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The California coastal wave monitoring and prediction system

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ABSTRACT

A decade-long effort to estimate nearshore (20 m depth) wave conditions based on offshore buoy observations along the California coast is described. Offshore, deep water directional wave buoys are used to initialize a non-stationary, linear, spectral refraction wave model. Model hindcasts of spectral parameters commonly used in nearshore process studies and engineering design are validated against nearshore buoy observations seaward of the surfzone. The buoy-driven wave model shows significant skill at most validation sites, but prediction errors for individual swell or sea events can be large. Model skill is high in north San Diego County, and low in the Santa Barbara Channel and along the southern Monterey Bay coast. Overall, the buoy-driven model hindcasts have relatively low bias and therefore are best suited for quantifying mean (e.g. monthly or annual) nearshore wave climate conditions rather than extreme or individual wave events. Model error correlation with the incident offshore wave energy, and between neighboring validation sites, may be useful in identifying sources of regional modeling errors.

1. Introduction

Spectral wave energy and radiation stresses, just prior to depth-limited wave breaking in the surfzone, are critical boundary conditions for modeling nearshore circulation, wave runup, and sediment transport. However, nearshore wave spectra in California often vary on relatively short longshore length scales [O(few wavelengths)] , owing to complex shelf bathymetry, making it impossible to measure directly the regional nearshore wave climate using existing measurement technology. Therefore, validated models for nearshore waves are important when managing nearshore hazards at both short and long time scales (e.g. 2 day to 50 year forecast scenarios of coastal flooding).

Nearshore waves in California are typically estimated using a Pacific ocean-scale wind-wave model (e.g. Wavewatch-III, Chawla et al., 2013) as a boundary condition for a "nested" coastal wind-wave hindcast model which resolves wavelength-scale shallow water bathymetric features (e.g. SWAN, Rogers et al., 2007; Adams et al., 2008; Van der Westhuysen et al., 2013, Barnard et al., 2014). The bias and skill of nearshore wind-wave hindcasts has improved significantly with improvements in the offshore boundary conditions (frequency-directional spectra) from the deep water wind-wave models, particularly in the swell frequency bands in the Pacific (Hanson et al., 2009). Nevertheless, challenges remain owing to the sensitivity of annual longshore wave-driven mass flux to a small bias in the nearshore wave direction parameters and the availability of historical high resolution coastal wind field boundary conditions (Rasmussen et al., 2009). Assimilating buoy measurements into wind-wave model hindcasts is an area of active research (Orzech et al., 2013; Panteleev et al., 2015), but in engineering practice nearshore buoys are mostly used for hindcast validation.

Here, in contrast to initializing a coastal wind-wave model with an ocean-scale model, a network of deep water directional buoy measurements are used to initialize a linear wave propagation model. The computationally fast model estimates nearshore wave energy and low-order directional spectra moments with O(1 wavelength) alongshore resolution. Future work combines offshore buoys and global scale models to improve the initialization of local models.

The California buoy array is described in Section 2. In Section 3, the Maximum Entropy Method (Lygre and Krogstad, 1986) is used to estimate hourly frequency-directional spectra at offshore deep water buoys, providing boundary conditions for a non-stationary linear wave propagation model (Pierson et al., 1952; Longuet-Higgins, 1957; Dorrestein, 1960; LeMehaute and Wang, 1982; O'Reilly and Guza, 1991, 1993, 1998). The spectrum is split into swell ($f = 0.0375–0.0875$ Hz) and sea ($f = 0.0875–0.5$ Hz) bands. For each nearshore prediction point, directional spectra estimates from multiple offshore buoys are combined with a weighting that depends on the frequency band, deep water wave direction and prediction buoy location (Appendix B).

In Section 4, the buoy-driven prediction methodology is validated with nearshore wave observations at 13 shallow (~20 m depth) sites. Prediction accuracy (R^2 skill, bias and rms error) is assessed for total wave energy, the centroid frequency, the peak frequency, and the mean direction.

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The model performs best in the southern section of the Southern California Bight (San Clemente Basin), poorly in the Santa Barbara and San Pedro Channel regions, and moderately well elsewhere.

The potential utility of the nearshore hindcast in practical coastal engineering applications is examined in Section 5. Predictions of the longshore radiation stress, S_{xy}, the principal driver of alongshore sediment transport, validate well in north San Diego and Orange Counties for a given shore normal direction. However, uncertainty in defining the local shoreline normal creates significant S_{xy} uncertainty.

The peak frequency, f_p, a commonly used parameter in empirical wave runup formulas (Stockdon et al., 2006), is shown to be unstable in southern California when sea and swell peak energies are similar.

In Section 6, long concurrent records from southern California buoys, sheltered from incident swell by the offshore Channel Islands, are used to examine the source of model error in the swell band. At some sheltered buoys, errors correlate most strongly with conditions offshore of the Channel Islands, while errors at other buoys are more highly correlated with errors at adjacent buoys. Section 7 is a summary.

2. Wave monitoring: the California Directional Wave Buoy network

A network of 17 Waveriders at fixed deep water locations monitored incident deep water wave conditions in three relatively highly populated coastal regions; southern California (U.S. Mexico border to Morro Bay), central California (Big Sur to Bodega Bay) and northern California (Humboldt Bay Area). Six buoys were moored well offshore, seaward of islands and shoals, to monitor incident swell (squares in Fig. 1), and 11 buoys were moored near the mainland shelf break to monitor locally generated seas and validate the swell model. These observations are combined to predict sea and swell at nearshore locations along the mainland coast (Section 3). The deployment periods ranged from 5 to 14 years, all between 2001 and 2014 (Tables 1, 2).

Waveriders are translational buoys that measure accurately the sea surface position (x, y and z) of swell (O'Reilly et al., 1996). Every half-hour, on-board analysis yields estimates of the wave energy, a0, and lowest order moments of the directional wave spectrum $S(f,\theta)$ at each frequency, retained as normalized directional Fourier coefficients a1, b1, a2, and b2 (e.g., Kuik et al., 1988).

Hourly wave energy and directional Fourier coefficients are obtained by merging half-hourly records, the directional coefficients are smoothed with a 3-hour running mean filter, and a directional estimator is used to make hourly $S(f,\theta)$ wave model input spectra. Different estimators use different optimizing criteria (e.g., maximum directional smoothness, maximum entropy). The Maximum Entropy Method (MEM, Lygre and Krogstad, 1986) used here fits the measured directional coefficients exactly, eliminating any possibility of time-averaged estimator bias in the resulting directional distribution moments, compared to the original observations. MEM also produces narrow directional peaks. These are desirable estimator attributes for wave climate estimation on a swell-dominated coast.

CDIP Waverider buoy stations in shallow water, usually deployed for a few years, are used to validate the prediction methodology (Table 3).

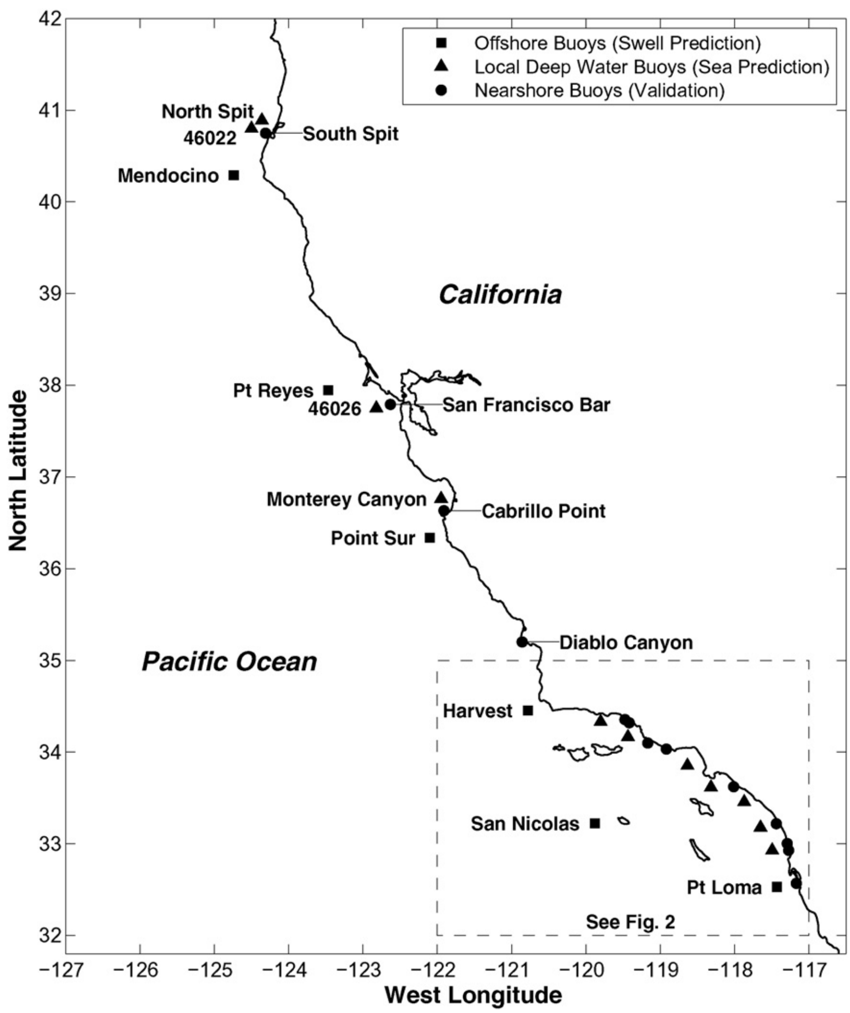

Fig. 1. Locations of buoys used to predict and validate nearshore wave parameters along the California coast. All buoys are Datawell Directional Waveriders, except 46022 and 46026 (NOAA 3 m discus buoys).