Contextualizing Marine Heatwaves in the Southern California Bight Under Anthropogenic Climate Change

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Abstract In early August 2018, record-high sea surface temperatures were recorded in the 102 year old Scripps Institution of Oceanography daily temperature time series (SIOT) at La Jolla, CA, USA. The previous record of 25.8 °C, set in July 1931, was broken four times over 9 days, peaking at 26.4 °C on 9 August 2018. Optimum Interpolation Sea Surface Temperature data suggest that the marine heatwave (MHW) manifested in the northern half of the Baja California Peninsula, tapering off into the Southern California Bight. Here we use the Optimum Interpolation Sea Surface Temperature data to categorize this MHW as severe with relatively high maximum intensity (3.9 °C) and long duration (44 days) when compared to other events in the time series. Glider profiles show that the thermal anomaly was largest near the surface and extended to at least 100 m depth. By detrending the SIOT to remove the long-term anthropogenic climate signal and comparing the resulting data set to the unadjusted, we contextualize this MHW with respect to the entire time series and demonstrate that the long-term trend played a crucial role in amplifying the intensity and duration of the MHW. In this case, the anthropogenic warming signal in the SIOT accounts for an additional 19 MHW days (from 24 to 43) and an increase in cumulative intensity of 56.8 °C (from 83.1 to 139.9).

Plain Language Summary Marine heatwaves, like their counterparts in the atmosphere, are becoming more frequent and intense relative to historical norms owing to the long-term increase of ocean temperature. The century-long, continuous ocean surface temperature measurements at La Jolla, CA, USA, are used to put the August 2018 record-breaking temperature into context. The duration and intensity of the event are altered significantly by the removal of the long-term ocean warming trend, indicating that the trend itself is largely responsible for the increase in MHW conditions.

1. Introduction
1.1. Study Region

The Southern California Bight (SCB) is a region south of Point Conception where the California Coast takes a sharp eastward turn that complicates atmospheric and oceanic flows (Gelpi & Norris, 2008; Hickey, 1979; Winant et al., 2003). The SCB encapsulates an area in which the California current departs from its shorebound southward flow to the north of Point Conception and extends off of the coastline as it flows toward the south. The current typically curls back toward the coastline in the vicinity of Punta Colonet, especially in the summer months (Dailey et al., 1993). This departure from and intersection with the coastline defines the northern and southern ends of the SCB, while the western edge is defined variably as the edge of the California current or as the continental slope. It is a mixing region between temperate central California and subtropically influenced Baja California, in which biological communities from both provinces interact (Briggs & Bowen, 2012; Hickey, 1979; Toonen et al., 2016). Ocean temperatures in the SCB are characterized by sharp gradients and strong seasonal and interannual variability (Hickey, 1979; Reid, 1965). Multiple origins of source water (Bograd et al., 2019) further influence water mass characteristics as well as variability in mixing strength, especially during summer (Dorman & Palmer, 1981).
1.2. Marine Heatwaves Defined

A marine heatwave (MHW) is a prolonged period of anomalously warm (in the sense of Hobday et al., 2016) water temperature over a specified time and space. A MHW can be calculated from both satellite and single-point time series of ocean temperature. Here we use the base period 1 January 1983 to 31 December 2012 to compute the 90th percentile departure from climatological norms for each Julian (ordinal) day. Four MHW categories are defined in order of severity with respect to the difference between the 90th percentile value and the mean ($\Delta T_{90}$) and the difference between the observed temperature and the mean ($\Delta T$) where categories are defined as moderate ($\Delta T > \Delta T_{90}$), strong ($\Delta T > 2\Delta T_{90}$), severe ($\Delta T > 3\Delta T_{90}$), and extreme ($\Delta T > 4\Delta T_{90}$). MHW intensity is calculated as the daily temperature anomaly for each day, and the integral of intensity throughout the MHW event is defined as cumulative intensity. This method of analysis allows for MHW to occur at any time of the year, as the definition is relative to the 90th percentile threshold calculated using the climatology of that particular period of the year. The base period is crucial to this definition, especially when considering any effects of trend in long time series on the severity and duration of MHWs. See Hobday et al. (2016, 2018) for conceptual figures and a detailed description.

2. Data and Methods

2.1. OISST V2

We use the National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature (OISST) high-resolution ((1/2)° latitude by (1/4)° longitude) satellite measurements (Reynolds et al., 2007) to calculate MHW intensity in the study region. The OISST product is widely applied to MHW research (e.g., Smale et al., 2019; Wernberg et al., 2011). Observations from 1 January 1983 to 31 December 2018 were used in the analysis, a total of 36 years. As suggested by Hobday et al. (2018), the 30 year base period used to calculate MHW thresholds was 1 January 1983 through 31 December 2012. OISST measurements were averaged spatially across the SCB to create a single time series for each Julian day of available data. In this case, a rectangular path from Point Conception to Punta Colonet is used in order to capture the maximum number of grid points from the OISST.

2.2. La Jolla SIOT

Daily sea surface temperature (SST) data have been collected in La Jolla, CA, USA, since 22 August 1916 (Figure 1). The program has implemented the same methods since its inception by using a weighted bucket to haul several liters of seawater through a hatch inside a room near the end of the 300 m long Ellen Browning Scripps pier. SST is measured to 0.1 °C using a hand-held, calibrated thermometer dipped into the bucket. Data flagged as suspicious by the Shore Stations Program (e.g., conflicting measurements, illegible entries, or unlikely readings) were removed from the time series.

The Scripps Institution of Oceanography daily temperature time series (SIOT) record used in this analysis is the time-of-day-adjusted SST time series, which compensates for variations in the time of day samples that were collected to more closely approximate the daily mean temperature. Details of the time series adjustment are presented by Rasmussen et al. (2020). The adjusted time series compensates for the degree of...
heating attributable to the diurnal insolation cycle. The adjustments take into account both time of day (hour) and calendar month and are derived from a sea surface heating model (Price et al., 1986) based on several years of observed insolation from Scripps Pier.

The linear trend in the SIOT record calculated using annual means shows an upward trend of 0.12° C per decade from 1917–2017 ($p < 0.001$, $R^2 = 0.23$). Annual average temperature varies approximately ±2° C from the long-term trend. The average date of peak summertime temperatures in SIOT is 7 August.

2.3. Spray Underwater Gliders

Spray underwater gliders (Rudnick et al., 2004; Sherman et al., 2001) are autonomous profiling vehicles fitted with instruments measuring a suite of parameters including temperature and salinity. As part of the California Underwater Glider Network (CUGN), these gliders fly along CalCOFI Line 90 across the SCB, with profiles to 500 m repeated at intervals of 3 hr and 3 km (Rudnick et al., 2017a; Rudnick et al., 2017b). The glider line extends over 500 km from shore and is completed in roughly 3 weeks at a glider speed of 0.25 m/s. There is a glider on this line at all times, with a fresh glider deployed upon recovery of a glider at the end of its mission. Gliders in the CUGN have achieved 97% coverage as measured by the number of days in the water since 2009 (Rudnick et al., 2017a). Anomalies averaged over the inshore 50 km are used in this paper and compared to SIOT anomalies. Anomalies from 9 August 2018 are displayed and compared to satellite surface anomalies. The data from the CUGN have been used in a number of analyses that addressed recent warm events, including the 2014–2015 MHW and the 2015–2016 El Niño (Rudnick et al., 2017a; Zaba et al., 2018; Zaba & Rudnick, 2016).

2.4. Ancillary Data Products

Albedo measurements from Geostationary Operational Environmental Satellite (GOES) data were used to obtain a qualitative view of anomalous surface shortwave radiative fluxes during the 2018 SCB MHW. This data set has a 4 km horizontal resolution and extends from 1996 to present and has been used in several studies examining cloud variability over the California coastal region (Clemesha et al., 2017; Iacobellis & Cayan, 2013; Simonis et al., 2017). Surface wind speeds observed at NOAA buoy 46086 (located southeast of San Clemente Island at 32.5°N, 118.1°W) were used to measure anomalies in wind speed and direction.
Precipitable water content (PWC) was measured by twice-daily radiosonde launches at San Diego Miramar Marine Core Air Station (Schwartz & Govett, 1992).

2.5. Analysis

We applied the heatwaveR package (Schlegel & Smit, 2018), which is based on the MHW definition by Hobday et al. (2016, 2018). Base periods were calculated using the same dates for each time series, 1 January 1983 through 31 December 2012. Despite the ability to use longer base periods for the SIOT, consistency in base period usage allows for direct comparison between time series with variable lengths. Each base period was used to compute the 90th percentile departure from the climatological mean for each Julian day in each record. To separate long-term warming from the detection of MHWs, SIOT was detrended using a sum of least squares approach in which the residuals are added to the long-term trend. This process in effect increases the temperature observations from the early portion of the time series and decreases the more recent temperature observations. We use a linear model to detrend this time series as it is the simplest method for estimating the signal of climate change while allowing for multiple drivers to influence the observed trend and relies on the fewest assumptions. Furthermore, the long-term increase in global ocean temperatures is equal to that of the climate change signal, as the temperature trend can be accounted for through anthropogenic influences (Barnett et al., 2005; Levitus et al., 2001). Both the unadjusted and detrended SIOT records, as well as the OISST, were passed to the category command.

Figure 3. OISST-derived satellite SST for 9 August 2018, the day of record breaking SIOT at La Jolla. OISST anomalies (a) calculated over the base period of 1 January 1983 through 31 December 2012. MHW categories (b) across the study area calculated using the heatwaveR library. Blue box represents the MHW study area from Point Conception to Punta Colonet; dashed line shows spray glider track “Line 90”. Green dot shows location of SIO pier in La Jolla, CA.

Figure 4. Daily measurements of SST (thick black lines) for (a) unadjusted SIOT, (b) detrended SIOT, and (c) spatially averaged OISST. Time series displayed with respect to climatological SST (thin black lines) and thresholds defining categories of MHW (green lines) as moderate (yellow), strong (orange), or severe (maroon).
in the heatwaveR package (base period in all cases 1 January 1983 through 31 December 2012), where each day was categorized as one of the four MHW types: Moderate, Strong, Severe, and Extreme. Changes in the number of MHW days per year in each time series were tested with a simple linear model. We subtract the difference between the two time series to estimate the amount of warming due to trend. Subtraction of the number of MHW days between the unadjusted and detrended time series highlights the role of the anthropogenic climate change signal present in the time series. The heatwaveR package was also used to determine the category, duration, start date, end date, and cumulative intensity of the 2018 SCB MHW.

3. Results and Discussion

3.1. The 2018 SCB MHW

The summer 2018 SCB MHW in the unadjusted (nondetrended) SIOT lasted from 19 July 2018 to 30 August 2018, peaked in intensity on 8 August 2018 and lasted 43 days. In the unadjusted SIOT, the mean MHW length is 16 days and the 95th quantile of observed MHW duration is 40 days, making the 2018 SCB MHW a relatively long MHW compared with the rest of the time series, the 6th longest of the 114 observed. The duration and intensity of this MHW is not consistent between the SIOT and detrended SIOT. Here we use both the unadjusted SIOT and the detrended SIOT to analyze events with and without the trend, thereby following a method of analysis more akin to sea level studies in which events are considered within the context of rising background levels (e.g., Vousdoukas et al., 2018). In the detrended SIOT, the MHW lasted from 22 July 2018 to 14 August 2018, a total of 24 days. We subtract the difference between the two time series to estimate the amount of warming due to trend. In the case of the 2018 SCB MHW, the trend is accountable for 19 additional days of MHW conditions and an increase in cumulative intensity of 56.8 °C/day. The difference in cumulative intensity alone is higher than the cumulative intensity of 102 of the 114 MHW observed in the unadjusted SIOT (Figure 2).

The margins of the 2018 SCB MHW extended well beyond the confines of the SCB and into the coastline of Northern Baja California (Figure 3), while north of the SCB in the vicinity of Point Conception, SST anomalies were negative. Spatially averaged OISST measurements from the SCB categorize the event as severe (Figure 4c). Extreme warming took place offshore in 3 pixels of OISST coverage (Figure 3b) at the southern end of the SCB and severe warming occurred along the coastline adjacent to the extreme anomaly. A broad area occupying much of the SCB and Northern Baja region, extending nearly from Point Conception to Punta Eugenia, experienced a strong MHW. Despite the existence of a small area of extreme warming conditions within the study area, we define this event as severe because it is the highest category observed during this event in the time series of daily averaged OISST measurements across the SCB (Figure 4c). MHW occurrence spatially averaged over the MHW study area (Figure 4) matches the SIOT pattern generally.

A yearly average of 27 MHW days is evident in the detrended SIOT (Figure 2a), with a maximum of 199 days in 2015 and none observed in 36 of the 101 years of observations. Both the unadjusted and detrended SIOT have experienced MHW throughout the collection period of 1916 to present. There is no significant trend in the number of MHW days derived from detrended SIOT (p = 0.95). Notably, the number of MHW days derived from unadjusted SIOT (Figure 2b) increases...
by 4.3 days per decade ($p < 0.005$, $R^2 = 0.12$). The long-term trend in the number of MHW days per year in the unadjusted SIOT is dominantly driven by the anthropogenic climate signal present in the time series.

### 3.2. Oceanic and Atmospheric Conditions

Observations from the CUGN are used to examine the depth dependence of temperature variability and its extension offshore. The annual cycle (climatology) for CUGN was calculated over 7 years from 2007–2013 (Rudnick et al., 2017a), on Line 90 and is averaged over the inshore 50 km (Figure 5), roughly the distance between the shore and Santa Catalina Island. The warmest and most stratified time of the year is in August–September. The strong stratification is a result of typically weak winds, reduced cloudiness, and high solar heat flux into the ocean during this time period.

The anomaly in temperature (Figure 6) shows that anomalous warmth has been present since early 2014, starting with the 2014–2015 warm anomaly (Zaba & Rudnick, 2016) and growing during the 2015–2016 El Niño (Rudnick et al., 2017a). This warmth has persisted through the present, leading to conditions that favor record setting temperatures. During the 2015–2016 El Niño, the anomaly extends to over 400 m deep, while the 2014 warm event and the 2018 SCB MHW are evident at least as deep as 100 m. Anomalies are generally warmest near the surface and decay with depth; thus, surface anomalies are a good indicator of conditions over the upper several tens of meters.

To examine the offshore extent of the warmth, consider the temperature anomaly at 10 m depth along Line 90 (Figure 7). The anomalous warmth since 2014 has extended offshore at least 500 km (Figure 7). The broad swath of warm water suggests that the processes causing the warm water are not merely local but may be related to basin-scale changes. Thus, the SIOT record is indicative of larger-scale anomalies since 2014. Whether all the MHWs detected by the 100 year pier record had a similar connection to the large scale is an open question. However, the similarities in recent years give confidence that SIOT is a useful indicator of past ocean temperatures in the SCB (McGowan, 1998). The increased surface temperature during MHWs in the SCB has been historically caused by reduced vertical mixing at the mixed layer base, by increased air-sea heat flux or by advection of warm water (Zaba & Rudnick, 2016; Holbrook et al., 2019; Zaba et al., 2019).

Albedo is a measure of reflected solar radiation back to space; thus, negative albedo anomalies indicate larger than normal amounts of solar radiation being absorbed at the surface. Figure 8 shows anomalously low albedo values over the 2018 SCB MHW region during the 2 weeks prior to the event onset and the first 4 weeks of the event. Surface wind speeds were lower than normal (based on 2003–2018 period of data) during much of the 2018 SCB MHW. During the 2 weeks prior and the first 4 weeks of the event, the mean wind speed anomaly was $-0.5$ m s$^{-1}$ (13% below normal). Surface fluxes of latent and sensible heat are strongly modulated by surface wind speed; thus, reduced wind speed would generally result in reduced heat loss from the ocean surface. Wind direction also impacts the temperature evolution of waters in the SCB. Due to Ekman transport, northerly winds are conducive to upwelling of deeper (cooler) waters in the SCB, while southerly winds have the opposite effect. During much of the 2018 MHW event, wind speed over the SCB was not only lower in magnitude as noted above but also the frequency of southerly (southerly, southwesterly, and southeasterly) winds was larger than normal. Wind rose plots were constructed from the buoy wind observations during the 2018 SCB MHW event and shown in Figure 9 together with climatology based on the 2003–2018 data record. During the 2 weeks prior to the event and throughout the first 4 weeks of the event, southerly winds were more frequent than normal at this buoy location. Atmospheric conditions away from the surface were also

![Figure 7. Anomaly of temperature at 10 m depth on Line 90.0 from the California Underwater Glider Network. The anomalous warmth since 2014 extends at least 500 km offshore.](image-url)
conducive for retention of ocean heat as PWC over the region was considerably higher than normal during the 2018 SCB MHW. The mean July–August climatological PWC value based on 1981–2010 radiosonde data is 25 mm. The mean radiosonde-derived PWC was 38 and 37 mm during the 2 weeks prior to the event and during the first 2 weeks of the event, respectively. The middle 2 weeks of the event had a mean PWC value of 31 mm. Everything else being equal, the additional atmospheric water vapor would result in a net reduction of infrared radiation leaving the ocean surface. The increased PWC values were associated with several southeasterly surges of monsoonal moisture over the SCB.

During the final 2 weeks of the event, the negative albedo anomalies subside over the near coastal waters, while positive albedo anomalies emerge over the outer waters of the region; the wind speed anomaly rose to 0.3 m s$^{-1}$ (6% above normal). Additionally, during the final 2 week period, the frequency of northwesterly winds increased and southerly winds decreased while the average PWC was 30 mm.

The lower than normal albedo and wind speed, along with increased PWC and frequency of southerly winds observed prior to and during most of the 2018 MHW provided favorable conditions for increasing surface water temperatures in the SCB. Additionally, during the final 2 weeks of the event, the favorable conditions lessened considerably which may have led to relative cooling and the end of the event. However, other important factors such as the horizontal advection of warm/cold water into the region along with vertical mixing at the base of mixed layer could either augment or diminish any warming.

Figure 8. GOES derived albedo anomalies over the 2018 MHW region during (a) the 2 weeks prior to the event (5–18 July), (b) first 2 weeks of the event (19 July to 1 August), (c) middle 2 weeks of the event (2–15 August), and (d) last 2 weeks plus 1 day of the event (16–30 August).
4. Summary and Conclusions

MHWs have occurred throughout the SIOT collection period of 1916 to present with the number of MHW days per year displaying upward trends through time. The detrended SIOT does not display any long-term trend in number of MHW days, confirming the conclusion from Oliver et al. (2018) that the increasing frequency of MHW is largely driven by increasing mean ocean temperatures. The considerable differences in trends in the number of MHW days between the SIOT and detrended SIOT suggest that the increasing number of MHW days per year in the SIOT is largely forced by the anthropogenic climate signal present in the record. Additionally, the season of occurrence of the record-breaking summer 2018 SCB MHW coincided with the mean warmest day annually in the SIOT, 7 August. Maps of the event derived from OISST reveal a large area of the SCB, and Northern Baja California was influenced. Data from the CUGN indicate that temperature anomalies were largest near the surface and extended to at least 100 m depth, indicating that surface temperature maps of the upper ocean are reflective of anomalies over the upper several tens of meters of depth. A thin mixed layer in the SCB coupled with decreased albedo due to anomalously low cloud formation, high PWC, and reduced winds were the main drivers of this regional MHW. The mixed layer is thinner than the shallowest 10 m depth included in the glider climatology, so any increases in surface heat flux or decreases in wind-driven mixing will lead to high temperatures at the surface.

Despite the record-breaking nature of this event, when analyzed with respect to climatology using the Hobday et al. (2016, 2018) methods, it was neither the longest nor the most intense in the SIOT record. It was however the most recent MHW and thereby most affected by background warming. The event also occurred during the warmest time of year, causing century old records to be broken. Changes in species
Acknowledgments

Kristi Seech, Sylvia Lee, and Jonathan Charendoff help maintain the Shore Stations Program. Aquarists from the Birch Aquarium at Scripps continue to take daily measurements at Scripps Pier. John McGowan kept the program running during periods of low funding. Jonathan Charendoff provided assistance in R. Current funding is provided by the California State Parks, Divisions of Boating and Waterways and Natural Resources Oceanography Program (Award C1670003) under contract with SIO. A large number of SIO and aquarium staff and volunteers contributed a century of effort to produce this data set, and we gratefully acknowledge all including Connie Fey. Mark Merrifield provided funding for open access of this article. We thank Robert Schlegel and an anonymous reviewer for their constructive comments in the publication of this article. The California Underwater Glider Network (CUGN) is supported by NOAA Ocean Observing and Monitoring Division (NA16OAR4320071) and Integrated Ocean Observing System (NA16NOS012022). Data from the CUGN climatology can be downloaded online (spraydata.ucsd.edu) (Rudnick et al., 2017). Data from the SIOT can be downloaded online (shorestation.ucsd.edu). NOAA’s OI SST data can be downloaded from www.esrl.noaa.gov/psd website. The GOES satellite measurements were obtained from NOAA’s Comprehensive Large Array-data Stewardship System (CLASS) website (avl.class.noaa.gov). Buoy measurements were downloaded from the National Data Buoy Center (NDBC) website (ndbc.noaa.gov) and the radiosonde measurements were downloaded at the NOAA website (noaa.gov/raobs).

distributions (Lenanton et al., 2017; Wernberg et al., 2011), abundances (Jones et al., 2018; Mills et al., 2013), and ecosystem structure (Smale et al., 2019; Thomsen et al., 2019; Wernberg et al., 2013) have been affected by MHWs, which are becoming more intense and frequent under anthropogenic climate change (Oliver et al., 2018). By comparing MHW occurrence in the detrended and unadjusted SIOT, we understand the relationship between two interwoven processes: a long-term increase in temperatures driven by anthropogenic climate change and large amplitude fluctuations that are enhanced because of that increase.

Author Contributions

J. F. M. C., L. R., R. F., and D. R. conceived the initial idea and contributed intellectually. L. R. calculated and provided the time-of-day adjusted Scripps sea surface temperature data. J. F. analyzed satellite and Scripps sea surface temperature data and produced Figures 1–4. D. R. wrote and analyzed California Underwater Glider Network Data and produced Figure 5–7. S. I. led atmospheric investigations and provided Figures 8 and 9. J. F. led manuscript preparation, while M. C., R. F., L. R., D. R., and S. I. contributed significantly to the manuscript.

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