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The significance of ultra-refracted surface gravity waves on sheltered coasts, with application to San Francisco Bay

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Ocean surface gravity waves propagating over shallow bathymetry undergo spatial modification of propagation direction and energy density, commonly due to refraction and shoaling. If the bathymetric variations are significant the waves can undergo changes in their direction of propagation (relative to deepwater) greater than 90° over relatively short spatial scales. We refer to this phenomenon as ultra-refraction. Ultra-refracted swell waves can have a powerful influence on coastal areas that otherwise appear to be sheltered from ocean waves. Through a numerical modeling investigation it is shown that San Francisco Bay, one of the earth's largest and most protected natural harbors, is vulnerable to ultra-refracted ocean waves, particularly southwest incident swell. The flux of wave energy into San Francisco Bay results from wave transformation due to the bathymetry and orientation of the large ebb tidal delta, and deep, narrow channel through the Golden Gate. For example, ultra-refracted swell waves play a critical role in the intermittent closure of the entrance to Crissy Field Marsh, a small restored tidal wetland located on the sheltered north-facing coast approximately 1.5 km east of the Golden Gate Bridge.

1. Introduction

It is well known that surface gravity waves undergo transformation when the water depth is less than approximately their wavelength. Depending on the severity of the bathymetry and its spatial gradient, phenomenon such as wave refraction, shoaling, reflection, diffraction, and dissipation may occur. In particular, the directions of wave and energy propagation can be drastically modified, mainly through refraction although the other phenomenon mentioned above can also contribute. For example, wave theory explains that when idealized single frequency waves approaching an isolated island from the deep ocean, the waves can actually impact the shoreline on the lee side of the island, having undergone a nearly 180° change in the direction of wave propagation (e.g. Lautenbacher, 1970; Jonsson et al., 1976; Liu et al., 1995). We will refer to surface gravity waves that have undergone a 90° or more directional change from their deepwater propagation direction as Ultra-Refracted Waves (URW). Because of the manner in which wave direction changes in response to bathymetry, URW can propagate into areas that appear to be sheltered from ocean waves, such as the lee side of islands, into coastal lagoons, bays, and estuaries, and onto coastlines protected by large scale cusps and promontories.

San Francisco Bay (see Fig. 1A) is one of the largest and most sheltered natural harbors on earth. The bay is normally protected from ocean waves by the coastal orientation, the offshore bathymetry, and the narrow entrance at the Golden Gate (hereafter referred to as GG). In fact, refraction and breaking of storm waves over the large ebb tidal delta plays a significant role in driving coastal processes near the mouth of San Francisco Bay (Eshleman et al., 2007; Shi et al., 2011). However, wave refraction (and other less significant processes) can also cause deep water ocean swell waves to enter through the GG straight and spread throughout central San Francisco Bay. The ocean waves that propagate through the GG can exert strong influence on coastal processes and ecology within the Bay (e.g., Talke and Stacey, 2003).

The present work utilizes a widely used numerical model for wave propagation to explore the degree to which URW penetrate through the GG straight and into San Francisco Bay. The role of wave frequency and deep water direction are explored through a series of model runs. Transects were created in the model at four locations, as shown in Fig. 1B, and the wave energy for various wave cases were evaluated on these transects. A sequence of simulations was conducted to explore the influence of deep water wave characteristics such as frequency, height, and direction.

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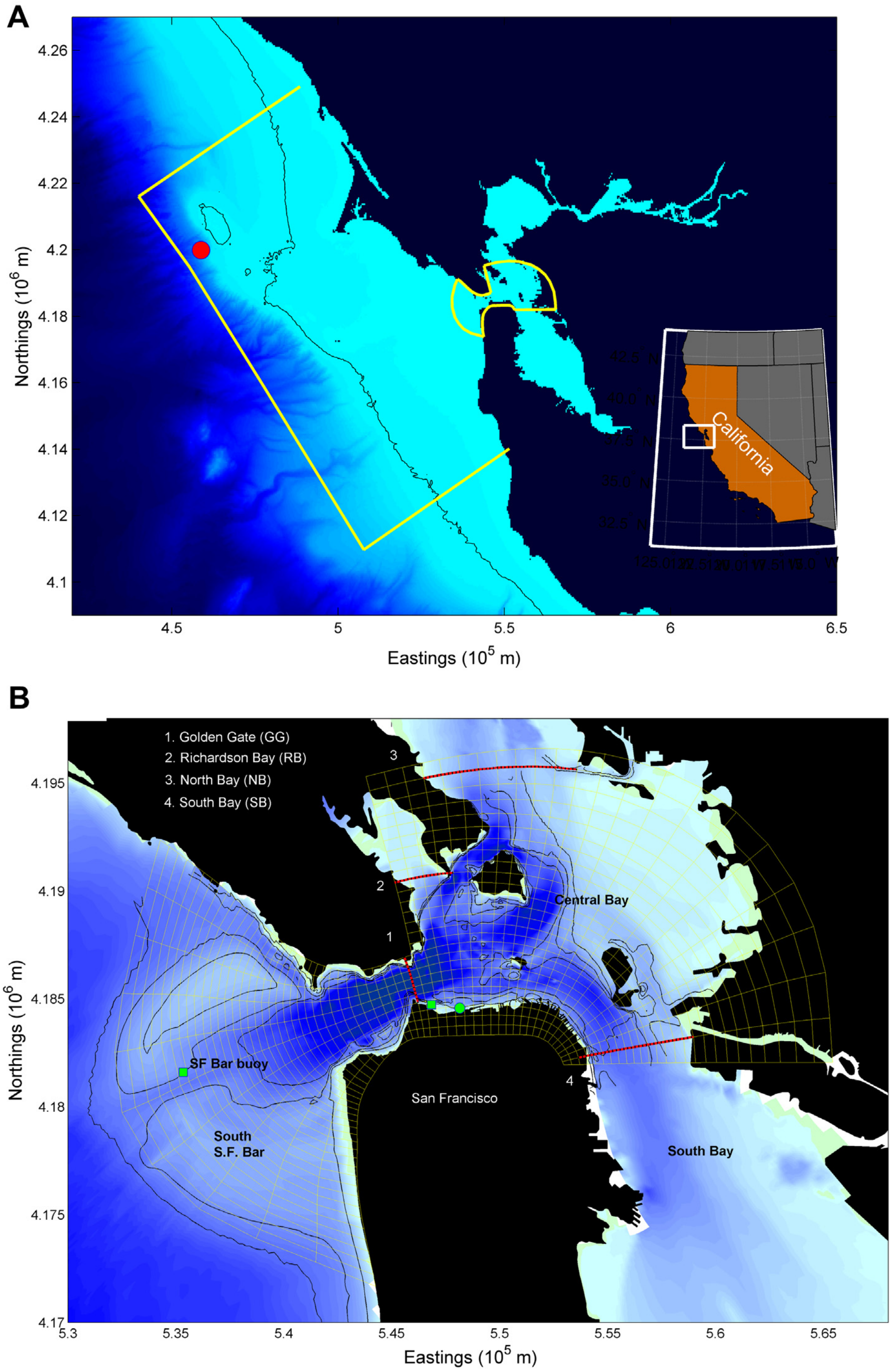

Fig. 1. A: Study area and model grids. Outlines of the two curvilinear grids used in the numerical are shown with solid yellow lines. Black lines are the 100 m isobaths. The red circle denotes location of the deep-water Pt. Reyes wave buoy. B: San Francisco Central Bay study area. Nested model grid (de-refined) is shown as light-colored hatching; red/black lines indicate transects discussed in text. Wave measurement locations: SF Bar wave buoy (green square), CF1 (green square) and CF2 (green circle) near shore Crissy Field shoreline. Contours are the 10, 15, and 20 m isobaths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Wave model

The spectral wave model SWAN (Booij et al., 1999; Ris et al., 1999) was used to simulate wave propagation from deep water. The model has been used widely in the coastal engineering and science community, and for this study was implemented through the Deltares Delft3D user interface (version 3.28.04, SWAN version 40.51). The SWAN model is a phase averaged numerical model capable of simulating wave refraction and shoaling owing to bathymetry, wave–current interaction, non-linear wave–wave energy transfers, and energy dissipation from white-capping, depth-induced wave breaking, and bottom shear stress. Evolution of the wave spectrum in SWAN is described by the spectral action balance equation, which in Cartesian coordinates may be expressed as,