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THE CIRCULATION OF MONTEREY BAY AND RELATED PROCESSES*

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Abstract The surface circulation of Monterey Bay is relatively weak. Early attempts to ascertain this circulation are initially summarized. Recent results indicate that the surface circulation is predominantly northward (i.e. cyclonic) with speeds usually in the range of 5 to 20 cm/sec; however, major reversals in flow direction do occur. The influx of fresh water, although relatively small, plus seasonal heating and residual tidal influence may all contribute to northward flow inside the Bay. During spring and summer, cooler waters which often occur across the entrance of Monterey Bay are most likely due to both local and advective processes.

Temperatures at intermediate depths in Monterey Bay (~25 to ~150 m) suggest that geostrophic flow within the thermocline may be opposite to that at the surface (i.e. anticyclonic). However, reversals in flow direction at depth from anticyclonic to cyclonic may occur when offshore flow in the California Undercurrent is weak. Seasonal changes in the deep circulation in Monterey Bay may be related to seasonal changes in the strength of the California Undercurrent. The deep flow in Monterey Submarine Canyon is vigorous (up to ~100 cm/sec) and frequently upcanyon, and oscillations in current speed and direction are often supertidal (i.e. of higher frequency). Nonlinear effects associated with very high amplitude internal waves may contribute to onshore flow within the Canyon. Supertidal frequency oscillations may also arise from nonlinear effects, and superinertial frequency oscillations may occur due to the narrowness of Monterey Submarine Canyon.

Residence times for bay waters estimated from sea surface temperatures (SSTs) inside and outside the Bay range from 5 to 12 days. Mean internal Rossby radii of deformation range from 10 km over Monterey Submarine Canyon to about 1 km around the periphery of the Bay, reflecting the strong influence of bottom depth. A scale analysis suggests that several processes, in addition to those usually indicated for the deep ocean may be important in the Monterey Bay coastal region.

Coastal upwelling through advection from outside the Bay, open ocean upwelling through positive wind stress curl and deep upwelling in Monterey Submarine Canyon may all contribute to the upwelled waters found in Monterey Bay. These waters, which are enriched through this unique combination of upwelling-related processes, most likely account for the very high biological productivity that characterizes this region.

A number of additional processes affect the circulation of Monterey Bay including winds, internal waves, mixing, tides, local heating and river discharge, eddies, oceanic fronts, spring transition events, 40–50 day oscillations and El Niño episodes. These processes are described.

The circulation in Monterey Bay is also strongly influenced by the circulation offshore. The circulation offshore is complex, consisting of eddies, interleaving alongshore flows involving

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the interaction of different water masses, and offshore jets. This complexity may be due, in part, to the presence of the Bay itself and the Canyon.

Finally, a conceptual model of bay circulation is presented that reflects a synthesis of the available observations and theory. Because of the importance of Monterey Submarine Canyon in influencing the circulation within Monterey Bay, 16 other bay/canyon systems are identified globally where canyons may influence the local circulation.

Introduction

Monterey Bay (MB) is located along the central California coast between 36.5 and 37°N (Fig. 1); it is 37km wide (between Point Pinos and Terrace Point) and is 19km from a line connecting Point Pinos and Terrace Point at the point of maximum depth (950m), to Moss Landing. It is semi-enclosed, has a free connection with the open sea and receives limited amounts of fresh water from several streams. MB is not an estuary because it is deep and broad and is not significantly diluted by the fresh water it receives except locally during brief periods of high river discharge.

The Bay is symmetrical in shape and covers an area of approximately 550km^2. The Monterey Submarine Canyon (MSC) is the major topograhic feature in MB and divides it more-or-less equally into northern and southern sectors. MSC is the largest submarine canyon along the west coast of North America (with the exception of the Bering Sea), having a volume of 420km^3 (Martin 1964). Two transects across the Canyon are shown in Figure 2. From Terrace Point to Point Pinos (transect B–B′), the distance across the Canyon (i.e. across the entrance of MB) at a depth of 150m (just below the canyon lip) is about 12km. Along this transect the maximum bottom depth approaches 900m. Further offshore, the Canyon width increases rapidly. Further inside the Bay, the Canyon width decreases significantly, to as short as approximately 3km at 150m, along transect A–A′. Although MSC represents a major depression that cuts across the continental shelf and slope, a significant fraction of the Bay is shallow. Approximately 80% of the Bay is shallower than 100m and 5% is deeper than 400m. There are two bights in MB, one to the south near Monterey and a second to the north between Santa Cruz and Aptos.

Offshore, the California Current transports relatively cool, fresh, subarctic water equatorward along the California coast (Reid et al. 1958). The mean flow is weak and instantaneous flows may often be poleward, especially near the coast. Along the central California coast, winds from the NW associated with the Subtropical High Pressure Cell produce coastal upwelling. Coastal upwelling influences coastal circulation and thermal structure strongly in this region and often starts abruptly with the so-called spring transition. At the latitude of MB, coastal upwelling usually occurs between March and October in accordance with the usually persistent upwelling-favourable winds. A frequently used indicator for the intensity of coastal upwelling is the upwelling index which provides a quantitative measure of wind-driven offshore Ekman transport (e.g. Bakun 1973). Figure 3 shows the daily (and weekly-averaged) time series of upwelling index on the coast at 36°N just south of MB for 1980. Coastal upwelling is relatively intense at this location compared to other locations along the US West Coast. The index becomes strongly positive in March at the time of the spring transition and gradually weakens during late summer and fall.

By early November, when coastal upwelling relaxes, a narrow (50 to 100km) near-shore countercurrent becomes established. Below depths of ~150m, this flow is termed the California Undercurrent and is present more-or-less year-round. During winter, the