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Nonlinear aspects of sea surface temperature in Monterey Bay

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Abstract

Nonlinear aspects of sea surface temperature (SST) in Monterey Bay are examined, based on an 85-year record of daily observations from Pacific Grove, California. Oceanic processes that affect the waters of Monterey Bay are described, processes that could contribute to nonlinearity in the record. Exploratory data analysis reveals that the record at Pacific Grove is non-Gaussian and, most likely, nonstationary. A more recent test for stationarity based on a power law approximation to the slope of the power spectrum indicates that the record is stationary for frequencies up to ~8 cycles per year (~45 days), but nonstationary at higher frequencies. To examine the record at Pacific Grove for nonlinear behavior, third-order statistics, including the skewness, statistical measures of asymmetry, the bicorrelation, and the bispectrum, were employed. The bicorrelation revealed maxima located approximately 365 days apart, reflecting a nonlinear contribution to the annual cycle. Based on a 365-day moving window, the running skewness is positive almost 80% of the time, reflecting the overall impact of warming influences. The asymmetry is positive approximately 75% of the time, consistent with the asymmetric shape of the mean annual cycle. Based on the skewness and asymmetry, nonlinearities in the record, when they occur, appear to be event-driven with time scales possibly as short as several days, to several years. In many cases, these events are related to warm water intrusions into the bay, and El Niño warming episodes.

The power spectrum indicates that the annual cycle is a dominant source of variability in the record and that there is a relatively strong semiannual component as well. To determine whether or not the annual and semiannual cycles are harmonically related, the bispectrum and bicoherence were calculated. The bispectrum is nonzero, providing a strong indication of nonlinearity in the record. The bicoherence indicates that the annual cycle is a major source of nonlinearity and further implies that the annual and semiannual cycles are harmonically related. Based on the wavelet power spectrum (WPS), the appearance of the semiannual cycle is transitory; however, pathways between the annual and semiannual cycles appear at certain times when nonlinear interaction between them could occur. Comparisons between the WPS and the running skewness suggest that there is a tendency for periods when pathways exist, to coincide with increased positive skewness, and, often, with El Niño warming episodes. The Hilbert–Huang transform, a relatively new tool for nonstationary and nonlinear spectral analysis, was used to further examine the origin of the semiannual cycle. The time-dependent Hilbert spectrum reveals large and erratic variations in frequency associated with semiannual cycle but far greater stability associated with the annual cycle. As a result, the time-integrated Hilbert spectrum does not indicate the presence of a semiannual cycle. The method of surrogates from the field of nonlinear dynamics was also employed to test the Hopkins record for nonlinearity. Differences between the data and the surrogates were found that were statistically significant, implying the existence of nonlinearity in the record. Using the method of surrogates together with a one-year moving window, El Niño warming episodes appear to be a

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likely source of nonlinearity, consistent with the other analyses that were performed. Finally, the influence of stochastic variability due to serial correlation in the data was examined by comparing standardized statistics for the observations and for simulations based on an autoregressive model whose properties were obtained from the observations. The magnitude of the variability for the simulations was found to be far less than that associated with the original data, and thus stochastic variability does not appear to be a factor that significantly affects the interpretation of our results.

Keywords: Monterey Bay; Sea surface temperature; Nonlinearity; Nonstationarity; Stochastic variability; Moving windows; Warm water intrusions; El Niño episodes; Spectral analysis; Method of surrogates

1. Introduction

Daily sea surface temperatures have been acquired at the southern end of Monterey Bay since 1919. The data have been collected at the Hopkins Marine Station in Pacific Grove, California (Fig. 1). This record is one of the longest oceanographic time series along the west coast of North America. The record originally contained numerous deficiencies including gaps, differences in the day-to-day acquisition times, a lack of homogeneity, and possible outliers. These problems have been addressed in creating a new, reconstructed record that extends from January 20, 1919 to December 31, 2004 (Breaker et al., 2005). The Hopkins time series of daily sea surface temperature (SST) from January 1, 1920 through December 31, 2004 is shown as a two-way layout by year and month in Fig. 2. The areas shaded in red correspond in most cases to periods of El Niño warming.

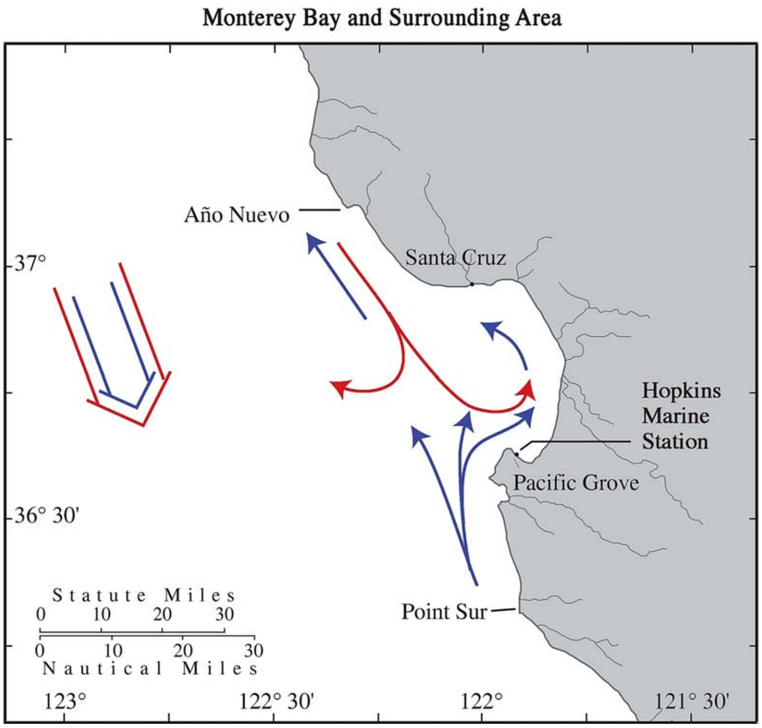

Fig. 1. Map of Monterey Bay and the surrounding area. The Hopkins time series has been acquired at Pacific Grove located at the southern end of Monterey Bay. The arrows indicate the generalized seasonal flow patterns. The red arrows represent the expected flow between April and October, and the blue arrows represent the expected flow between November and March. The larger arrows further off the coast correspond to the predominantly equatorward flow associated with the main body of the California Current.