast are generally reduced in amplitude and delayed in time at Hopkins located inside the bay compared to Granite Canyon located on the open coast ~15 km to the south (Figure 1). In retrospect, monitoring sites along the coast may have been preferable to those located in southern Monterey Bay for daily monitoring, but during the early years of this programme, there was not sufficient information to make well-informed decisions on site selection.
5. Coastal observations may be of slightly higher quality than data acquired from models where spatial and/or temporal interpolation is required as is often the case today. Thus, model-derived data essentially correspond to smoothed estimates of the true values.
6. The abrupt and sustained increase in SST in May 1929 that was observed in the Hopkins record may represent a local manifestation of the global increase in SST that took place during the 1920s and 1930s. Although this observation has been discussed in other reports, the interpretation given here is new.
7. Spectral analysis of the Hopkins record conducted by Denny and Paine (1998) revealed a maximum in the spectrum at 18.6 years, which is consistent with the lunar nodal tide. Only from a record of 40 years or more, it would have been possible to identify the lunar nodal tide.
8. Prior to the MHW onset in 2014, the highest temperature that had been recorded over the 100 years of record was on 26 September 1983 during the 1982–1983 El Niño. In 2015, that value was exceeded by a measurement of 21.02°C (adjusted to 21.24° based on TOD corrections in our reconstructed record) on 7 July during a period of calm seas and sunny weather.

9. The changes in coastal waters from Baja, California, to the Gulf of Alaska, and more specifically, the changes that have been observed along the coast of California and within Monterey Bay are due primarily to the MHW that began in 2014 and *are unprecedented*. This statement is supported by the observations that have been acquired at HMS over the past 100 years.
10. Although the amplitude of the annual cycle at Scripps Pier far exceeds the annual cycle at Hopkins, when both of them are removed, the two records are surprisingly similar.
11. It has been concluded based on this record and many of the other records along the U.S. West Coast that, overall, they have been vastly underutilised (e.g., Breaker 2005).
12. Finally, with regard to the importance of coastal monitoring, Micheli et al. (2020) state that marine observing sites can play a unique and critical role as ‘sentinels’ of ocean change. The Hopkins record has been used precisely for this purpose in relation to the major warming event that occurred in May 1929, as well as in biological studies that correlate temperature increases with species shifts over long time periods and studies that use the data as inputs into models designed to hindcast and forecast organismal performance and survival.

Data availability

The Shore Stations Program at Scripps Institution of Oceanography provides copies of the Pacific Grove SST records at their website https://shorestations.ucsd.edu and a permanent digital archive at https://doi.org/10.6075/J0S75GHD. A copy of the gap-filled and time-of-day adjusted 1919–2020 dataset presented in this manuscript is provided in a Zenodo archive: https://doi.org/10.5281/zenodo.7041718

Dedication and acknowledgements

This review is dedicated to those individuals who have made it possible to celebrate the first 100 years of sea-surface temperature (SST) data collection at the Hopkins Marine Station (HMS) in Pacific Grove.

The timely assistance of Dr. Joe Wible and Dr. Amanda Whitmire is much appreciated. In addition, without the assistance of Donald Kohrs, this work would not have been possible. We thank Former Director of the NOAA/National Marine Fisheries Laboratory in Pacific Grove, California, Mr. Gunter Seckel, for his comments on observing, first hand, the spring transition to coastal upwelling over a period of several years. Finally, it is with great pleasure that we acknowledge the assistance that Mr. Alan Baldrige gave the author over many years, first at the Naval Postgraduate School and then at the Moss Landing Marine Laboratories.

We would further like to acknowledge the unexpected interest that has been shown in recent years in the report entitled “Reconstructing an 83-year time series of daily sea-surface temperature at Pacific Grove, California”, by Breaker, Broenkow, and Denny (2006). We have received many requests for copies of this report which may be due to the fact that it was never published in a peer-reviewed journal and, as a result, has been more difficult to access. Copies can be obtained directly from http://aquaticcommons.org/3129/.

We thank Aya Kareem for her efforts in re-examining the log sheets stored at Hopkins Marine Station and entering data used in the reconstruction of the 100-year dataset. This is contribution #83 of the San Diego State University Coastal and Marine Institute.

Original water temperature data were provided by the Shore Stations Program sponsored at Scripps Institution of Oceanography by California State Parks, Division of Boating and Waterways, Award# C1670003. Contact: shorestation@ucsd.edu.

References

Amaya, D.J., Miller, A.J., Xie, SP. & Kosaka, Y. 2020. Physical drivers of the summer 2019 North Pacific marine heatwave. *Nature Communications* **11**, 1903.

Amos, C.L., Al-Rashidi, T.B, Rakha, K., El-Gamily, H. & Nichols, R.J. 2015. Sea surface temperature trends. *Current Development in Oceanography* **6**, 1–13.

Anderson, J.R. & Rosen, R.D. 1983. The latitude-height structure of 40–50 day variations in angular momentum. *Journal of Atmospheric Sciences* **40**, 1584–1591.

Atkinson, D. 1994. Temperature and organism size: A biological law for ectotherms? *Advances in Ecological Research* **25**, 1–58.

Barry, J.P., Baxter, C.H., Sagarin, R.D. & Gilman, S.E. 1995. Climate-related long-term faunal changes in a California rocky intertidal community. *Science* **267**, 672–675.

Blender, R., & Fraedrich, K. 2003. Long time memory in global warming simulations. *Geophysical Research Letters* 30, 1769–1772.

Bloomfield, P. 1976. *Fourier Analysis of Time Series: An Introduction*. New York: John Wiley & Sons.

Brady, B.C. 2008. *Long-term changes in biological characteristics and fishery of* Loligo opalescens. Master's thesis, San Jose State University, 83.

Breaker, L.C. & Carroll, D. 2019. The impact of regime shifts on long-range persistence and the scaling of sea surface temperature off the coast of California. *Journal of Geophysical Research: Oceans* **124**, 3206–3227.

Breaker, L.C. & Lewis, P.A.W. 1988. A 40–50 day oscillation in sea surface temperature along the central California coast. *Estuarine, Coastal and Shelf Science* **26**, 395–408.

Breaker, L.C. 2005. What's happening in Monterey Bay on seasonal to interdecadal time scales? *Continental Shelf Research* **25**, 1159–1193.

Breaker, L.C. 2006. Nonlinear aspects of sea surface temperature in Monterey Bay. *Progress in Oceanography* **69**, 61–89.

Breaker, L.C. 2007. A closer look at regime shifts based on coastal observations along the eastern boundary of the North Pacific. *Continental Shelf Research* **27**, 2250–2277.

Breaker, L.C. 2019. Long-term changes in sea surface temperature off the coast of central California and Monterey Bay from 1920 to 2014: Are they commensurate? In *Coastal and Marine Physical Processes and Numerical Modeling*, J.S.A.D. Carmo (ed.). London: IntechOpen Limited, 45–74.

Breaker, L.C., Broenkow, W.W. & Denny, M.W. 2006. Reconstructing an 83-year time series of daily sea surface temperature at Pacific Grove, California. MLML Technical Report 06-2, Moss Landing Marine Laboratories, 50 pp.

Breaker, L.C., Lewis, P.A.W. & Orav, E.J. 1983. Analysis of a 12-year record of sea surface temperatures off Pt. Sur, California. Report Number NPS55-83-018, Naval Postgraduate School, Monterey, California.

CalCOFI Report 2016. State of the California Current 2015–16. Comparisons with the 1997–98 El Niño **57**.

CalCOFI Report 2018. State of the California Current 2017–18. Still not quite normal in the North and getting interesting in the South **59**.

CalCOFI Report 2019. State of the California Current 2018–19. A novel anchovy regime and a new marine heat wave? **60**.

Checkley, D.M., & Lindgren, M. 2014. Sea surface temperature variability at the Scripps Institution of Oceanography pier. *Journal of Oceanography* **44**, 2877–2892.

Dalton, M.G. 2001. El Niño, expectations, and fishing effort in Monterey Bay, California. *Journal of Environmental Economics and Management* **42**, 336–359

Denny, M.W. & Dowd, W.W. 2012. Biophysics, environmental stochasticity, and the evolution of thermal safety margins in inertial limpets. *The Journal of Experimental Biology* **215**, 934–947.

Denny, M.W. & Paine, R.T. 1998. Celestial mechanics sea level changes, and intertidal ecology. *Biological Bulletin* **194**, 108–115.

Denny, M.W., Miller, L.P. & Harley, C.D.G. 2006. Thermal stress on intertidal limpets: Long-term hindcasts and lethal limits. *The Journal of Experimental Biology* **209**, 2420–2431.

Denny, M.W., Hunt L.J.H. , Miller L.P. & Harley C.D.G. 2009. On the prediction of extreme ecological events. *Ecological Monographs* **79**(3), 397-421, doi: 10.1890/08-0579.1

Di Lorenzo, E. & Mantua, N. 2016. Multi-year persistence of the 2014/2015 North Pacific marine heatwave, *Nature Climate Change* **6**, 1042–1047.

Elahi, R., Miller, L.P. & Litvin, S.Y. 2020. Historical comparisons of body size are sensitive to data availability and ecological context. *Ecology* **101**(9), e03101, doi:10.1002/ecy.3101

Enfield, D.D. & Mestas-Nunez, A.M. 2001. Interannual to multidecadal climate variability and its relationship to global sea surface temperature. In *Interhemispheric Climate Linkages*, V. Markgraf (ed.)., 17–29. London: Cambridge Univeristy Press.

Field, D.B., Baumgarter, T.R., Charles, C.D., Ferreira-Bartrina, V. & Ohman, M.D. 2006. Planktonic Foraminifera of the California Current reflect 20th century warming. *Science* **311**, 63–66.

Fraedrich, K. & Blender, R. 2003. Scaling of atmosphere and ocean temperature correlations in observations and climate models. *Physical Review Letters* **90**, 108501.

Frölicher, T.L. & Laufkötter, C. 2018. Emerging risks from marine heat waves. *Nature Communications* **9**(1), 650, doi:10.1038/s41467-018-03163-6

Frölicher, T.L., Fischer, E.M. & Gruber, N. 2018. Marine heat waves under global warming. *Nature* **560**, 360–364.

Gaines, S.D. & Denny, M.W. 1993. The largest, smallest, highest, lowest, longest, and shortest extremes in ecology. *Ecology* **74**, 1677–1692.

Genner, M.J., Sims, D.W., Wearmouth, V.J., Southall, E.J., Southward, A.J., Henderson, P.A. & Hawkins, S.J. 2004. Regional climatic warming drives long-term community changes of British marine fish. *Proceedings of the Royal Society of London. Series B: Biological Sciences* **271**(1539), 655–661, doi:10.1098/rspb.2003.2651

Gerard, V.A. 1976. Some aspects of material dynamics and energy flow in a kelp forest in Monterey Bay, California. Ph.D. thesis, University of California, Santa Cruz, 173 pgs.

Glynn, P.W. 1965. Community composition, structure, and interrelationships in the marine intertidal *Endocladia muricata - Balanus glandula* association in Monterey Bay, California. *Beaufortia* **12**(148), 1–198.

Greig, M.J., Ridgway, N.M. & Shakespeare, B.S. 1988. Sea surface temperature variations at coastal sites around New Zealand. New Zealand *Journal of Marine and Freshwater Research* **22**, 391–400.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R. & Watson, R. 2008. A global map of human impact on marine ecosystems. *Science* **319**(5865), 948–952.

Harley, C.D.G, Denny, M.W. Mach, K. & Miller, L.P. 2009. Thermal stress and morphological adaptations in limpets. *Functional Ecology* **23**, 292–302.

Hawkins, D.W. & Olwell, D.H. 1998. *Cumulative Sum Charts and Charting for Quality Improvement*. New York: Springer.

Hawkins, S.J., Southward, A.J. & Genner, M.J. 2003. Detection of environmental change in a marine ecosystem—evidence from the western English Channel. *Science of The Total Environment* **310**(1), 245–256, doi:10.1016/S0048-9697(02)00645-9

Hayes, T.P., Kinney, J.R. & Wheeler, N.J.M. 1984. *California Surface Wind Climatology*. Sacramento, California: California Air Resources Board, Aerometric Data Division.

Hewatt, W.G. 1937. Ecological studies on selected marine intertidal communities of Monterey Bay, California. *American Midland Naturalist* **18**(2), 161–206.

Hines, A.H. 1982. Coexistence in a Kelp Forest: Size, Population Dynamics, and Resource Partitioning in a Guild of Spider Crabs (Brachyura, Majidae). *Ecological Monographs* **52**(2), 179-198, doi: 10.2307/1942610

Hubbs, C.L. & Schultz, L.P. 1929. The northward occurrence of southern forms of marine life along the Pacific Coast in 1926. *California Fish and Game* **15**, 234–241.

Hunt, L.J.H. 2006. *The rise of* Endocladia muricata*: Punctuated change at an abrupt range edge*. PhD thesis, Stanford University. 152 pp.

Hurst, H.E. 1951. Long-term storage capacity of reservoirs. *Transactions of the American Society of Civil Engineers* **116**, 770–808.

Huyer, A., Sobey, E.J.C. & Smith, R.L. 1979. The spring transition in currents over the Oregon continental shelf. *Journal of Geophysical Research* **84**, 6995–7011.

Jo, Y-H., Breaker, L.C., Tseng, Y-H. & Yeh, S-W. 2014. A temporal multiscale analysis of the waters off the east coast of South Korea over the past four decades. *Terrestrial Atmospheric and Oceanographic Science* **25**, 415–434.

Johnson, S.E. 1975. Microclimate and energy flow in the marine rocky intertidal. In *Perspectives of Biophysical Ecology*. D.M. Gates & R.B. Schmerl (eds.). New York: Springer-Verlag, 559–587.

Kantz, H. &. Schreiber, T. 2004. *Nonlinear Time Series Analysis*. Cambridge: Cambridge University Press.

Kaplan, A., Cane, M.A., Kushnir, Y., Clement, A.C., Blumenthal, M.B. & Rajagopalan, B. 1998. Analyses of global sea surface temperature 1856–1991. *Journal of Geophysical Research* **103**, 18567–18589.

LaScala-Gruenewald, D.E. & Denny, M.W. 2020. Long-term mechanistic hindcasts predict the structure of experimentally–warmed intertidal communities. *Oikos* **129**(11), 1645–1656, doi:10.1111/oik.07468

Liebmann, B., Dole, R.M., Jones, C., Blade, I. & Allured, D. 2010. Influence of choice of time period on global surface temperature trend estimates. *Bulletin of the American Meteorological Society* **91**, 1485–1492.

Lima, F.P. & Wethey, D.S. 2012. Three decades of high-resolution coastal sea surface temperatures reveal more than warming. *Nature Communications* **3**(1), 704.

List, E.J. & Koh, R.C.Y. 1976. Variations in coastal temperatures on the southern and central California. *Journal of Geophysical Research* **81**, 1971–1979.

Madden, R.A. & Julian, P.R. 1971. Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *Journal of Atmospheric Science* **28**, 702–708.

Maul, G.A., Davis, A.M. & Simmons, J.W. 2001. Seawater temperature trends at USA Tide Gauge sites. *Geophysical Research Letters* **28**(20), 3935–3937.

McEwen, G.F. 1919. Instructions for Cooperative Observer. Informal Memorandum, Scripps Institution of Oceanography.

Micheli, F., Carlton, J., Pearse, J., Selgrath, J., Elahi, R., Watanabe, J., Mach, M., McDevitt-Irwin, J., Pearse, V., Burnett, N. & Baxter, C. 2020. Field stations as sentinels of change. *Frontiers in Ecology and the Environment* **18**(6), 320–322, doi:10.1002/fee.2231

Miller, L.P., Harley C.D.G. & Denny M.W. 2009. The role of temperature and desiccation stress in limiting the local-scale distribution of the owl limpet, *Lottia gigantea. Functional Ecology* **23**(4), 756-767, doi: 10.1111/j.1365-2435.2009.01567.x

Miller, L.P. & Denny, M.W. 2011. Importance of behavior and morphological traits for controlling body temperature in Littorinid snails. *Biological Bulletin* **220**, 209–223.

Mislan, K.A.S. & Wethey, D.S. 2011. Gridded meteorological data as a resource for mechanistic macroecology in coastal environments. *Ecological Applications* **21**(7), 2678–2690.

Monin, A.S., Kamenkovich, V.M. & Kort, V.G. 1977. *Variability of the Oceans*. New York: John Wiley & Sons.

Morris, D.J., Pinnegar, J.K., Maxwell, D.L., Dye, S.R., Fernand, L.J., Flatman, S., Williams, O.J. & Rogers, S.I. 2018. Over 10 million seawater temperature records for the United Kingdom Continental Shelf between 1880 and 2014 from 17 Cefas (United Kingdom government) marine data systems. *Earth System Science Data* **10**, 27–51.

Newman, M., Alexander, M.A., Ault, T.R., Cobb, K.M., Deser, C., Di Lorenzo, E., Mantua, N.J., Miller, A.J., Minobe, S., Nakamura, H. & Schneider, N. 2016. The pacific decadal oscillation revisited. *Journal of Climate* **29**(12), 4399–4427.

Nirenberg, W.A. 1975. Surface water temperatures at shore stations. SIO Reference 75–8, La Jolla, California: University of California, Scripps Institution of Oceanography.

Nixon, S.W., Granger, S., Buckley, B.B, Lamont, M. & Rowell, B. 2004. A one hundred and seventeen year coastal water temperature record from Wood’s Hole, Massachusetts. *Estuaries* **27**, 397–404.

Parrish, R.H., Schwing, F.B. & Mendelssohn, R. 2000. Mid-latitude wind stress: The energy source for climate shifts in the North Pacific Ocean. *Fisheries Oceanography* **9**, 224–238.

Pelletier, J.D., & D.L. Turcotte.1997. Long-range persistence in climatological and hydrological time series. *Journal of Hydrology* **203**, 198–208.

Philippart, C.J.M., Anadon, R., Danovaro, R., Dippner, J.W., Drinkwater, K.F., Hawkins, S.J., Oguz, T., O’Sullivan, G. & Ried, P.C., 2011. Impacts of climate change on European marine ecosystems: Observations, expectations and indicators. *Journal of Experimental Marine Biology and Ecology* **400**, 52–69.

Quinn, W.H., Zopf, D.O., Short, K.S. & Kuo-Yang, R.T.W. 1978. Historical trends and statistics of the Southern Oscillation, El Nino, and Indonesian droughts. *Fishery Bulletin* **76**, 663–687.

Rasmussen, L.L., Carter, M.L., Flick, R.E., Hilbern, M., Fumo, J.T., Cornuelle, B.D., Gordon, B.K., Bargatze, L.F., Gordon, R.L. & McGowan, J.A. 2020. A century of Southern California coastal ocean temperature measurements. *Journal of Geophysical Research: Oceans* **125**(5), e2019JC015673.

Renard, R.J. 1999. Summary of the December 1998 weather on the Monterey Peninsula. Informal Report, Naval Postgraduate School, 4 pp.

Robinson, M.K. 1960. The use of a common reference period for evaluating climatic coherence in temperature and salinity records from Alaska to California. CalCOFI Report 8, Sacramento, California: California Fish and Game, 121–130.

Roden, G.I. 1961. On non-seasonal temperature and salinity variations along the west coast of the United States and Canada. CalCOFI Report 8, Sacramento, California: California Fish and Game, 95–115.

Roll, H.U. 1965. *Physics of the Marine Atmosphere*. London: Academic Press.

Sagarin, R.D., Barry, J.P., Gilman, S.E. & Baxter, C.H. 1999. Climate-related change in an intertidal community over short and long time scales. *Ecological Monographs* **69**, 465–490.

Scripps Institution of Oceanography Reference 81-30, 1981. *Surface Water Temperatures at Shore Stations United States West Coast 1980*. La Jolla, California: Marine Life Research Committee and Marine Life Research Group, University of California, Scripps Institution of Oceanography, 45.

Send, U., Weller, B., Cunningham, S., Eriksen, C., Dickey, T., Kawabe, M., Lukas, R., McCartney, M. & Osterhus, S. 2001. Oceanographic timeseries observatories. In *Observing the Oceans in the 21st Century*. C.J. Koblinsky & N.R. Smith (eds.). Melbourne: Bureau of Meterology, 376–390.

Shearman, R.K. & Lentz, S.J. 2010. Long-term sea surface temperature variability along the U.S. east coast. *Journal of Physical Oceanography* **40**, 1004–1017.

Shears, N.T., Bowen, M.B., 2017. Half a century of coastal temperature records reveal complex warming trends in western boundary currents. *Scientific Reports* **7**, 14527.

Skogsberg, T. 1936. Hydrography of Monterey Bay, California. Thermal conditions, 1929–1933. *Transactions of the American Philosophical Society* **29**(1), i-152.

Southward, A.J. 1991. Forty Years of Changes in Species Composition and Population Density of Barnacles on a Rocky Shore Near Plymouth. *Journal of the Marine Biological Association of the United Kingdom* **71**(3), 495–513.

Southward, A.J., Hawkins, S.J. & Burrows, M.T. 1995. Seventy years' observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature. *Journal of Thermal Biology* **20**(1), 127–155, doi:10.1016/0306-4565(94)00043-I

Southward, A.J., Langmead, O., Hardman-Mountford, N.J., Aiken, J., Boalch, G.T., Dando, P.R., Genner, M.J., Joint, I., Kendall, M.A., Halliday, N.C., Harris, R.P., Leaper, R., Mieszkowska, N., Pingree, R.D., Richardson, A.J., Sims, D.W., Smith, T., Walne, A.W. & Hawkins, S.J. 2004. Long-term oceanographic and ecological research in the western English Channel. *Advances in Marine Biology* **47**, 1–105, doi:10.1016/S0065-2881(04)47001-1

Spillane, M.C., Enfield, D.B. & Allen, J.S. 1987. Intra-seasonal oscillations in sea along the west coast of the Americas. *Journal of Physical Oceanography* **17**, 313–325.

U.S. Coast and Geodetic Survey. 1945. Surface water temperatures, Coast and Geodetic Survey tide stations: Pacific Coast. Department of Commerce, Washington D.C., 34 pgs, doi: 10.5962/bhl.title.38179. [No longer accessible]

Talley, L.D., Pickard, G.L., Emery, W.J. & Swift, J.H. 2011. *Descriptive Physical Oceanography: An Introduction*. Amsterdam: Elsevier, Sixth edition.

Thompson, S.A., Sydeman, W.J., Santora, J.A., Morgan, K.H., Crawford, W. & Burrows, M.T. 2012. Phenology of pelagic seabird abundance relative to marine climate change in the Alaska Gyre. *Marine Ecology Progress Series* **454**, 159–170.

Thomson, R.E. & Emery, W.J. 2001. *Data Analysis Methods in Physical Oceanography*. Amsterdam: Elsevier, Third edition.

Traganza, E.D., Conrad, J.C. & Breaker, L.C. 1981. Satellite observations of a cyclonic upwelling system and giant plume in the California Current. In *Coastal Upwelling. Volume 1*, F.A. Richards (ed.). Washington, D.C.: An AGU Publication

Wallace, J.M. 1988. Atmospheric response to Equatorial sea surface temperature anomalies. In *El Nino North: El Nino Effects in the Eastern Subarctic Pacific Ocean*, Wooster and Fluharty (eds.). Washington Sea Grant Program.

Weedon, G.P. 2003. *Time Series Analysis and Cyclostratigraphy: Examining Stratigraphic Records of Environmental Cycles*. New York: Cambridge University Press.

Wells, B.K., Schroeder, I.D., Bograd, S.J., Hazen, E.L., Jacox, M.G., Leising, A., Mantua, N., Santora, J.A., Fisher, J., Peterson, W.T. & Bjorkstedt, E. 2017. State of the California Current 2016–17: Still anything but “normal” in the north. CalCOFI Report 58.

Zhang, C., Hendon, H.H., Kessler, W.S. & Rosati, A. 2001. A workshop on the MJO and ENSO. *Bulletin of the American Meteorological Society* **82**, 971–976.

Zhu, X., Fraedrich, K. & Liu, Z. 2010. A demonstration of long-term memory and climate predictability. *Journal of Climate* **23**, 5021–5029.