A Century of Southern California Coastal Ocean Temperature Measurements

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Abstract Scripps Institution of Oceanography Pier has been the site of daily temperature measurements since the original structure was built in 1916. The time series is the longest continuous record of temperature on the Pacific Rim and is frequently cited as an indicator of ocean temperature trends in the region. The over 100-year long record of daily surface temperature and slightly shorter bottom temperature data are presented here, with adjustment for bias owing to changes in sampling time of day. Data were generally collected near 8:00 a.m. in the early years, when water temperatures are cooler, and gradually shifted later in the day, when temperatures are warmer. In addition, cold surges from irregular internal tidal bores complicated attempts to estimate daily heating-cooling cycles solely as a function of time of day. To isolate the effect of the solar heating cycle, adjustments were calculated based on seasonally variable diurnal solar heating using a surface ocean heating model and locally measured insolation data. Although the observed warming trends in nearshore temperatures are reduced by about 0.2 °C per century in the adjusted data, they still retain a significant increase of 1.24 °C per century at the surface and 1.67 °C per century in bottom waters.

1. Introduction

Scripps Institution of Oceanography (SIO) has collected and published daily manual measurements of ocean surface temperature from Scripps Pier since it was completed in August 1916 and bottom temperature since 1926. The pier, located in La Jolla, CA, between two large submarine canyons (Figure 1) extends out to a depth of approximately 6–7 m. The time series is the longest continuous record of temperature on the Pacific Rim and is frequently cited as an indicator of ocean temperature trends in the region. Recently, the Scripps Pier time series received national scientific and media attention when century-long record highs were broken, exceeding the 1931 record four times over 9 days in August 2018 during an extended marine heat wave (see analysis in companion paper Fumo et al., 2020). However, the pier data have been used by scientists for many decades for studies of both local ecosystems and broader oceanographic and climate processes, for example, regional ecosystems and fisheries dynamics (Barry et al., 1995; Mantua et al., 1997; Miller & McGowan, 2013), algal blooms (McGowan et al., 2017), regime shifts (Breaker, 2007; Hare & Mantua, 2000), climate variability and ocean warming (DiLorenzo et al., 2005; Kim & Cornuelle, 2015; Matthews & Matthews, 2014; McGowan et al., 1998), kelp forest ecology (Dayton & Tegner, 1984; Parnell et al., 2010; Tegner et al., 1997), and larval transport (Pineda, 1991). The growing concern over interannual variability and global climate change has given long-term observations such as these added significance (Cheng et al., 2019; Roemmich, 1992; Wijffels et al., 2016). Long time series are particularly essential for understanding large-scale physical phenomena like episodic El Niño–Southern Oscillation events and for tracking long-term changes in sea surface temperature (SST) and ocean heat content that are major factors in understanding the role of the oceans in contributing to or mitigating atmospheric warming and extreme weather events.

Determining the baselines and steady states of natural systems from which to measure anomalies and trends is another challenge facing climate scientists for which time series data are essential. The problem is compounded when attempting to measure changes in ecosystems that are composed of numerous
biogeochemical processes operating and interacting over a wide range of temporal and spatial scales, many of which are not fully understood and can be extremely problematic to model prospectively. Cross analysis of long time series of multiple ecosystem properties is an objective way to quantify system behavior even when the details of the intermediary mechanisms are unknown (McGowan, 1990).

Kent et al. (2017) also highlight the importance of long time series of SST in particular, and the problems inherent with interpreting an assemblage of historical data from widely varying platforms, most of which were not stationary (e.g., ships and drifting buoys). The disparate collection methods, in both instrumentation and what is considered "surface," often require intercomparison and possibly correction for systematic biases. The issue is compounded for stationary sources like fixed moorings or coastal stations because of the scarcity of other nearby data sets of comparable length.

The Scripps Pier temperature measurements have been collected in a remarkably similar manner since 1916 (Figure 2 and section 2), by lowering containers manually off the pier and using high-resolution, frequently calibrated thermometers, once per day, with no substantive interruptions. However, no firm time of day (TOD) was ever set for the sampling, in part, because after the initial decades, the task was passed along to a succession of scientists, staff, and aquarists, all of whom performed the sampling as volunteers in addition to their own work schedules. Thus, the sampling TOD has varied over the years. This introduces a problem in calculating a long-term trend or comparing different time periods because diurnal temperature fluctuations occur, especially in summer when solar heating of the water column is the greatest. Manual sampling times have ranged from early morning to middle afternoon, averaging between 08:00 and 12:00 depending on the year (Figure 3a). Analysis of 10 years of high-resolution electronic thermistor data from the pier shows that temperatures at noon and midnight are closest to the daily mean, and temperatures at 08:00 and 16:00 are farthest, being, respectively, cooler and warmer. Thus, interpretation of the daily manual measurements as representative of the mean is problematic in that most pier readings will be skewed toward the cooler temperatures before noon, with the magnitude of the difference dependent on both the TOD (diurnal solar cycle) and the time of year (seasonal solar cycle).

Figure 1. Bathymetry near Scripps Pier with La Jolla Canyon on the left (south) and Scripps Canyon on the right (north). Contours are in 3.05 m (10-ft) increments. Inset: Nearshore circulation patterns documented by Shepard and Inman (1930). Points A and B are the locations of persistent rip currents during both southward (pictured) and northward alongshore flows. (Bathymetry by F. Shepard, at Woods Hole Oceanographic Institution PV Lab, https://pv-lab.org/ncex/canyon-maps-and-bathymetry/).
Attempts to estimate deviations from the daily mean temperature by TOD and month of sampling using a decade of high-resolution, near-surface, and near-bottom electronic thermistor data taken close to the manual sampling location were also problematic. In addition to the diurnal solar heating and cooling cycle, pulses of cold water occur from tidal period internal wave bores propagating shoreward over steep bathymetric irregularities throughout the region, including the nearby La Jolla and Scripps canyons (Arthur, 1954; Lerczak et al., 2003; List & Koh, 1976). Cold pulses observed in the thermistor data may occur once or more per day or not at all (Figure 4). The cold pulses are not correlated with daily or monthly tidal fluctuations, and they can produce temperature changes many times as large as those caused by the daily solar heating and cooling. Internal wave bore events observed in other studies at Scripps Pier were also

![Figure 2](image-url)  
**Figure 2.** (a) The original 1,000-ft (305 m) Scripps Pier (right) built in 1916, alongside the new 1,084-ft (330 m) pier during construction, 1988. (b) Pier sampling well, Claude W. Palmer, 1949. (Photographs from SIO Photographic Laboratory, UC San Diego Digital Collections).

![Figure 3](image-url)  
**Figure 3.** (a) Mean annual sampling time (blue, solid) and mean annual surface temperature (red, broken), 1917–2017. (b) Difference between time of day adjusted and raw monthly means. Positive values occur where the original temperatures have been adjusted upward.
uncorrelated with the barotropic tide, and the associated cold pulses changed temperature up to several degrees in less than an hour (Sinnett et al., 2018). At 160-m offshore of the mean low tide line, temperature dropped 4 °C in 36 min, and rapid oscillations of 0.5 °C in 90 s could occur for 1–2 hr (Sinnett & Feddersen, 2014).

Such unpredictable nonlinear internal wave activity is characteristic of regions like the U.S. West Coast where moderate- to high-amplitude barotropic tides propagate parallel to the coast as Kelvin waves and encounter irregular bathymetric features. Influenced by the background stratification, subsequent refraction, reflection, or superposition of waves from multiple sources, the resulting wave field exhibits high spatial and temporal variability (Nash et al., 2012; Sherwin et al., 2002; Suanda & Barth, 2015). The large, irregular signals from nonlinear internal wave cold pulses thus frequently obscure the diurnal heating and cooling cycle, which is itself subject to irregular variation due to atmospheric conditions like air temperature, wind, and cloud cover. When the high-resolution temperature record is averaged to reconstruct “typical” monthly diurnal heating and cooling, the result is a range that is much too large due to the presence of cold surges unrelated to the solar radiative cycle. This is especially problematic in summertime when surface heating and stratification are most pronounced and subject to disruption by cold pulses.

An adjusted time series has been constructed to compensate for variations in the TOD samples were collected and more closely approximate the daily mean temperature. The adjustments are intended to compensate only for the variability attributable to the seasonal diurnal insolation cycle without the confounding factors of internal tide surges, advection, or upwelling. The adjustments were calculated for both TOD (hour) and calendar month, based on modeled estimates of the diurnal heating and cooling cycle at the sampling site. The resulting time series consists of monthly means from the adjusted daily temperatures and should more accurately reflect the long-term warming trend.

2. Methods

2.1. Pier Sampling Procedures

The La Jolla Shore Station sampling equipment is housed in one of two rooms near the end of Scripps Pier and consists of a pulley-operated bottle sampler, Niskin bottles, for collecting bottom water and a calibrated digital thermometer (The other room contains the National Oceanic and Atmospheric Administration (NOAA) tide gauge that has been in operation since 1925.). A well extending through the base of the pier enables sampling bottles to be lowered in virtually any weather condition. An insulated sampling bucket is used to collect surface water from approximately 0.5-m depth, and a calibrated digital thermometer is immediately placed inside the bucket to measure SST to the nearest 0.01 °C. Temperature measurements are rounded and reported to the nearest 0.1 °C. For salinity measurements, surface water is poured into glass bottles with airtight seals after triple rinsing with sample water. These procedures have remained essentially unchanged since daily temperature measurements began in August 1916. Although early records on methods and instrumentation are scarce, glass mercury thermometers were the scientific standard during the late
nineteenth century and well into the twentieth. At Scripps Pier the earliest measurements were recorded to 0.1 °C, but no information can be found on calibration techniques.

From 1956 on, records indicate that ocean temperature measurements were taken using precision-engraved stem mercury immersion thermometers with 0.1 °C divisions. The primary source was Kahl Scientific Instruments Corporation, a local San Diego County manufacturer established in 1935. The instruments were calibrated against certified primary standards during the manufacturing process. Instruments used at Scripps Pier and Farallon Islands were recalibrated by the Oceanic Data Facility at SIO in a water bath with 0.01 °C temperature control. In December 2008 the program switched to digital thermometers because of the mercury ban in the State of California. The thermometers are read to 0.01 °C and rounded to the nearest 0.1 °C.

The original 305 m (1,000 ft) long pier was replaced by another completed in 1988, just to the south alongside the original (Figure 2a). The old pier was 25 m shorter, and the sampling room was about 10 m inshore from the new location. Measurements continued uninterrupted during construction and sampling procedures have remained the same.

2.2. Time of Day Adjustment

The daily cycle in water temperature was simulated with an adaptation of the Price-Weller-Pinkel 1-D upper ocean diurnal heating, cooling, and wind mixing model (Price et al., 1986) with input from downwelling short wave radiation (SWR) data collected at the end of Scripps Pier. One-minute resolution SWR data from 2009–2012 were first averaged to provide a 365-day, 1-hr resolution data set and then averaged by month into twelve 24-hr segments (Figure 5a). There is evidence of global and hemisphere-wide variation in SWR over the course of the pier time series. The 11-year sunspot cycle contributes a very small fluctuation of ±1 W/m². In addition, a SWR decrease is seen in the Northern Hemisphere between about 1960 and 1990, followed by a subsequent increase to near prior levels, a shift that was likely the result of changes in anthropogenic aerosol emissions (Wild, 2012). The fluctuation estimates vary considerably depending on spatial and temporal coverage of measurements, measurement method, and location (Hinkelman et al., 2009), with the majority of stations located over continental land masses. The total decrease during the dimming phase is estimated at 3–9 W/m globally (Wild, 2012), which is small compared to the range of daily SW insolation in the pier record (400–800 W/m at solar maximum).

The Price-Weller-Pinkel model was run for each month with its respective mean diurnal SWR cycle as input. Outgoing long wave radiation and latent heat flux were averaged from 5 years of International Satellite Cloud Climatology Project data from the WHOI OAFlux program (Yu et al., 2008; Zhang et al., 2004). A wind stress value equivalent to an average 18.5 km/hr (10 kt) land-sea breeze provided the necessary vertical mixing. Initial temperature and salinity profiles were set to reflect typical seasonal conditions as observed at the pier. To retain heat in a shallow water column, a sharp artificial thermocline was introduced to simulate the bottom boundary. Twelve monthly insolation-driven water temperature cycles were obtained by averaging each daily cycle after the model stabilized or approximately the last 10–14 days of each 4-week run (Figure 5b). The diurnal temperature range of ±0.2 °C in winter to ±0.5 °C in summer is consistent with that recorded by electronic thermistors when cold surges driven by internal wave activity are not present.

The diurnal heating curves for each month are the basis for TOD adjustment offsets. The offsets are equal to the average difference between the estimated mean daily temperature (around noon) and that at the TOD the sample was collected. To adjust for sampling time in the data, the appropriate offset is subtracted from the recorded temperature. For example, an offset for a 9:00 a.m. sample in the summer might be −0.3 °C (i.e., 0.3° lower than the estimated daily mean), so if the raw measured temperature was 14.5 °C, the adjusted...
temperature would be 14.8 °C. The final adjusted time series consists of the monthly means of the TOD-adjusted temperatures.

### 2.3. TOD Adjustment Test Case

To test the utility of the TOD adjustment method in estimating daily mean temperatures from spot measurements at various times, the adjustments were applied to a 10-year high-resolution SST data set from electronic thermistors mounted on a pier piling near the location of the daily manual sampling. It should be noted that the thermistor readings do not match the manual measurements exactly because the depths are not exactly the same and the thermistors capture the in situ temperature over smaller effective water volumes than the manual collection. To create test data sets, hourly averages were calculated from the 4-min resolution, 10-year thermistor data set. The data for five different times of day were extracted to create separate time series simulating once daily sampling at 0800, 1000, 1200, 1400, and 1600 hr (essentially “electronically sampling” at the given times). The TOD adjustments were then applied to each simulated “daily” time series. Monthly averages were calculated for both the raw and adjusted data sets, giving five THERM-RAW and five THERM-ADJ series for the five selected times of day. The actual daily means and monthly averages were calculated from the full thermistor data set. The mean error and root-mean-square error were calculated for the THERM-RAW data sets versus the actual means and for the THERM-ADJ versus actual means. The TOD-adjusted data more closely approximate the actual means, as seen in Table 1. As expected from previous analyses, the data sets extracted from 1200 (noon) were adjusted the least, and the difference between the raw and adjusted errors was <0.005 °C. The 0800- and 1600-hr data sets were adjusted the most, with the mean error for each reduced by 58% and 86%, respectively, and the RMSE by 39% and 52%, respectively.

### 3. Results and Discussion

Overall, the adjustments for sampling time alter the temperatures the most in the earlier decades of the time series when measurements were usually taken near the daily minimum at 08:00. In later decades, when samples were taken at noon, closer to the time representative of the daily mean, the adjustment was smaller and occasionally in the opposite direction (Figure 3b). Raw and adjusted monthly mean surface and bottom temperatures at Scripps Pier are shown in Figures 6a and 6c. Included are 100-year trend lines for each time series. The effect on the measured long-term surface and bottom warming trends is to flatten the slopes slightly because earlier year temperature data were further from the daily mean than later years. Raw surface temperature increased at a rate of 1.46 °C ± 0.09 per century, versus 1.24 °C ± 0.10 per century after TOD adjustment (error ranges = 95% confidence intervals for linear regression). Bottom temperature shows a greater increase of 1.92 °C ± 0.10 per century in the raw data versus 1.67 °C ± 0.10 in the TOD-adjusted series.

Other estimates of regional and global ocean surface warming are included in Table 2, along with breakouts of the pier SST for specific time periods. Analyses of the Southwest U.S. Coast using California Cooperative Fisheries Investigations (CalCoFI) data include Roemmich (1992) at 0.8 °C from 1949–1990 (1.9 °C per century) and DiLorenzo et al. (2005) finding 1.3 °C from 1949–2000 (2.5 °C per century), both higher than the
SIO Pier trend. However, Liebmann et al. (2010) discuss the problems inherent in assessing trends in SST because of the choice of time periods selected or dictated by the data set. In general, data sets longer than a few decades show positive trends over the twentieth century, and more recent data sets (ca. 1950s forward) are most likely to have large positive trends. Confining the Scripps Pier calculation to the same time period as the California Current estimates (post-1950) gives a warming of 2.56 °C per century, quite close to the estimate in DiLorenzo et al. (2005). Most coastal boundary systems also have larger positive trends than adjacent gyres or basins, as in the Fifth Intergovernmental Panel on Climate Change (IPCC) assessment (Hoegh-Guldberg et al., 2014), which reports an increase of 0.252 °C from 1950–2009 in the East Pacific Gyre (0.42 °C per century) and an increase of 0.732 °C (1.22 °C per century) in the California Current. Strong regional trends between and within major ocean basins are also evident in the IPCC analysis, which a single global mean SST trend does not reveal.

Previously, Checkley and Lindegren (2014) suggested a different trend adjustment for temperature change at Scripps Pier to account for an apparent discrepancy between local warming of 1.1 °C per century as

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**Figure 6.** Monthly mean Scripps Pier temperature and trend lines for (a) surface and (c) bottom. Raw temperatures are in green, time of day (TOD) adjusted in black with dark blue trend line. Beneath the monthly means are 1-year running average TOD-adjusted temperatures for (b) surface and (d) bottom. Dotted line is the beginning of 1982.
measured from 1916–2012 in the raw pier data and the average global change in SST of 0.7 °C per century (from IPCC fourth assessment, Trenberth & Josey, 2007, and Smith et al., 2008). Their adjusted trend of 0.6 °C per century is predicated on the theory that reconstruction of the pier in 1988 caused a discontinuity in the temperature record due to enhanced rip currents induced by the new pilings transporting warm water offshore. However, a 1-year running mean of the time series (Figure 6b) shows how average annual surface temperature has changed over time with respect to the mean. A major shift is evident around 1982, well before the pier reconstruction, when the 1-year running mean transitions from predominantly lower than the 102-year mean of 17.45 °C to predominantly higher. A similar shift is observed in the bottom temperature (Figure 6d).

Recent and historical studies of surfzone processes at Scripps Beach do not indicate the presence of persistent rip currents immediately beneath or adjacent to the pier that would systematically influence temperature at the new pier sampling station with respect to the original location. Shepard and Inman (1950) observed persistent rip currents approximately 122 m (400 ft) and 914 m (3,000 ft) south of the original pier, located at either end of a wave convergence zone caused by local shoreline and complicated submarine canyon topography. Another persistent rip is seen at the head of Scripps Canyon, north of the pier, and transient rips occur with an average of 500-m spacing. Smith and Largier (1995) noted that the position and spacing of rip currents in their 1992 observations, when the new pier was in place, were consistent with that of Shepard and Inman (1950): a persistent rip current 50–150 m to the south, with recurrent but transient rips 300–500 m away. These rips dissipated beyond ~150 m offshore (half the pier length) and by 200 m offshore both temperature and turbidity were at ambient levels. More recent studies have shown that undulations in the submarine canyon walls exert further control on the position of recurrent rip currents in this area (Long & Özkan-Haller, 2005).

Models of rip currents with Scripps Beach shelf bathymetry and stratification also demonstrated surface cooling rather than warming due to enhanced vertical mixing (Kumar & Feddersen, 2017). Cooler nearshore water is also observed as a result of a threefold increase in albedo from breaking wave foam in the surf and swash zones (Sinness & Feddersen, 2018). Cold surges from internal waves also influence the surfzone for disproportionately long time periods compared to the deeper nearshore zone, with lower temperatures persisting for hours (Sinness et al., 2018; Sinnett & Feddersen, 2014).

NOAA Optimal Interpolation Sea Surface Temperature data compiled from AVHRR satellite and in situ data are available for 1983 to present (Banzon et al., 2016) and provide another means of detecting discontinuity in SIO pier temperature measurements after pier reconstruction (Figure 7a). SST from the nearest (1/4)° (approximately 15 km) grid cell tracks the pier temperature variations closely, though the pier temperature runs slightly cooler (approximately 0–0.75 °C) than satellite temperature in the winter and reaches higher temperatures (approximately 0.5–1.5 °C) in the summer, likely a result of the shallower water column. However, if the measured pier temperatures shifted systematically upward after the construction of the new pier, there would be a larger discrepancy between the two after construction than before, particularly if the responsible mechanism was increased rip currents in summer-stratified water. Comparing the monthly means of the two data sets for the 5 years before pier construction (January 1983 to December 1987), there is an RMSE of 0.698 °C. In the 5 years after construction (January 1989 to December 1993), the RMSE is 0.705 °C, an increase of only 0.007 °C. Extending the postconstruction comparison out through 1989–2018, the error actually decreases by 0.022 °C to an RMSE of 0.682 °C. Because the raw and TOD-adjusted time series track so closely (averaging about 0.2 °C offset), the pier data shown are from the TOD-adjusted time series only.

Another NOAA product, the Extended Reconstructed SST (ERSST), has coarser resolution (2° grid cells) but allows comparison of the prereconstruction and postreconstruction measurements for a longer period with records compiled from recent and historical ship, buoy, mooring, and other in situ data (Huang et al., 2017).
The mean annual RMSE between the ERSST record at the nearest 2° grid cell and pier surface temperature is highly variable from year to year (Figure 7b) but fluctuates consistently in the 1–2 °C range over the 40-year period centered on 1988. As with OISST, temperature in the ERSST cell (approximately 120 km wide) runs slightly cooler than that at the shoreline.

The observations and process studies of both position and temperature structure of rip currents at Scripps Beach, as well as trends reported for other regional SST data sets, make it unlikely that small differences in old and new pier locations and piling configurations would be responsible for 0.5 °C of the observed warming trend.

In publishing this time series, our aim is to present both the raw daily data, as has been available on the web site, and an adjusted monthly mean time series that we consider more accurate for use in assessing long-term trends. The central problem in using the time series for a long-term trend analysis is that there was a systematic shift in the TOD of sampling between the earlier and latest decades which would skew the trend—in this case toward a greater heating trend. Because this is a function solely of the sampling procedure and because the solar heating effect has a constant periodicity that can be modeled, our goal was to mitigate the skewing of the trend from this artifact. On the other hand, internal tides/cold surges, advection, and upwelling are aperiodic, nonlinear, and unpredictable processes and so do not introduce a systematic bias that affects the long-term trend (see, e.g., Sinnett et al. (2018) for the most up-to-date analysis of internal tides). These processes will certainly affect the temperatures recorded if the once daily sample catches a strong and short-lived cold surge, but as this is a random chance, it will not be a source of systematic bias. Internal tide effects are influenced by the steep and irregular bathymetry of the two large submarine canyons, by the direction and strength of waves and currents, and by water column stratification. While currents and stratification may be changing over time with ocean warming, any change they cause in the frequency or intensity of cold surges would still not systematically skew the long-term trend; they are part of the actual temperature record that is captured randomly in the daily sampling.

Figure 7. Comparisons of Scripps Pier and hybrid-satellite temperature records. (a) Monthly mean temperature from NOAA OISST (black) and Scripps Pier (red). Dotted vertical lines span the period of pier reconstruction. RMSE is calculated for the 5 years prior to and after reconstruction, as well as the full record postreconstruction. (b) Annual mean RMSE between NOAA ERSST v5 and Scripps Pier SST for the 20 years prior to and after pier reconstruction (solid line = TOD-adjusted data, dashed line = raw data, red dots = 1988).
4. Summary and Conclusions

The century-long records of daily surface and bottom temperature data at Scripps Institution of Oceanography Pier are presented here, adjusted for bias owing to changes in sampling TOD using a diurnal heating model and measured insolation data. The observed warming trends in surface (bottom) temperatures were thus reduced by about 0.2 °C per century, from 1.46 to 1.24 °C per century (1.92 to 1.67 °C per century). The adjusted time series of monthly means should more accurately reflect long-term trends that can be useful in other climate studies. While the magnitude of the warming trend is slightly lower in the TOD-adjusted time series, notable features of the record remain evident, such as the ongoing shift to temperatures warmer than the long-term mean that occurred around 1980 which had parallels and consequences both regionally (Breaker, 2007; Hare & Mantua, 2000; McGowan et al., 2003) and globally (Reid et al., 2016; Reid & Beaugrand, 2012).

Author Contributions

L. R. developed the final scientific approach, conducted the modeling, and wrote the final paper, with M. C., R. F., and J. F. collaborating on all aspects of the analysis and writing. M. C. managed the Shore Stations program; R. F. conceived the original idea for TOD adjustment, drafted the original paper, and financially supported the study as the funding agency program manager. B. C. advised on data analysis approaches and application of the heating model. J. F. and M. H. were members of the Shore Stations field and lab team, and B. G. R. G., and L. B. collaborated on early approaches to TOD bias adjustments, reviewed, and edited the manuscript. As the previous long-time manager of the program, J. A. McGowan was directly responsible for its survival through lean times and provided invaluable insights to our understanding of the data.

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