

Chapter 21

Oceanographic Processes and Marine Productivity in Waters Offshore of Marbled Murrelet Breeding Habitat

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Abstract: Marbled Murrelets (*Brachyramphus marmoratus*) occupy nearshore waters in the eastern North Pacific Ocean from central California to the Aleutian Islands. The offshore marine ecology of these waters is dominated by a series of currents roughly parallel to the coast that determine marine productivity of shelf waters by influencing the rate of nutrient flux to the euphotic zone. Immediately adjacent to the exposed outer coasts, wind driven Ekman transport and upwelling in the vicinity of promontories and other features create zones of enhanced primary production in which primary and secondary consumers may aggregate. In the more protected waters of the sounds, bays and inlets of British Columbia and Alaska, tidal processes dominate the physical mechanisms responsible for small-scale variation in primary production and prey aggregations.

In North America, Marbled Murrelets (*Brachyramphus marmoratus*) occupy coastal marine waters from central California to the Aleutian Islands of Alaska. To understand factors controlling marine resources in the habitats occupied by Marbled Murrelets, it is useful to review the coastal oceanography of the region between California and Alaska. For the purposes of this review, I focus on three types of habitat: shelf waters, influenced primarily by the major long-shore current systems; inshore waters of the open coasts; and the relatively sheltered waters of sounds, inlets and bays.

This chapter provides an overview for the non-marine specialist of the types of habitats, and the processes that determine the distribution and abundance of marine resources used by Marbled Murrelets.

Determinants of the Shelf Circulation

The major offshore currents off the west coast of northern North America originate as eastward flowing currents crossing the North Pacific Ocean. One of these, the North Pacific Current, divides into two branches west of the continental shelf off the British Columbia coast (Reed and Schumacher 1987, Thomson 1981). The northern branch curves northeast as the Alaska Current, and forms a counterclockwise rotating gyre in the Gulf of Alaska (*fig. 1*). The second branch of the North Pacific Current turns southeast as the California Current and flows along the edge of the continental slope off Washington, Oregon and California. The division of the North Pacific Current is seasonally variable; it is most abrupt in winter, and most diffuse and spatially variable in summer (Thomson 1981).

The Alaska Current is relatively wide (400 km) and slow (30 cm/s) as it moves through the eastern Gulf of Alaska (Reed and Schumacher 1987). As the Alaska Current passes Kayak Island in the northern Gulf of Alaska, it forms a strong (>50 cm/s), clockwise rotating gyre in the island's lee (Royer and others 1979). A branch of the Alaska Current, the Alaska Coastal Current, diverges from the gyre and approaches the Kenai Peninsula coast (*fig. 1*). In fall, the Alaska Coastal Current shows a marked increase in velocity, apparently as a result of both increased freshwater runoff and easterly winds that constrain the current in a narrow coastal stream and produce coastal convergence (movement of water toward the coast, with attendant downwelling) (Royer 1979, 1983; Schumacher and Reed 1980). Much of this flow passes through Kennedy Entrance, south of the Kenai Peninsula, and thence into either Cook Inlet or westward into Shelikof Strait between Kodiak Island and the Alaska Peninsula. The main Alaska Current exits the Alaska Gyre to the west as the Alaska Stream, flowing along the Alaska Peninsula and the south side of the Aleutian Islands. West of Kodiak Island, it becomes narrow (100 km) and swift (~100 cm/s) (Reed and Schumacher 1987). Although these currents are for the most part seaward of the distribution of Marbled Murrelets in the Gulf of Alaska (Piatt and Ford 1993), the currents are important to marbled murrelets because they influence the transport of plankton into coastal waters and also because they can play an important role in the transport of oil slicks when spills occur (Piatt and others 1990).

The California Current varies in its intensity, definition, and direction of flow geographically and seasonally (*fig. 2*) (Mooers and Robinson 1984; Thomson 1981). It is relatively weak off the Washington and Oregon coasts, where it has a southward flow only 20 percent of the time. In contrast, off California, the current is usually well defined and flows southward about 50 percent of each month. The California Current is most often southward and strongest between March and September.

Changes in the direction and intensity of flow of the California Current have important effects on offshore marine production (Chelton 1981, Chelton and others 1982). When the current moves strongly southward, water throughout the water column moves away from the coast (offshore transport) due to the Coriolis Effect. In addition, offshore transport of surface water, also related to the Coriolis Effect (Ekman transport), results when north and northwest winds force increased surface flow to the south. Water transported offshore is replaced by the upwelling of deep, cold, nutrient rich water that supports enhanced productivity. These seasonal and interannual fluctuations in the California Current system and its productivity have been linked to changes in the

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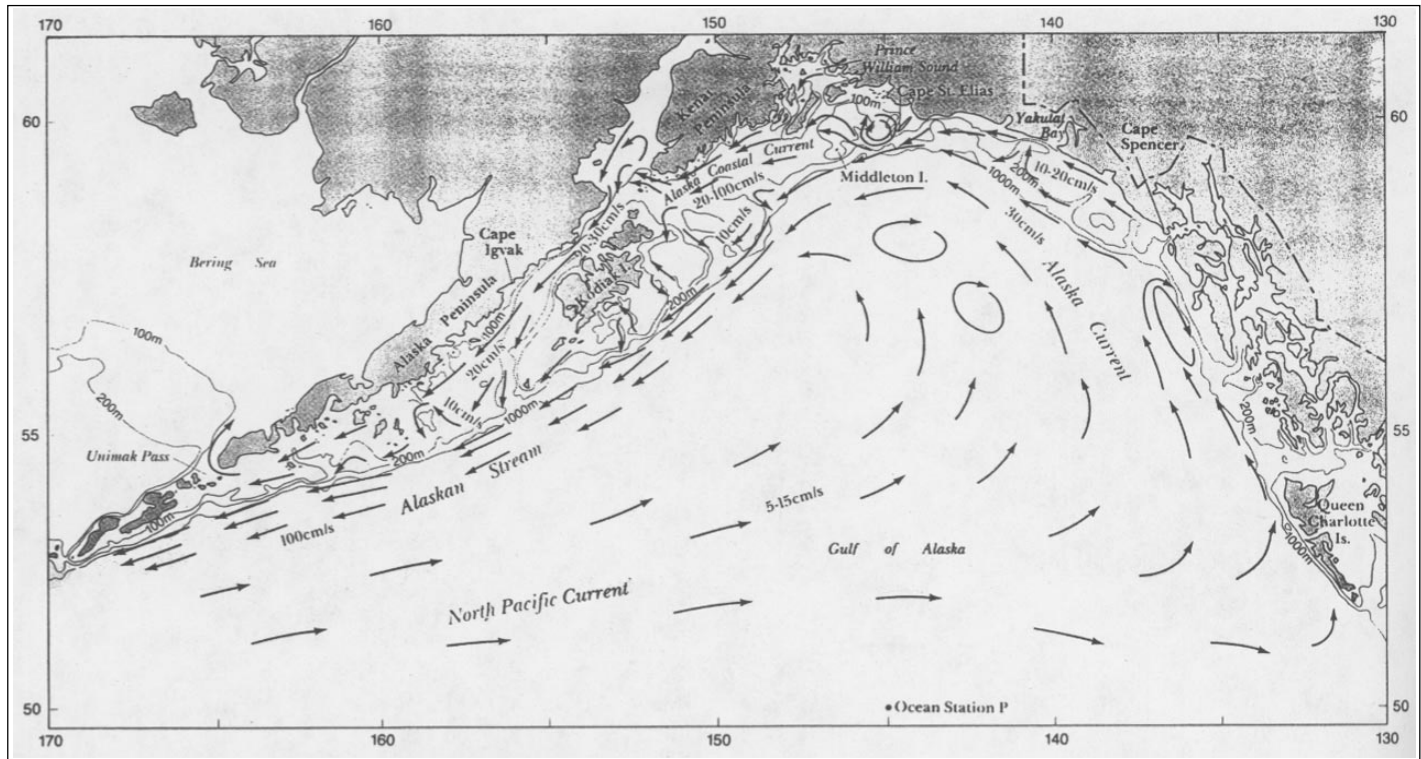


Figure 1—Major features of ocean circulation in the Gulf of Alaska. From Reed and Schumacher (1987), by permission.

breeding success of seabirds (Ainley and Boekelheide 1990, Ainley and others, in press) and in the numbers and distribution of seabirds at sea (Briggs and others 1987).

Inshore of the California Current, the Davidson current flows northward seasonally from about 32° to about 50° N (*fig. 2*). The onset of the Davidson Current usually occurs in October, when the overall average movement of water in the California Current system shifts toward the north until March (Thomson 1981). When the northward flowing Davidson Current prevails, upwelling is suppressed because northward flowing water is deflected by the Coriolis Effect toward the shore and downwelling is likely to prevail (McLain and others 1985). The seasonal shifts in the flow of the California Current system are largely the result of changes in the direction of the prevailing winds. In spring and summer, the winds blow from the northwest and move the surface water southward, whereas in winter, prevailing winds are from the southwest and surface water movements are to the north.

Off Vancouver Island, a northwestward coastal current flows inshore of the southeastward flowing southern branch of the North Pacific Current (Thomson 1981). This inshore current originates in the outflow of the Strait of Juan de Fuca and is confined in summer to within 15-20 km of the coast. The speed of the coastal current is determined by the velocity of the winds. In winter, the coastal flow merges with that of the Davidson Current.

Strong El Niño-Southern Oscillation events cause a reversal of flow in the California Current System, the presence

of a surface layer of warm, nutrient-depleted water, and the replacement of coastal upwelling with downwelling (Johnson and O'Brien 1990; Norton and others 1985; Rienecker and Mooers 1986). A consequence of these events is a marked reduction in primary production, followed by a reduction in zooplankton populations and reduced survival of at least some larval fish (Barber and Chavez 1984, MacCall 1986, Percy and Schoener 1987). These events result in a marked decrease in seabird reproductive success and in striking changes in the offshore distribution and abundance of seabirds (Ainley and Boekelheide 1990; Ainley and others, in press; Briggs and others 1987).

Inshore Waters of the Open Coasts

Large oceanic currents determine regional marine habitat types and are responsible for a major portion of the seasonal variation in production on the shelf. However, marine waters within a few kilometers of the shore are where Marbled Murrelets spend most of their time. In these areas, currents interacting with bathymetry can create fronts (boundaries between water masses where convergences or upwelling may occur) and upwellings that either enhance productivity, or cause organisms to accumulate because of behavioral responses to physical gradients. For example, upwelling results when a current passes a promontory and draws away surface water that is then replaced by water from depth (Pingree and others 1978; Thomson 1981). Fronts associated with these processes provide foraging sites for seabirds.

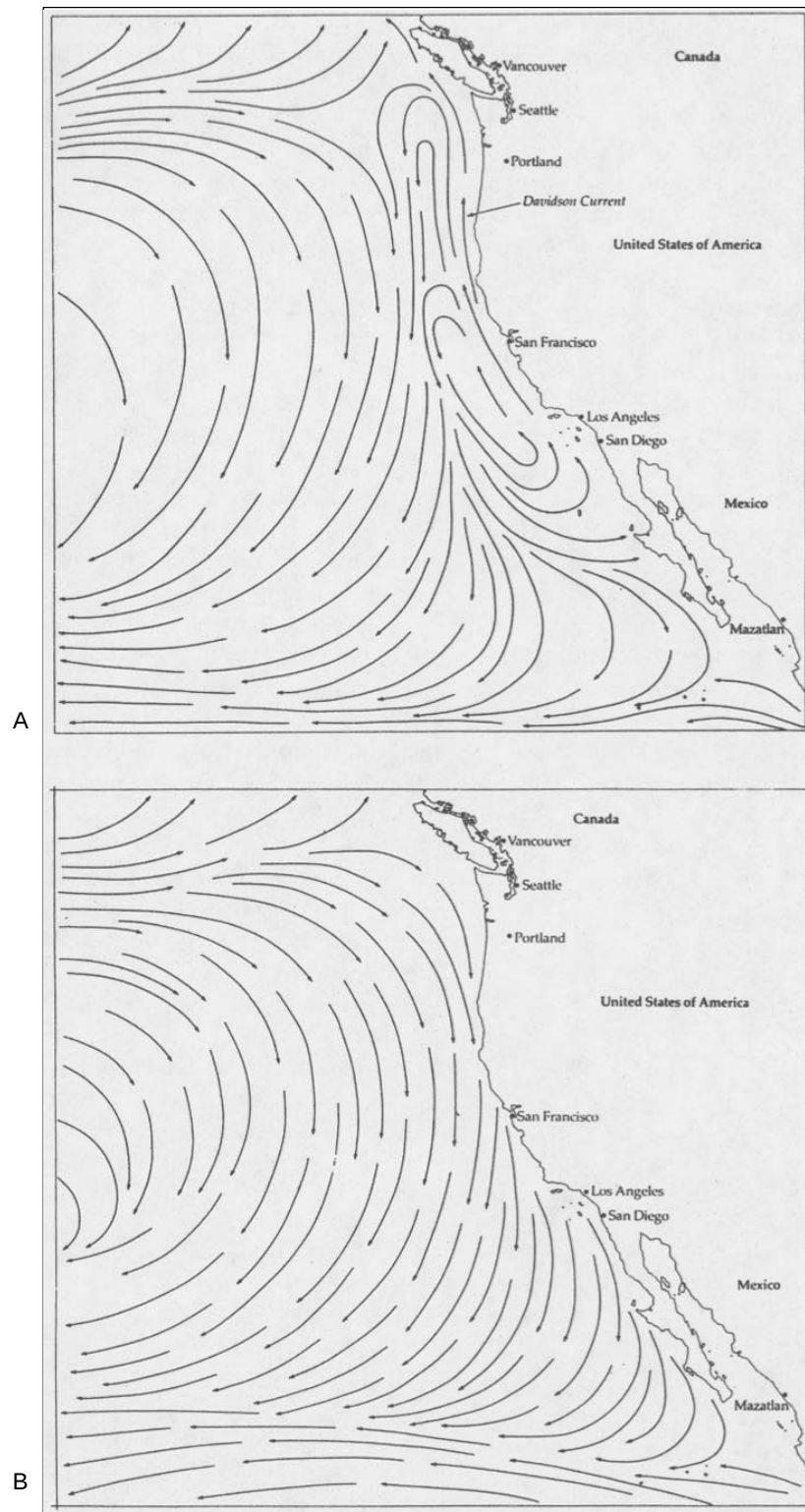


Figure 2—Schematic of the circulation of the California Current in (a) February and (b) August. From Ingmanson and Wallace (1989), by permission.

In coastal waters, strong winds cause upwelling by two mechanisms. In the first, water is displaced from near the coast by winds blowing parallel to the coast from the north. In the northern hemisphere, if water depths are sufficient, surface waters will move at approximately 90 degrees to the right of the direction of the surface wind because of the Coriolis Effect (Ekman transport). When this occurs near the coast, the displaced water is replaced by nutrient rich water from depth. In the second, winds blowing from the shore cause inshore upwelling. If the water is sufficiently shallow, the Ekman transport is effectively canceled by friction with the bottom, and surface flows will be in the same direction as the wind. When strong land breezes blow surface water away from a lee shore, inshore surface waters are replaced with water from greater depth.

Along the open coasts of California, Oregon, and Washington, localized nearshore upwelling due to Ekman transport and offshore winds blowing water away from lee shores provides regions of enhanced primary and secondary production. These upwelling processes, and fronts associated with river discharges are expected to be the most important physical features in determining murrelet foraging opportunities. Ainley and others (this volume) provide one of the only examples of the sort of mesoscale studies needed to link murrelet foraging distributions to physical and biological processes that result in exploitable concentrations of prey.

Sheltered Waters of Sounds, Inlets and Bays

The physical and chemical oceanographic processes controlling primary production in the fjords and estuaries of the Gulf of Alaska and the British Columbia coasts are reviewed by Burrell (1987) and Reeburgh and Kipphut (1987). In these fjords, freshwater input, primary production, and other biogeochemical processes are highly seasonal. Freshwater, less dense than saltwater, forms a surface layer in the fjords and is discharged from these upper layers into the Gulf of Alaska; waters from the Gulf of Alaska circulation episodically penetrate the fjords to replace intermediate and deep resident waters (Burrell 1987). These exchanges influence the availability of nutrients to, and the residence time of, phytoplankton. Both factors also affect the timing and magnitude of primary production in the fjords. Coastal frontal zones associated with shallow areas with increased water flow can be the site of elevated primary production because of enhanced vertical flux of nutrients (Parsons and others 1983, 1984). High tidal ranges present in British Columbia and along the coast of the Gulf of Alaska would promote these enhanced vertical fluxes in the vicinity of sills at the mouths of fjords (Burrell 1987). In late summer and early fall, turbidity from river inflows may progressively limit primary production in the upper ends of fjords (e.g., Goering and others 1973).

Fjords may support one of two generalized trophic pathways (Burrell 1987, Matthews and Heindal 1980). In shallow fjords or those with shallow sills, the pathway may lead from small phytoplankton to small copepods to jellyfish. In deeper fjords, and fjords with deep sills, the trophic pathway may include large net phytoplankton (primarily diatoms), large copepods and finfish. Apparently, the depth of the sill is a critical feature; if it intercepts the pycnocline (the layer in which water density changes rapidly with depth, and which inhibits vertical mixing of water), the upper layer of out-flowing fresh water inhibits the recruitment of large calanoid copepods from outside the fjord. The ontogenetic migration to the upper water column of *Neocalanus plumchrus* and related oceanic copepod species in the North Pacific occurs at the same time as the coastal convergence mentioned above (Burrell 1987). Their presence in the upper water column at this time allows them to be transported into adjacent fjord environments according to observations by R. T. Cooney, as cited by Burrell (1987). These large copepods are likely to be important prey for the small fish taken by Marbled Murrelets. One might hypothesize, then, that murrelets would be more likely to forage in fjords supporting populations of large copepods than in fjords lacking this component of trophic transfer. Additionally, one might expect that Marbled Murrelets would be more likely to forage at the seaward ends and near the sills of these fjords, rather than at their inner ends.

In the inland waters of the sounds and channels of Washington, British Columbia, and Alaska, tidal processes are likely the most important determinants of localized foraging opportunities for marbled murrelets and other seabirds. Upwellings can be caused by currents impinging on an obstruction and being driven to the surface, such as when strong tidal currents encounter a sill and flow over it. In these circumstances planktonic organisms are driven to the surface (Brown and Gaskin 1988; Vermeer and others 1987), or may be concentrated at depth where their ability to swim against a gradient is matched by an opposing current (e.g., Coyle and others 1992).

Superimposed on the physical mechanisms that enhance primary production and concentrate prey are the seasonal variations in production and the movements of prey of suitable size. We know of few studies of physical processes and fish movements at temporal or spatial scales appropriate for understanding murrelet foraging, and none for which murrelets were a focus of the study. This paucity of data makes it difficult to assess, in oceanographic terms, the characteristics of habitats critical for foraging murrelets.

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