A summary of major upper ocean sub regions found within Parks Canada's five Natural Marine Regions on the Pacific coast of Canada

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Abstract

The overall objective of this work was to contribute information to discussions regarding the conservation of pelagic marine diversity on the Pacific coast of Canada. Conceivably, resulting maps from this report could be used to inform the development of networks of marine protected areas by considering that Pacific Canada marine waters can be subdivided into major upper ocean sub regions with recurring physical oceanographic processes and potentially different marine plankton diversity. Although the surrogacy of the sub regions and diversity remains to be tested, the sub regions offer a starting point for recognizing that the ocean is not an homogenous water mass.

The main objective of this report was to describe the major upper ocean sub regions associated with each of five Natural Marine Regions along the Pacific coast of Canada. The analysis was restricted to the upper ocean (~20-30 m depth) and to oceanographic processes linked to enhancing nutrient supply to surface waters. Ignored are processes such as those transporting oxygen to basin habitats where waters can be well oxygenated to anoxic depending upon restrictions of deep water circulation. Further, because many physical and chemical oceanographic processes can change markedly from season-to-season and year-to-year, it was necessary to simplify the analysis by considering ocean processes that occurred during the summer only (mid June to mid September). It was assumed that each ocean sub region has a suite of recurring and enduring physical oceanographic processes that distinguish itself from its neighbour, and that the oceanographic processes result in lower trophic level properties (e.g., primary production) that influence the organization and production of higher trophic levels, such as fish, seabirds and marine mammals. Conceptually, the boundaries of the upper ocean sub regions should be considered "fuzzy" because of temporal and spatial variability in the location of water masses due to surface winds and tidal currents, but pragmatically, the boundaries are represented on the maps as hard lines to facilitate presentation. Finally, it should be noted that the shoreward boundary of the upper ocean sub-regions described is the kelp zone or 'white-strip' (~ depth of 30 m).

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Introduction

Parks Canada Agency is federally legislated under the National Marine Conservation Areas Act of Canada (2002) to establish a system of National Marine Conservation Areas (NMCAs). The NMCAs are intended to represent the full range of marine diversity found on Canada's Atlantic, Arctic, and Pacific coast, and the Great Lakes. The mandate of the federal legislation is to establish one NMCA within each of 29 natural marine regions (NMRs) identified for Canada's coasts; five natural marine regions have been identified on the Pacific coast of Canada. Ultimately, each NMCA must represent, as much as possible, a NMRs geological diversity, oceanographic diversity, and marine biodiversity, in addition to major archaeological, cultural and historical features.

The main objective of this report was to describe the major upper ocean sub regions associated with each of the five NMRs along the coast of British Columbia. The analysis was restricted to the upper ocean (~20-30 m depth) and to oceanographic processes linked to enhancing nutrient supply to surface waters. Further, because many physical and chemical oceanographic processes can change markedly from season-to-season and year-to-year (Robinson 2002), it was necessary to simplify the analysis by considering ocean processes that occurred during the summer only (mid June to mid September). It was assumed that each ocean sub region has a suite of recurring and enduring physical oceanographic processes that distinguish itself from its neighbour, and that the oceanographic processes result in lower trophic level properties (e.g., primary production) that influence the organization and production of higher trophic levels, such as fish, seabirds and marine mammals. Ware and Thomson (2005) for example, showed how satellite-derived chlorophyll (as a surrogate for primary production) was associated with resident fish production along the northwest coast of North America. Conceptually, the boundaries of the upper ocean sub regions should be considered "fuzzy" because of temporal and spatial variability in the location of water masses due to surface winds and ocean and tidal currents, but pragmatically the boundaries are represented on the maps in this report as hard lines to facilitate presentation. Finally, it should be noted that the shoreward boundary of the upper ocean sub-regions described below is the kelp zone or 'white-strip' (~ depth of 30 m).

General approach to oceanographic regionalization

The main approach used in this study included review of more than 20 years of published oceanography studies, analysis of satellite imagery, and oceanographic simulation modelling results, and discussions with oceanographic experts. From this information, upper ocean sub regions were subjectively identified in each of the five Natural Marine Regions: Queen Charlotte Shelf, Queen Charlotte Sound, Hecate Strait, West coast Vancouver Island shelf, and Strait of Georgia. The upper ocean sub regions were defined primarily using information about oceanographic processes that occur above the thermocline, which across the continental shelf along the west coast of Vancouver Island in summer is about 20-25m deep (Thomson and Fine 2003).

In the remainder of the report, the upper ocean sub regions associated with each Natural Marine Region are described. First, the dominant recurring oceanographic process that can readily be identified within the sub region is described, and then the information used to identify the boundary is discussed. The following information was used to help describe a boundary for a sub region. This process is subjective but hopefully the accompanying maps will convey the utility of the proposed boundaries:

- A composite advanced very high resolution radiometer (AVHRR) satellite image generated for June-August 1998-2000 and a composite chlorophyll image from SeaWiFs (1999-2004) produced by DFO were used to delimit boundaries of the upper ocean sub regions in the 3 northern NMRs, and coast-wide respectively.
- Crawford et al. (2007) discussed several recurring oceanographic features in northern BC from a single snap-shot of sea surface temperature from a NOAA satellite image (see Figure C.10 in Crawford et al. 2007).
- Coast-wide average water column speeds were obtained from FUNDY5SP which is an extension of the 3-dimensional, triangular-grid, barotrophic finite element model FUNDY5 described in Foreman et al. (1995, 2008). The modelled tidal current information provides a link between bottom topography and water column processes that will recur over time. These tidal speeds may be considered as a proxy for tidal mixing and primary productivity.
- Interpolated and modelled sea surface and bottom temperature and salinity data were obtained from M. Foreman (DFO) for the entire coast. These data included all available CTD casts from DFO cruises over the last several decades (Foreman et al. 2008), and was used to help identify the average position of boundaries.

The remainder of this report is divided into two parts. Part 1 describes the 24 upper ocean sub regions within the context of major recurring surface oceanographic processes, and describes their approximate boundaries. Part II of the report places the upper ocean sub regions within the context of the five Natural Marine Regions (NMRs).

Part I. Upper ocean sub regions

Twenty-four upper ocean sub regions were identified for the BC coast (**Figure 1**) ranging in surface area from about 195 km^2 in the southern Strait of Georgia to more than 170,000 km^2 in the offshore Pacific (**Table 1**). The remainder of this section discusses the major recurring surface oceanographic processes in each sub region, and the approximate sub region boundary. Refer to **Figures 2-8** for comparisons between upper ocean sub regions and satellite/modelled oceanographic data.

Table 1. A listing of surface area, volume, mean depth and maximum depths for each of the 24 upper ocean sub regions identified along the Pacific coast of Canada.

ID	Upper ocean sub region	Surface Area (km2)	Volume* (km3)	Mean Depth (m)	Max Depth (m)
1	Offshore Pacific Ocean	170471	533753	3131	3650
2	Coastal Mixing	161455	357105	2212	3400
3	SE Alaska Mixing	6823	2926	429	2653
4	Dixon Entrance Coastal Flow	7159	1240	173	681
5	West Coast QCI Upwelling	5237	5591	1068	2500
6	Low Flow Nearshore	4615	270	58	692
7	Dogfish Bank Frontal	2368	33	14	57
8	Rose Spit	1994	99	50	200
9	Hecate Strait	12032	1089	90	359
10	Aristazabal Upwelling	5832	619	106	420
11	Mainland Fjords	10877	1830	168	769
12	Cape St. James Tidal Mixing	6562	10667	1625	2706
13	Eastern Queen Charlotte Sound	6348	782	123	391
14	Cape Scott Tidal Mixing	12493	9310	745	2141
15	Queen Charlotte and Johnstone Straits	2572	340	132	533
16	Vancouver Island Shelf Break Upwelling	5309	2626	495	1101
17	Vancouver Island Inner Shelf	8900	733	82	534
18	Northern Strait of Georgia	2862	425	148	556
19	Central Strait of Georgia	3007	623	207	447
20	Southern Strait of Georgia	195	27	137	243
21	Interior Gulf Islands	886	43	49	255
22	Haro Strait and Rosario Passages	420	38	91	372
23	Juan de Fuca Strait	1585	185	117	263
24	Juan de Fuca Eddy	1942	239	123	603
	TOTAL	**441944**	**930591**		

* Volume calculated as surface area (km^2) multiplied by mean depth (km)

Upper ocean sub region 1. Offshore Pacific Ocean

Oceanographic process: The major oceanographic process operating in the *offshore Pacific* sub region in summer is a stratified water column that has a deep thermocline (~50m), and is characterized by relatively low chlorophyll concentrations that remain constant throughout the summer. The offshore NE Pacific Ocean in summer is also relatively warm, saline and has high macro nutrient concentrations such as nitrates, but low micro nutrient concentrations such as iron (Whitney et al. 2005). Biologically the offshore region is not considered very productive and is primarily dominated by small-bodied plankton, and a vertebrate food web that has adapted to the biological desert- like conditions.

Oceanographic boundary: The *offshore Pacific* sub region extends along the BC coast and encompasses a large surface area (**Figure 1**). The boundary between the *offshore Pacific* and the adjacent coast-wide upper ocean sub region *coastal mixing* was determined from examination of ocean colour data from Seawifs (**Figure 4**), and Coastal Zone Colour Scanner. For example, in **Figure 4** the boundary between offshore and coastal was derived as a straight line that runs parallel to the coast and separates the ocean colour into blue (offshore) and green (coastal). Yin et al (2005) considered the oceanic domain to include waters > 2750m and seaward of 170oW (off southern Vancouver Island).

Upper ocean sub region 2. Coastal mixing

Oceanographic process: The second largest upper ocean sub region on the BC coast, the *coastal mixing sub region*, encompasses more than 161,000 km^2, and serves as an intermediary between the highly productive upper ocean sub regions on the continental shelf and the low production *offshore Pacific* upper ocean sub region. In general, highly productive waters generated over the continental shelf or in other near shore areas moves southward and seaward during the summer because of the dominant NW winds experienced along the southern BC coast, and the predominantly westerly winds along the northern coast. This region of mixing of cooler productive coastal waters with warmer oceanic waters is spatially and temporally highly variable, and is characterized by squirts, jets and eddies that are easily observed on ocean colour and sea surface temperature satellite imagery (see **Figures 4,7,8**). Off the west coast of Vancouver Island the southward flowing California Current dominates the coastal mixing zone in summer because of strong NW winds. Note that upwelling along the north coast of BC is very weak compared with the west coast of Vancouver Island or further south in the California Upwelling Domain. Winds in the north coast are sufficient to displace warm surface waters, exposing nutrient rich water, but isopycnal surfaces are not drawn towards the surface from any appreciable depth (Whitney et al. 2005).

Oceanographic boundary: The coastal mixing sub region and boundary was easy to establish because, by default, it lies between the large *offshore oceanic* sub region and the remaining near shore upper ocean sub regions.

Upper ocean sub region 3. SE Alaska Mixing

Oceanographic process: The southern coast of Alaska is a region of highly productive waters due to several dominant processes supplying nutrients to the photic layer in summer, including relaxed downwelling that results in high salinity and nutrient rich waters to move onto the shelf, tidal mixing in the straits, and stabilization of the surface layer by high fresh-water input (Whitney et al. 2005).

Oceanographic boundary: The boundary for the SE Alaska mixing region was considered as the cool water region along the outer coast and moving into Dixon Entrance as derived from the 1998-2000 composite AVHRR SST image (**Figure 7**).

Upper ocean sub region 4. Dixon Entrance Coastal Flow

Oceanographic process: Thomson (1989) originally identified Dixon Entrance as one of the three major oceanic domains surrounding the Queen Charlotte Islands. This region is influenced by estuarine circulation and is driven by freshwater from the Skeena and Nass rivers flowing into the coastal areas. Deep water return flows are directed eastward year-round. Crawford (2001) states that in Dixon Entrance, "Fresh water from the Skeena River mixes with salt water in Chatham Sound, and flows out of Chatham Sound as a five metre deep layer of brackish water. Sediments in this water absorb light, which warms this layer as it flows northward out of the Sound, then westward across Dixon Entrance. Any brackish water that flows out of Chatham Sound through channels to the west passes through narrow channels with strong tidal currents that mix deep cold water up to the surface, and cool this layer". The waters of Dixon Entrance eventually meet and mix with cool, nutrient rich waters that have upwelled from along the southern Alaskan Panhandle. It is the persistence of the wind-induced upwelling and tidal mixing in summer that makes this region so rich in seabirds and marine mammals.

Oceanographic boundary: The Dixon Entrance sub oceanographic region boundary was derived from the 1998-2000 composite AVHRR SST satellite image (**Figure 7**).

Upper ocean sub region 5. West Coast Queen Charlotte Islands Upwelling

Oceanographic process: This upper ocean sub region was originally identified by Thomson (1989) as the 'oceanic domain'. The continental shelf along the west coast of the Charlottes is the narrowest in British Columbia (< 5km wide) and experiences the least amount of freshwater input (Crawford et al. 2007). During summer, there is a significant region of cool water along the west coast of Haida Gwaii that is a result of wind-induced upwelling of cool, deeper nutrient-rich waters along the continental slope and narrow continental shelf. Crawford (2001) indicates "Summer winds generally blow from the northwest in this region, pushing the surface waters downwind. The effect of the rotation of the earth is to turn these currents to the right, away from west coast of the Queen Charlotte Islands. Waters that move away from the coast are replaced at the ocean surface by deeper colder water all along the west coast of Graham Island and much of Moresby Island." The upwelled waters are quickly carried off the west coast of the WCI into the *coastal mixing* upper ocean sub region because of the narrowness of the continental shelf.

Oceanographic boundary: The boundary of the WCQCI upwelling region was derived from the satellite imagery in Crawford (2001) and from the composite 1998-2000 AVHRR satellite image (**Figure 7**) and extends parallel to the west coast along Moresby and Graham Islands.

Upper ocean sub region 6. Low Flow Nearshore

Oceanographic process: Crawford et al. (2007) identified three major types of coastal watersheds in the PNCIMA region, of which, one type is considered here as characteristic of the *low flow nearshore* upper ocean sub region. Along the coast of the Queen Charlotte Islands and the west coast of Vancouver Island, there are many small-watershed rivers that have relatively low summer and annual flows, and they are dominated by rainfall later in autumn or winter. The shallow (< 50 m) near shore regions adjacent to these low flow watersheds are characterized by waters that have relatively high salinities, but low surface nutrient concentrations (e.g., Peterson et al. 2007). Surface nutrient concentrations and subsequently primary production is highly variable location-to-location and year-to-year, and tends to be determined by local processes, such as tidal mixing.

The *low flow nearshore* sub regions are known to be connected with other coastal regions as major outflow events from Barkley Sound and Juan Perez Sound. The outflow of warm surface water from these sounds is clearly visible on satellite imagery (**Figures 7 and 8**), and is thought to result in cocolithophore blooms (Robinson et al. 2005).

Oceanographic boundary: The boundary of the *low flow nearshore* regions was derived for the Queen Charlotte Islands and west coast of Vancouver Island as straight lines from headland-to-headland areas of the near shore coast.

Upper ocean sub region 7. Dogfish Bank Frontal

Oceanographic process: Waters in north central Hecate Strait in summer are characterized by a sharp thermal front, which occurs at the edge of Dogfish Banks, at depths of 20-30 m. The shallow waters over Dogfish Bank are 2-3^{o} C warmer in summer (1-2^{o} C colder in winter) than seas to the east (Jardine et al. 1993). Crawford et al. (2007) note that the eroding shores of eastern Graham Island provide sediments to the NW Dogfish Banks. A combination of strong tidal mixing and wave forced mixing keeps portion of this bank well mixed most of the time. This region is the warmest in summer and coolest in winter of all PNCIMA regions on the continental shelf. The Dogfish Banks sub region is the first to experience spring phytoplankton blooms and higher chlorophyll concentrations primarily because the depth of vertical mixing is limited by the shallow depths (< 30m). The blooms tend to exhaust nutrient supply by May and there appears to be little exchange of waters between Dogfish Bank and adjacent deeper areas.

Oceanographic boundary: The boundary of this sub oceanographic region was determined using the 1998-2000 composite AVHRR SST satellite image (**Figure 7**).

Upper ocean sub region 8. Rose Spit

Oceanographic process: In summer, warm, fresh water flow from the Skeena and Nass Rivers is clearly seen in northern Dixon Entrance because of the inflow of colder, saline water near Langara Island. The upper ocean sub region characterized by the flow in eastern Dixon Entrance in summer is which circulates counterclockwise in central Dixon Entrance (Crawford 1997). And the major oceanographic feature of this upper ocean sub region is linked to strong tidal mixing in the shallow region off Rose Spit.

Oceanographic boundary: The 1998-2000 composite AVHRR SST satellite image was used to delineate the Rose Spit sub region boundary (**Figure 7**).

Upper ocean sub region 9. Hecate Strait

Oceanographic process: The seas on the eastern side of Gwaii Haanas are relatively shallow (< 100m), and somewhat protected from NW winds, allowing for heating of the surface waters in summer. In fact, the waters of the western Hecate Strait are typically 2-5^{o} C warmer than seas in the eastern portion of the Strait (Jardine et al. 1993). Crawford (2001) also indicate that there is little average flow through Hecate Strait in summer. McQueen and Ware (2002) summarized available studies looking at oceanographic properties in a region encompassing Hecate Strait, Queen Charlotte Sound and Dixon Entrance, and they made two observations relevant to this analysis. First, there can be very different surface patterns in temperature and salinity in the region, but there were no significant differences in surface (0-5 m) nutrient or chlorophyll concentrations among stations across the region. Second, McQueen and Ware (2002) determined that a mixed layer is common and the depth of the upper wind-mixed layer likely varies between 10-30 m. This depth range is consistent with other coastal areas (Thomson, 1981). The authors also noted that summer concentrations of nutrients were typically low in the surface 0-5 m, roughly doubled from 5-15 m, and gradually increased with depths > 20 m. In addition, chlorophyll concentrations were low (< 2.0 ug l^{-1}) in the top 20 m of the water column, but increased significantly between 20-30 m. This observation indicates an accumulation of chlorophyll at the bottom of the mixed layer, a feature common in many coastal seas (Thomson 1989).

Oceanographic boundary: The boundary of the *Hecate Strait* upper ocean sub region was for the most part determined by boundaries of other upper ocean sub regions such as the *Dogfish Bank frontal* region, *Rose Spit Eddy*, and *Aristazabal/Banks upwelling*. The southern boundary was defined to run from the edge of the Cape St. James tidal mixing sub region north-eastward along the edge of Morseby Trough (200 m)

Upper ocean sub region 10. Aristazabal Upwelling

Oceanographic process: The major oceanographic process in the Aristazabal Upwelling Region in summer is characterized on the ocean's surface by colder waters progressively penetrating into Queen Charlotte Sound and Hecate Strait in spring through late summer. This plume of cold water is mostly attributed to a relaxation of winter downwelling conditions, and to NW winds causing wind-induced upwelling (Crawford et al. 2007). The cool nutrient rich water generated by upwelling near Banks Island and Aristazabal Island gradually moves seaward through Mitchell's Trough in QCS to the *coastal mixing* region, demonstrating the interconnectivity of the two oceanic regions, and the importance of coastal upwelling to oceanic regions.

Oceanographic boundary: The boundary of the Aristazabal/banks upwelling oceanographic region was derived from the composite 1998-2000 AVHRR SST satellite image (**Figure 7**).

Upper ocean sub region 11. Mainland Fjords

Oceanographic process: Lucas et al. (2007) identified three types of watersheds in coastal BC, and many of the mainland watersheds have small to medium sized rivers that empty into the deep inlets with slow tidal currents. These medium sized watershed include snowfields and glaciers that provide maximum summer freshwater flows emptying into fjords or inlets. The outflow plumes of freshwater from these watersheds are typically < 5m deep and often result in the classic two-layer estuarine flow, whereby a thin surface layer of fresh waters flow seaward, and it draws a deeper saline layer landward. Oceanographers consider each Inlet to be oceanographically unique.

Oceanographic boundary: The boundary of the *mainland inlets* upper ocean sub region was taken from Crawford et al. 2007.

Upper ocean sub region 12. Cape St. James Tidal Mixing

Oceanographic process: Strong tidal currents are found off Cape St. James, where both rapid changes in bathymetry and coastline occur. In summer, the winds from the northwest push the warm surface waters of Hecate Strait southward past Cape St. James and seaward into the *coastal mixing* region. Crawford (1996) indicates that the strong outflow of Hecate Strait waters past Cape St. James is mostly confined to within 12-15 km of shore, and that a strong current flows southward along Kunghit Island. The tidal currents at Cape St. James then bring deep cold water to the surface where they partially mix with warmer surface waters. Crawford (2001) states that water from this 'cold tidal jet' can flow more than 100 kilometres southwestward into the Pacific Ocean, forming distinctive surface 'plumes' of the *coastal mixing* region. Crawford et al. (2007) note that nutrient rich waters mixed to the surface at Cape St. James will move away from the Cape within a couple of days. The lack of high surface chlorophyll concentrations in the Cape St. James region on the ocean colour satellite image (**Figure 4**) is likely due to the strong vertical mixing at the Cape and a lack of freshwater which means that surface waters do not stratify and maintain phytoplankton near the sunlit surface.

Oceanographic boundary: The boundary of the *Cape St. James tidal mixing* region was derived as the cold water region observed on the 1998-2000 composite AVHRR SST satellite image (**Figure 7**).

Upper ocean sub region 13. Eastern Queen Charlotte Sound

Oceanographic process: In this upper ocean sub region in summer, freshwater runoff can be expected to modify the circulation in the region when large volumes of snowmelt are discharged into coastal estuaries (Thomson 1989). Note that runoff has only a marginal influence on the surface currents in Hecate Strait and Queen Charlotte Sound, which is primarily dominated by tidal currents and NW winds (Thomson 1989). Outflow from Fitz Hugh Sound and Smith Inlet is often warmer than surrounding coastal waters most likely due to the presence of sediments to absorb sunlight and to the shallow depth of the surface freshwater plume (Crawford et al. 2007), and this region of warmer water is easily note on the satellite imagery (**Figure 7**). When the warm, fresh water of Fitz Hugh Sound meets with the cold waters from Queen Charlotte Strait phytoplankton growth rates are high. Overall, the central coast region between Fitz Hugh Sound and Chatham Sounds receives lower freshwater flows than the Dixon Entrance region in northern Hecate Strait, but relatively high surface concentrations of chlorophyll are maintained by an estuarine-like circulation driven by moderate freshwater discharge from the coastal mountains flowing though inlets such as Smith Inlet. Whitney et al. (2005) indicate that the surface fresh water outflow from Rivers Inlet enters Queen Charlotte Sound with little mixing, overflowing any outflow from Queen Charlotte Strait.

Oceanographic boundary: The boundary was derived from Crawford's analysis (e.g., **Figure 8**) and the 1998-2000 composite AVHRR SST satellite image (**Figure 7**).

Upper ocean sub region 14. Cape Scott Tidal Mixing

Oceanographic process: This oceanographic region receives the well mixed outflow from *Johnstone Strait* upper ocean sub region and the fresher shallow outflow layer from the Fitz Hugh Sound and Smith Sound (*Eastern Queen Charlotte Sound* sub region). Strong tidal flow and tidal mixing over shallow Cook Bank, near the Scott Islands, removes any near surface stratification and results in a region of cool, nutrient rich water. The combination of cold sub surface nutrient rich water mixing with the Rivers Inlet plume sets up a buoyancy flow on Cook Bank which moves southward towards Brooks Peninsula. Satellite imagery shows an offshore-directed cold plume flowing westward from Cape Scott, and a second westward flowing cold plu,e at Cape Cook on Brooks Penisula, and moving into the *coastal mixing* region (Whitney et al. 2005; Crawford et al. 2007). The authors support this observation by noting that drifters released in Queen Charlotte Sound drifted south and southwest during NW winds, but did not ground south of Brooks Peninsula. This region of mixing in and around Cook Bank and the Scott Islands is well known for large colonies of sea birds, indicating good plankton conditions.

Oceanographic boundary: The southern boundary is delimited by Brooks Peninsula, and the seaward boundary was determined from the 1998-2000 composite AVHRR SST satellite image (**Figure 7**). The eastern boundary is the *Queen Charlotte Strait/Johnstone Strait* sub region boundary, and the *eastern Queen Charlotte Sound* sub region boundary.

Upper ocean sub region 15. Queen Charlotte and Johnstone Straits

Oceanographic process: The most characteristic oceanographic process occurring within this region is the strong tidal mixing within Seymour Narrows, Discovery Passage and Johnstone Straits. Waters are typically well mixed from top to bottom within the channels, and because the channels are so well mixed, primary productivity is low. In addition to the strong tidal mixing, there is an estuarine circulation in Johnstone Strait that results in a mean seaward (westward) upper layer flow on the mainland side and a mean lower layer flow eastward on the Vancouver Island side (Crawford et al. 2007). In summer, the well-mixed nutrient rich waters (near uniform top-to-bottom temperature and salinity) leave the Johnstone Strait region and enter the Queen Charlotte Strait, which eventually flows into the *Cape Scott tidal mixing* region.

Oceanographic boundary: The northern boundary of Queen Charlotte Strait/Johnstone Strait oceanographic region is defined by a line running from Cape Sutil, at the north end of Vancouver Island, to Cape Caution on the mainland. The southern end of the Queen Charlotte Strait/Johnstone Strait upper ocean sub region is the Natural Marine Region boundary separating Queen Charlotte Sound NMR and the Strait of Georgia NMR. It is not known why the NMR boundary was placed through the middle of Quadra Island.

Upper ocean sub region 16. Vancouver Island Shelf Break Upwelling

Oceanographic process: During the summer, strong NW winds result in the upwelling of deep cool and nutrient rich waters occurs along the edge of the shelf break (through canyons on the continental slope) onto the continental shelf. When the low salinity and high nutrient rich waters of the Juan *de Fuca Strait* sub region are discharged onto the southern Vancouver Island inner shelf, they result in a surface layer characterized by phytoplankton blooms. The nutrient rich region extends across the continental shelf to the highly productive *shelf break* oceanographic region (Whitney et al. 2005). Only a small portion of the inner shelf primary production is exported to the open ocean, but rather it is entrained in the south flowing shelf break current which dominates the *shelf break* oceanographic region. As outflow from the *Juan de Fuca Strait* upper ocean sub region enters the *inner shelf* sub region, it is initially directed northward along the coast in the surface buoyant flow, Vancouver Island Coastal Current.

Oceanographic boundary: The seaward boundary of the upwelling region roughly follows the 1000-m depth contour and is bounded shoreward by the 150m depth contour.

Upper ocean sub region 17. Vancouver Island Inner Shelf

Oceanographic process: Thomson (1981) described a persistent near shore ‘counter-current’ that flows to the northwest along the shore of Vancouver Island against prevailing winds during the summer. The Vancouver Island Coastal Current (VICC) is confined to within 15-20 km from shore from the entrance to Juan de Fuca Strait (upper ocean sub region 23) to Brooks Peninsula. The current is fed by low density (fresher) surface outflow from the Juan de Fuca Strait (primarily from Fraser River runoff) and by local fresh-water runoff from Vancouver Island (e.g., Somass River and Barkley Sound). The low density surface water creates a horizontal pressure gradient that interacts with the Coriolis force to create a northward flow that hugs the coast. This current runs counter to the surface wind-driven current that flows equator-ward over the mid- and outer-shelf in the summer. The VICC is also an important source of nutrients (due to intense mixing in Haro Strait, the source of this current) and supports significant PP in the area.

Oceanographic boundary: The seaward boundary of the Vancouver Island inner shelf sub region was defined using the 150 m depth contour.

Upper ocean sub region 18. Northern Strait of Georgia

Oceanographic process: This region is roughly 2371 km^2, and extends from the southern tip of Texada Island to Discovery Passae (southern tip of Quadra Island), and this region is typified by weak and variable tidal currents and summer thermal stratification (Thomson 1981; Mackas and Harrison 1997). The north eastern side is more stratified due to surface heating and a somewhat lower salinity due to the Fraser River flow (Harrison and Yin 1998). The west side is more productive (diatom dominated) possibly because of the nutrient rich tidal jet flowing out of Discovery Passage during the flood tide (Harrison and Yin 1998).

Oceanographic boundary: The northern extent of the Fraser River plume as it pushes along the southern shore of Texada Island, and a straight line from the southern shore of Lasqueti Island south to Nanoose Bay on Vancouver Island forms the southern boundary of the Northern Strait of Georgia. The northern boundary is the Strait of Georgia Natural Marine Region Boundary.

Upper ocean sub region 19. Central Strait of Georgia

Oceanographic process: Freshwater from the Fraser River, which drains about 25% of the BC land-base, makes up 25% of the volume of water in the SSoG in summer, and > 80% of this freshwater leaves the Strait via Juan De Fuca Strait. A 2604 km^2 region characterized by the "showpiece" Fraser River plume (LeBlond 1983), and hence turbid, warm, low salinity and highly stratified waters. This region in summer typically extends roughly from a line extending from Pt. Roberts westward to the Saanich Penisula, and northward to Texada Island (Thomson 1981; Masson and Cummins 2007). The Fraser plume is relatively deep 5-15m, and increases stratification, which leads to reduced wind mixing (Harrison and Yin 1998). The plume commonly 'piles' up in the southern Strait under the influence of NW winds. The plume can also jet across the Strait to the Gulf Islands, or flow northward along the eastern side of the Strait. When the plume is well developed in June, it is dark under the plume, but there are layers of relatively high chlorophyll and zooplankton, which are presumably formed outside the plume and then sucked under during ebb tides. There are also higher than expected juvenile and adult fish abundances under the plume. Therefore, the plume area maybe considered a "separate ecosystem" (Harrison and Yin 1998). Yin et al. (1997) show how the distribution of nutrients and phytoplankton biomass in the estuarine plume responds quickly to wind events and fluctuations in river discharge, and how vertical mixing frequently supplies nutrients to the plume region to enhance primary productivity.

On a final note, sharp transitions occur between the highly stratified areas of the brackish Fraser outflow and well-mixed areas generated by strong tidal currents (LeBlond 1981). The tidal front associated with the edge of the Fraser River Plume in the southern portion of the SSoG is most pronounced in May-July when river discharge is high. However, because the front moves in relation to fluctuations in river discharge, winds, and with the ebb and flood tides, it is difficult to map the 'typical' location, and thus the front is not considered a separate region in this analysis.

Oceanographic boundary: Satellite imagery was used to demark the boundary of the central Strait of Georgia that is dominated by the turbid, warm, low salinity and highly stratified waters of the Fraser River.

Upper ocean sub region 20. Southern Strait of Georgia

Oceanographic process: This area includes about 177 km^2 and extends from the southern channels northward to the typical southern extreme of the Fraser plume (Thomson 1994). This region is characterized by relatively strong mixing via tidal currents. Near the southern end of the Strait, flood currents are so strong and tidal mixing so intense that surface wind effects are minimal. The main oceanographic process reported in this region includes vigorous flow exchange and mixing in southern channels and main body of Strait (Thomson 1994). The resulting water properties in summer are well mixed, with moderate surface temperatures and salinities, and relatively low in chlorophyll.

Oceanographic boundary: The boundary of the southern Strait of Georgia was delimited by the US border, satellite observations of tidal mixing (ie., cold water area), and bounded to the west by the shores of Tumbo and Mayne Islands.

Upper ocean sub region 21. Interior Gulf Islands

Oceanographic process: In the southern Strait of Georgia, the interior of the southern Gulf Islands (507 km^2) is bounded from the Strait of Georgia by several well-defined tidal passages (Dodd's Narrows, Active Pass, Porlier Pass). The tidal passages are narrow and shallow, and are the site of strong topographic upwelling, where deep waters are brought to the surface (LeBlond 1981). These tidal passes 'isolate' the interior Gulf Islands from strong surface freshwater influence. Hence, the waters within the southern Gulf Islands tend to be less influenced by freshwater driven estuarine circulation or tidal currents and more so by regional winds, coastline and bottom topographic effects (Thomson 1994).

Oceanographic boundary: The boundary of the interior Gulf Islands sub region was derived simply as the outer edge of the islands facing the Strait of Georgia.

Upper ocean sub region 22. Haro Strait and Rosario Passages

Oceanographic process: This area includes about 369 km^2 of sea surface. There are pronounced gradients of phytoplankton concentration associated with tidal frontal near Haro and Rosario Straits because of nutrient additions by tidal mixing (Harrison and Yin 1998). Cool temperatures characterize the surface waters. At the entrance to the main channels, large vertical currents develop due to the rough flow in the channels and the abrupt changes in the seafloor (Thomson 1994). Mixing over the shallow sill of Rosario and Haro Straits during flood and ebb tide influences water properties in this region. Vertical sections of chlorophyll between the Victoria sill and Boundary Pass (A. Pena's Fig. 70 in DFO 2006) shows that the Haro region is well mixed in the surface 40 m during April and September, and that chlorophyll concentrations are slightly lower than those observed in region Juan de Fuca and much lower than values observed in central and northern SSoG.

Oceanographic boundary: The north-eastern boundary of the Haro Strait and Rosario Passage sub region was derived from satellite derived observations of thermal fronts while the western bounded by Victoria sill.

Upper ocean sub region 23. Juan de Fuca Strait

Oceanographic process: The Juan de Fuca Strait (JDFS) sub region consists of about 1585 km^2 of sea surface, and extends from the Pacific entrance at Cape Flattery to the Victoria sill (Thomson 1981). JDFS is a long, narrow submarine valley, and it is about 250 m deep at the Pacific edge and 55 m deep at the Victoria sill, and the depths are considerably less than those in the Strait of Georgia (Thomson 1981). Water in JDFS is kept cool year round in part by direct exposure to the Pacific Ocean. In addition, the strong tidal streams through the eastern passes of JDFS constantly mix the water from top to bottom. The transition between upper-layer seaward flow and deep-shoreward estuarine flow is between 50-100 m (Mackas and Harrison 1997). The properties of the water mass being transported eastward into the SSoG in the lower layer depends on the duration and intensity of upwelling that takes place over the continental shelf off the south west coast of Vancouver Island (Thomson 1994). In the 1980s, several studies examined the origin of nutrients on the south western Vancouver Island shelf. It was concluded that the estuarine outflow from Juan de Fuca Strait provides the largest supply of new nutrients to the southern Vancouver Island shelf (Whitney et al. 2005). Strong tidal mixing in the Haro Strait-Boundary Passage sub oceanographic region combined with Fraser River discharge results in a strong buoyancy flow through Juan de Fuca Strait to the southern shelf. It is estimated that the flow takes about 1 week to reach the Vancouver Island shelf from the Haro-Boundary mixing region, and that some of the Juan de Fuca outflow is modulated by the spring-neap tidal cycle (Whitney et al. 2005).

Oceanographic boundary: The boundary of the Juan De Fuca Strait oceanographic sub-region was marked by a north-south line extending from the Victoria sill (south of Victoria) southward to the US marine border in the middle of the Strait.

Upper ocean sub region 24. Juan De Fuca Eddy

Oceanographic process: In the summer, a quasi-permanent clockwise gyre (about 60 km in diameter) forms off the mouth of Juan de Fuca Strait in response to outflow from the Strait meeting southerly flowing shelf-break waters (Thomson 1981, Dovetail Consulting 2005), and tidal mixing off Cape Flattery also seems to play an important role (Foreman et al. 2008b).

Oceanographic boundary: The boundary of the Juan De Fuca Eddy region was estimated from satellite imagery of surface water temperature (**Figure 9**).

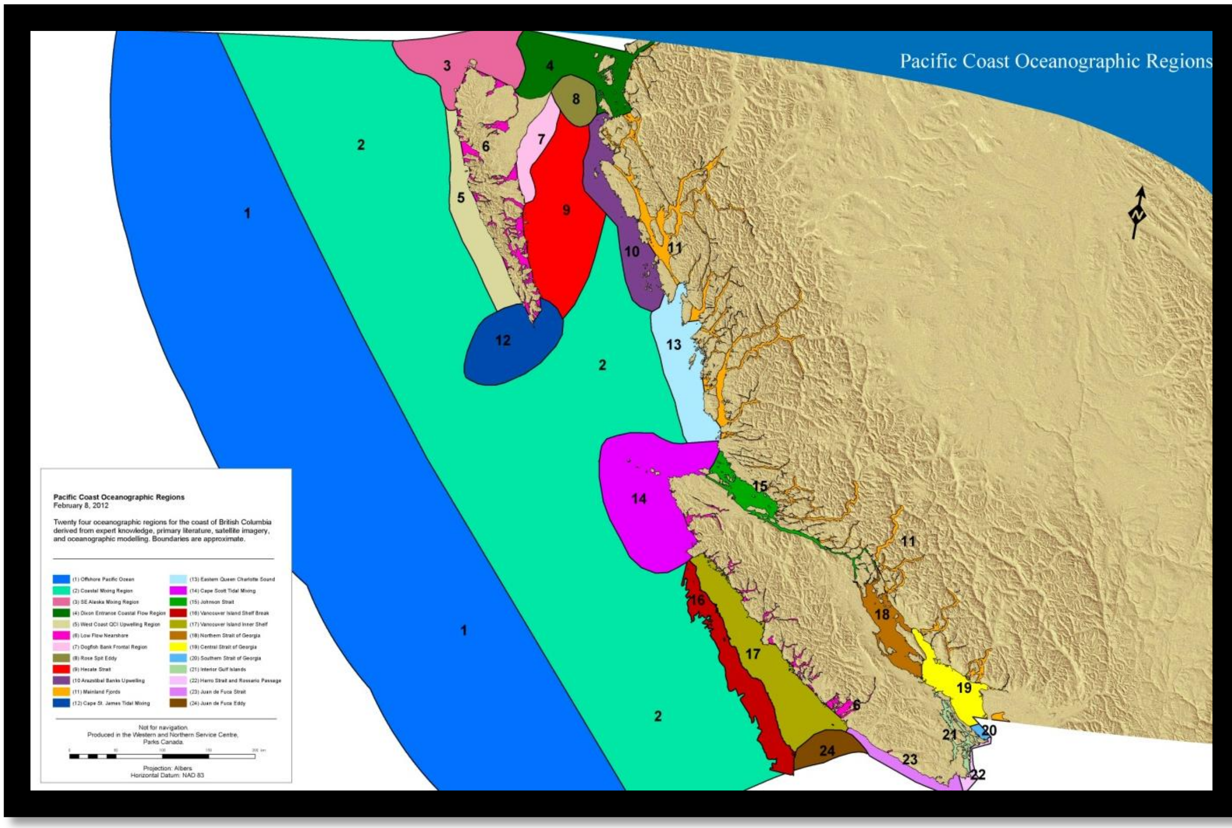

Figure 1. The 24 upper ocean sub regions identified in this study.

Figure 2. Overlay of the oceanographic regions on 4 major depth classes.

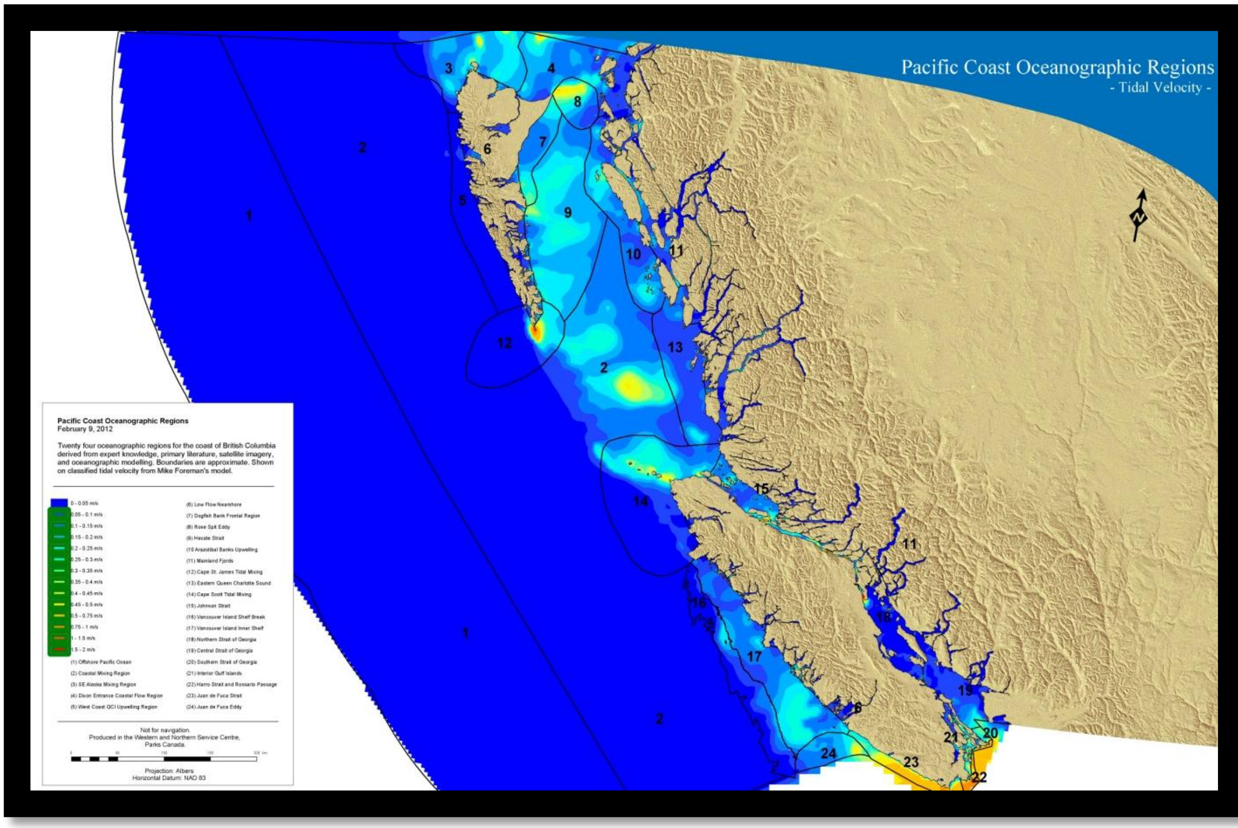

Figure 3. Overlay of the upper ocean sub regions on water column averaged tidal current speeds. The modelled data are courtesy of Mike Foreman (IOS, DFO).

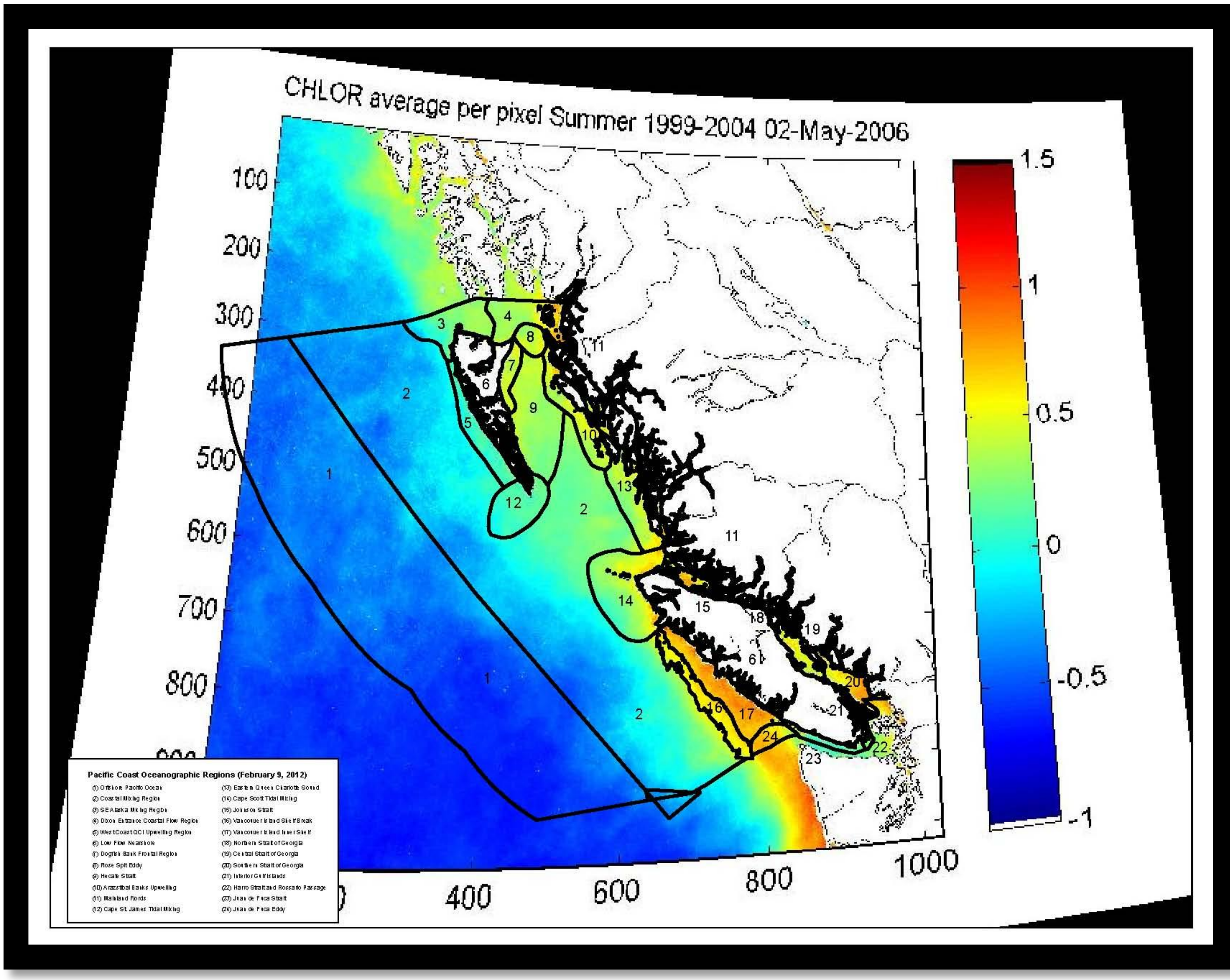

Figure 4. Overlay of the upper ocean sub regions on ocean colour (chlorophyll) derived from the SeaWiFs satellite imagery (1999-2004).

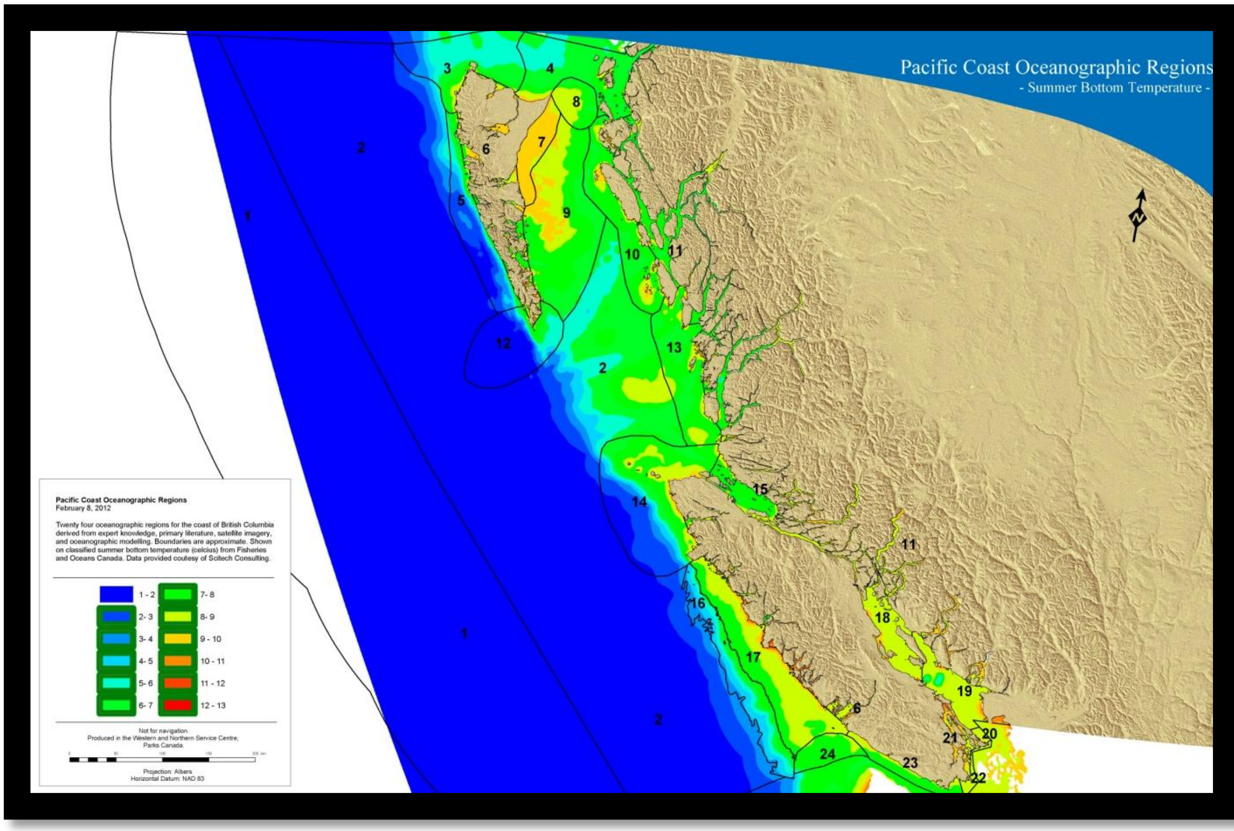

Figure 5. Overlay of the upper ocean sub regions on observed bottom sea temperature. The water property data are courtesy of Mike Foreman (IOS, DFO). Note that in general, bottom temperature is strongly correlated with depth except for fjords and the Strait of Georgia where topography and mixing control waters entering basins.

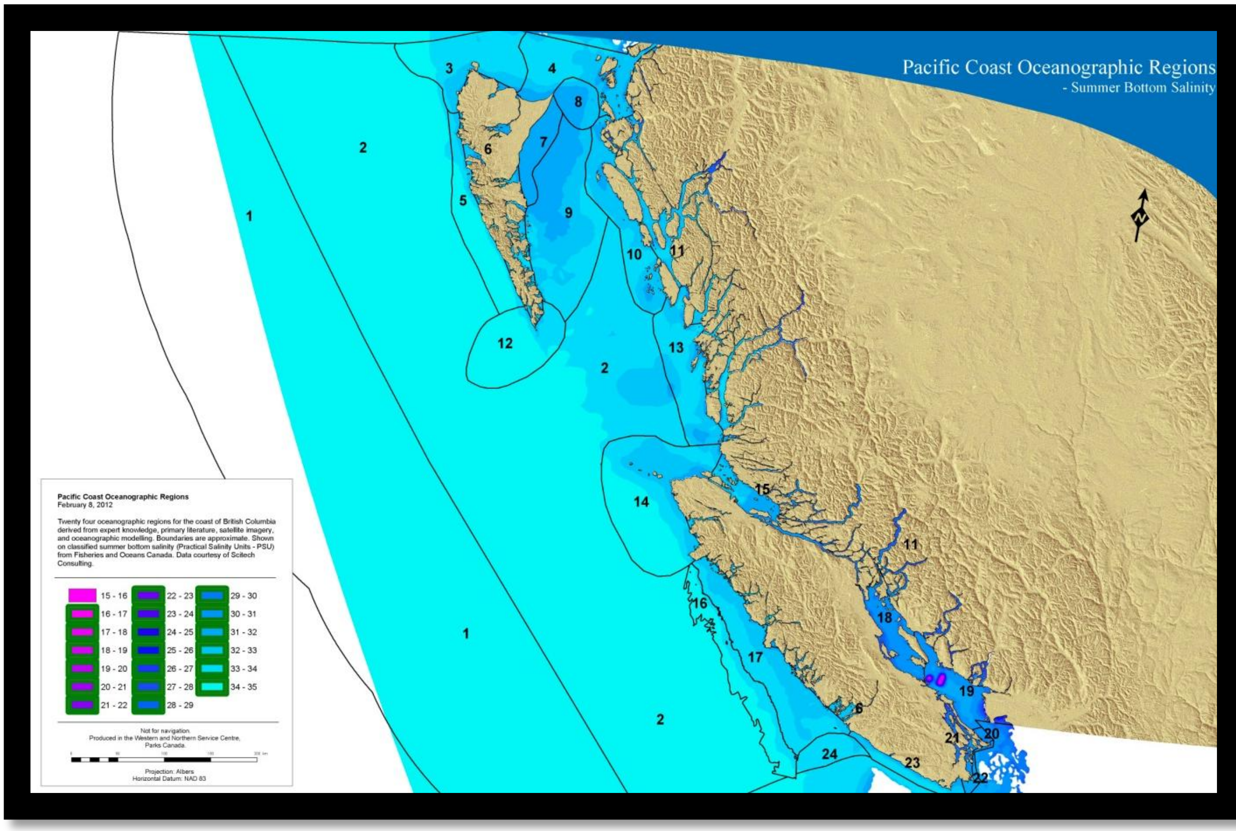

Figure 6. Overlay of the upper ocean sub regions on observed bottom sea salinity coast-wide. The water property data are courtesy of Mike Foreman (IOS, DFO). Note that in general, bottom salinity is strongly correlated with depth except for fjords and the Strait where topography and mixing control waters entering basins.

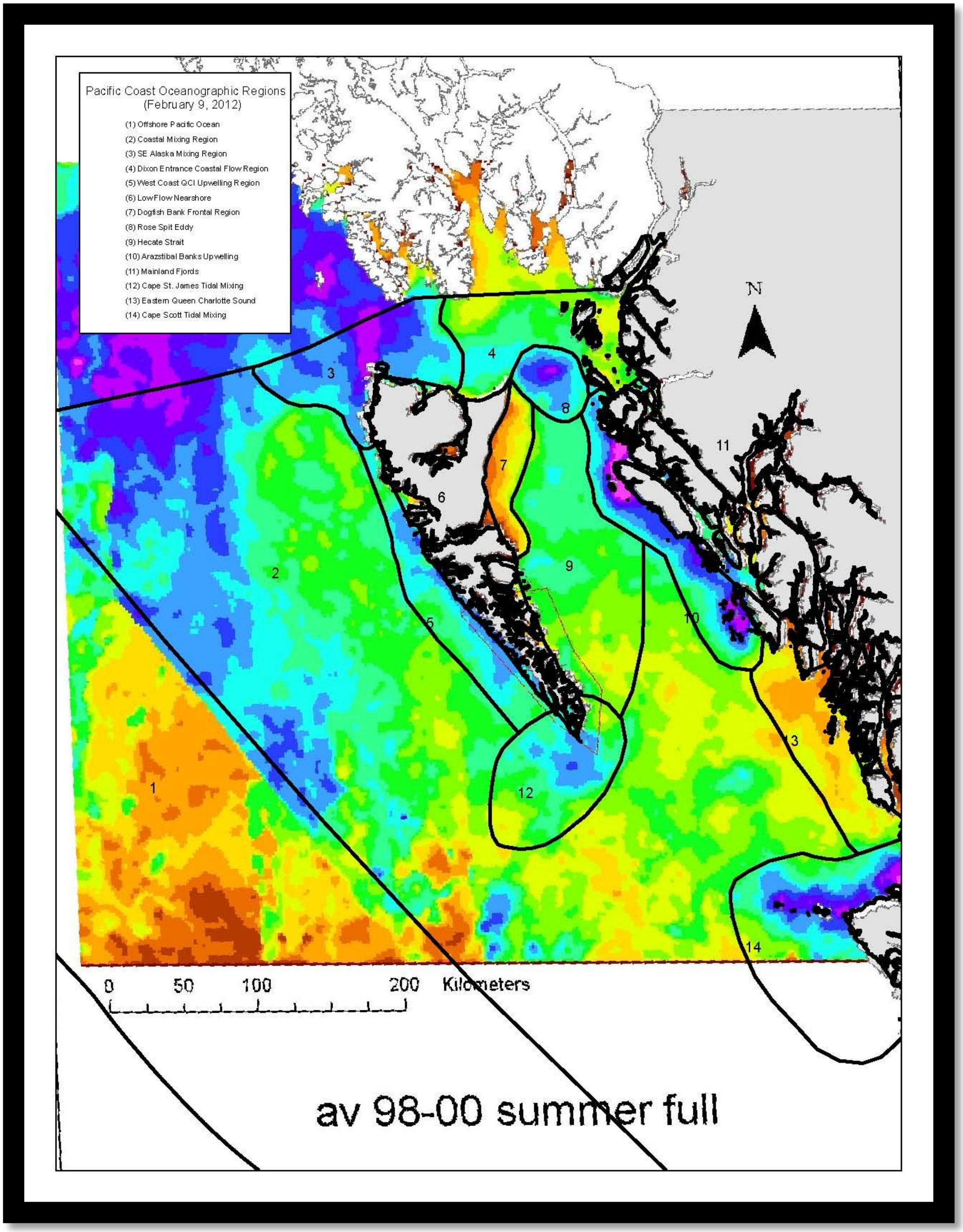

Figure 7. Overlay of some of the northern upper ocean sub regions on AVHRR sea surface temperature for summer 1998-2000. Purple-blue areas are cool, and green-yellow areas in the image are warm.

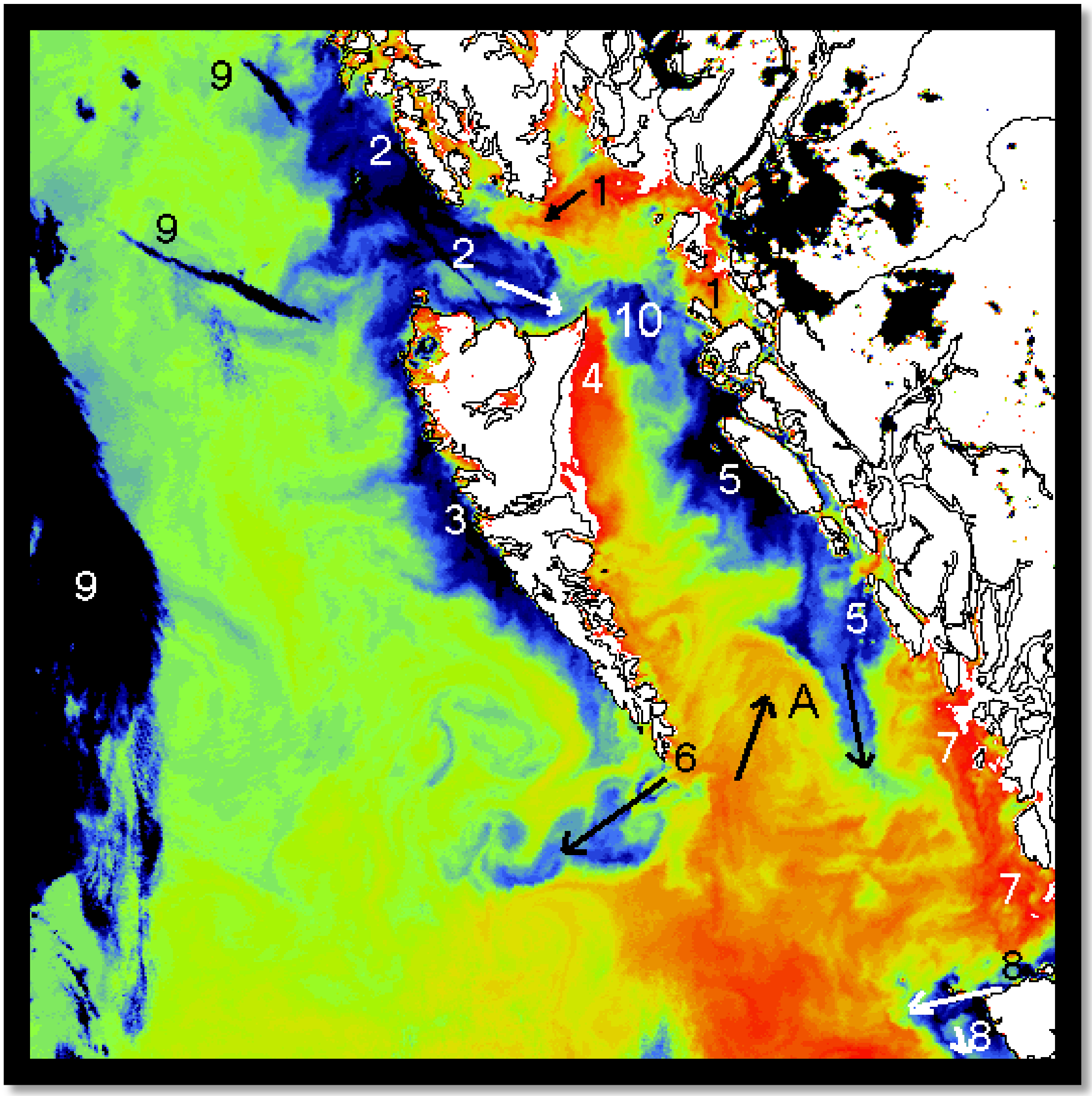

Figure 8. Satellite image of summer sea surface temperature, based in measurements of infrared light by NOAA satellite on 24 July 1994, and processed by Jim Gower and John Wallace of DFO, Institute of Ocean Sciences. Dark blue regions are about 10C; bright red regions are about 16C, and temperatures increase through colours from blue to green to yellow to orange to red. Black regions are clouds or jet contrails. White denotes land. Arrows denote direction of surface currents implied by this image. Letter A denotes centre of persistent clockwise eddy in summer, identified by drifter tracks.

The numbers in Figure 8 denote the following oceanographic features, as described by Bill Crawford (DFO).

1. Fresh water from the Skeena River mixes with salt water in Chatham Sound, and flows out of Chatham Sound as a five metre deep layer of brackish water. Sediments in this water absorb light, which warms this layer as it flows northward out of the sound, then westward across Dixon Entrance. Any brackish water that flows out of Chatham Sound to the southwest passes through narrow channels with strong tidal currents that mix deep cold water up to the surface and cool this layer.
2. Summer winds generally blow from the northwest in this region, pushing the surface waters downwind. The effect of the rotation of the earth is to turn these currents to the right, away from Alaskan shores. This waters are replaced at shore by colder deep water that upwells to the surface, and is blown into Dixon Entrance when the northwest winds are especially strong.
3. The effect of the earth rotation is also to turn currents to the right, away from west coast of the Queen Charlotte Islands. Waters that move away from the coast are replaced at the ocean surface by deeper colder water all along the west coast of Graham Island and much of Moresby Island.
4. Waters here are generally 10 to 20 metres deep, much less than in other areas, and are also the warmest in summer.
5. Strong tidal currents are found at the southern tip of Moresby Island, within a few kilometres of Cape St. James and the Kerouard Islands, where speeds as high as 5 knots are found. In summer the winds from the northwest push the warm surface waters of Hecate Strait southward past Cape St. James and into the open Pacific Ocean. Tidal currents at this cape bring deep cold water to the surface where they partially mix with warmer surface water. All these water masses flow about 100 kilometres southwestward into the Pacific Ocean, forming a distinctive plume in this image.
7. On this day the fresh water from Rivers Inlet was in a layer only a few metres thick along the eastern shores of Queen Charlotte Sound. This layer was heated by the sun as it gradually drifted into Queen Charlotte Sound
8. Strong tidal currents on Cook Bank and near Cape Scott mix cold deep waters into warm surface flows. The winds from the northwest push these waters up against the shore, and then westward into the Pacific Ocean and also to the southeast along the west coast of Vancouver Island.
9. Clouds to the West and jet contrails to the Northwest of Graham Island are shown in black..
10. Rose Spit extends far to the northeast from Queen Charlotte Islands, and strong tidal mixing cools the surface waters there.

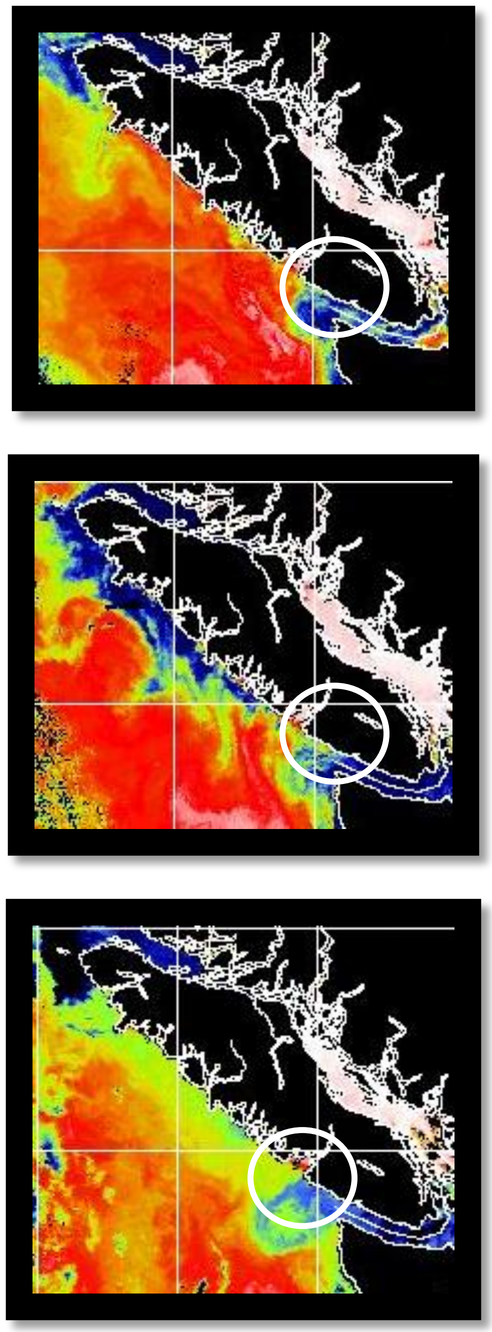

Figure 9. Sea surface temperature from AVHRR satellite images from the Institute of Ocean Sciences (DFO) collected on June 19 1994; July 8 1996; and August 6 1997 showing the extent of the Juan de Fuca Eddy off the mouth of Juan de Fuca Strait.

Part II. Upper ocean sub regions within Natural Marine Regions

In this section, the upper ocean sub regions discussed above in Part I are now placed within the context of the five Natural Marine Regions (NMRs). Refer to **Figure 10**.

Natural Marine Region: Hecate Strait

Overall, 10 upper ocean sub regions were identified for the Hecate Strait NMR, of which, Dogfish Bank Frontal Region, Rose Spit Eddy, Hecate Strait, Arazstibal Banks Upwelling, and Dixon Entrance Coastal Flow Region are considered unique. The upper ocean sub regions identified were derived from the following sources: 1) Thomson (1989) who described 3 oceanic domains around the Queen Charlotte Islands including oceanic, eastern coastal, and Dixon Entrance; 2) the identification of oceanographic features from the analysis of advanced very high resolution radiometer satellite imagery by Jardine et al (1993); 3) Perry and Waddell (1997) identified 6 general areas around the Queen Charlotte Islands that may increase the availability of zooplankton to higher trophic levels, because of predictable, recurring physical oceanographic processes such as shelf-break fronts, eddies, tidal fronts, and coastal upwelling; 4) Figure 8 from Crawford's (2001) DFO project "Oceans of the Queen Charlotte Islands" (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/QCI/qci_e.htm**;** 5) analysis of coastal zone colour scanner ocean colour data (e.g., Robinson et al. 2004); 6) Whitney et al (2005) discussion of physical processes that enhance nutrient transport and primary production in the coastal and open ocean of the subarctic Pacific, 7) Robinson's (2006) oceanography overview for Gwaii Haanas's Legacy Report Series on coastal processes, 8) the DFO ecosystem overview report that identified 8 upper ocean sub regions in PNCIMA based on physical and phytoplankton related processes that are common to each region (Lucas et al. 2007), and 9) the Crawford et al. (2007) PNCIMA physical and chemical oceanography overview.

Natural Marine Region: Queen Charlotte Shelf

Overall, 6 upper ocean sub regions were identified for the Queen Charlotte Shelf NMR, of which, West Coast QCI Upwelling Region is considered unique. The upper ocean sub regions were derived from the following sources:

1) Thomson (1989) who described 3 oceanic domains around the Queen Charlotte Islands, including oceanic, eastern coastal, and Dixon Entrance;

2) the identification of oceanographic features from the analysis of advanced very high resolution radiometer satellite imagery by Jardine et al (1993);

3) Perry and Waddell (1997) identified 6 general areas around the Queen Charlotte Islands that may increase the availability of zooplankton to higher trophic levels, because of predictable, recurring physical oceanographic processes such as shelf-break fronts, eddies, tidal fronts, and coastal upwelling;
4) Figure 8 is from Crawford's (2001) DFO project "Oceans of the Queen Charlotte Islands" (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/QCI/qci_e.htm,
5) Analysis of coastal zone colour scanner ocean colour data (e.g., Robinson et al. 2004);
6) Whitney et al (2005) discussion of physical processes that enhance nutrient transport and primary production in the coastal and open ocean of the subarctic Pacific;
7) Robinson's (2006) oceanography overview for Gwaii Haanas's Legacy Report Series on coastal processes;
8) the DFO ecosystem overview report that identified 8 upper ocean sub regions in PNCIMA based on physical and phytoplankton related processes that are common to each region (Lucas et al. 2007);
9) Crawford et al. (2007) PNCIMA physical and chemical oceanography overview.

Natural Marine Region: Queen Charlotte Sound

Overall, 7 upper ocean sub regions were identified for the Queen Charlotte Sound NMR, of which Eastern Queen Charlotte Sound and Johnstone Strait are considered unique. The upper ocean sub regions were derived from the following sources:

1) Thomson (1989) who described 3 oceanic domains around the Queen Charlotte Islands, including oceanic, eastern coastal, and Dixon Entrance;
2) Identification of oceanographic features from the analysis of advanced very high resolution radiometer satellite imagery by Jardine et al (1993);
3) Crawford's (2001) DFO project "Oceans of the Queen Charlotte Islands" (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/QCI/qci_e.htm**;**
4) Analysis of coastal zone colour scanner ocean colour data (e.g., Robinson et al. 2004);
5) Whitney et al (2005) discussion of physical processes that enhance nutrient transport and primary production in the coastal and open ocean of the subarctic Pacific;
6) the DFO ecosystem overview report that identified 8 upper ocean sub regions in PNCIMA based on physical and phytoplankton related processes that are common to each region (Lucas et al. 2007);
7) Crawford et al. (2007) PNCIMA physical and chemical oceanography overview.

Natural Marine Region: Vancouver Island Shelf

Overall, 8 upper ocean sub regions were identified for the Vancouver Island Shelf NMR, of which, Vancouver Island Shelf Break, Vancouver Island Inner Shelf, and Juan de Fuca Eddy are considered unique. The upper ocean sub regions were derived from the following sources:

1) Thomson (1981) who describes recurring physical oceanographic processes occurring along the west coast of Vancouver Island;
2) satellite imagery of sea surface temperature;
3) Bathymetry;
4) several published papers that describe the oceanographic conditions along the well-studied west coast of Vancouver Island (e.g., Foreman et al. 2000; McFarlane et al. 1997).

Natural Marine Region: Strait of Georgia

Overall, 6 upper ocean sub regions were identified for the Strait of Georgia NMR, of which, Northern Strait of Georgia, Central Strait of Georgia, Southern Strait of Georgia, Interior Gulf Islands, Harro Strait and Rossario Passage are considered unique. In general, three major processes influence oceanographic features in the Strait of Georgia (SoG) in summer: Fraser River discharge, NW winds, and strong diurnal tides. Overall, the SoG is considered a large semi-enclosed basin with an estuarine circulation. The discharge of the Fraser River flows seaward and induces a return flow of salt water at depth drawn from beyond the confines of the Strait via the Straits of Juan De Fuca (Davenne and Masson 2001; Masson 2002). Hence, the surface layer consists of relatively warm, low salinity water, and the lower layer consists of cold, high salinity oceanic water (Thomson 1994). This inward oceanic flow also contributes to the renewal of SoG deeper waters by re-oxygenation and replenishment of nutrients (LeBlond 1981). Sills, deposited by retreating glaciers, are of prime importance to the oceanography of the SoG (Thomson 1994). Two sills separate the SoG into three main basins. The Victoria sill located south of the city of Victoria, which has a depth of 55 to 100 m, and the sill at Boundary Pass, within the Gulf Islands, which has a depth of about 150 m. The first basin stretches along the Strait of Juan de Fuca for about 100 kilometres from Cape Flattery to the Victoria sill, and is 25 km wide with depths ranging from 180m to 250m on the pacific coast side and 55m at the Victoria sill. Extending from the Victoria sill for about 50 km to a second sill within Boundary Pass, is Haro Strait, which is only about 5 km wide to the US border and is about 300m deep. North and west of the Boundary Pass sill, the Strait of Georgia is about 220 km long and 20-40 km wide. It covers about 6,000 km^2, and has a volume of more than 1250 km^3. The mean depth is 155 m, with only 5% of the SoG having depths > 360 m; the maximum depth is 420 m located south of Texada Island (Thomson 1994). Tidal currents are the dominant flows in the SoG (LeBlond 1984). The combined actions of river runoff, wind and tides lead to temporally and spatially varying patterns of current and water properties in the Strait of Georgia.

Table 2. Summary of upper ocean sub regions found within each Parks Canada Natural Marine Region. Refer to Figure 9.

Natural Marine Region	Upper ocean sub region
Hecate Strait	2, 3, 4, 6, 7, 8, 9, 10, 11, 12
Queen Charlotte Shelf	1, 2, 3, 5, 6, 12
Queen Charlotte Sound	1, 2, 11, 12, 13, 14, 15
West Coast Vancouver Island	1, 2, 6, 14, 16, 17, 23 24
Strait of Georgia	18, 19, 20, 21, 22, 23

ID	Upper ocean sub regions
1	Offshore Pacific Ocean
2	Coastal Mixing
3	SE Alaska Mixing
4	Dixon Entrance Coastal Flow
5	West Coast QCI Upwelling
6	Low Flow Nearshore
7	Dogfish Bank Frontal
8	Rose Spit
9	Hecate Strait
10	Aristazabal Upwelling
11	Mainland Fjords
12	Cape St. James Tidal Mixing
13	Eastern Queen Charlotte Sound
14	Cape Scott Tidal Mixing
15	Queen Charlotte and Johnstone Straits
16	Vancouver Island Shelf Break Upwelling
17	Vancouver Island Inner Shelf
18	Northern Strait of Georgia
19	Central Strait of Georgia
20	Southern Strait of Georgia
21	Interior Gulf Islands
22	Haro Strait and Rosario Passages
23	Juan de Fuca Strait
24	Juan de Fuca Eddy

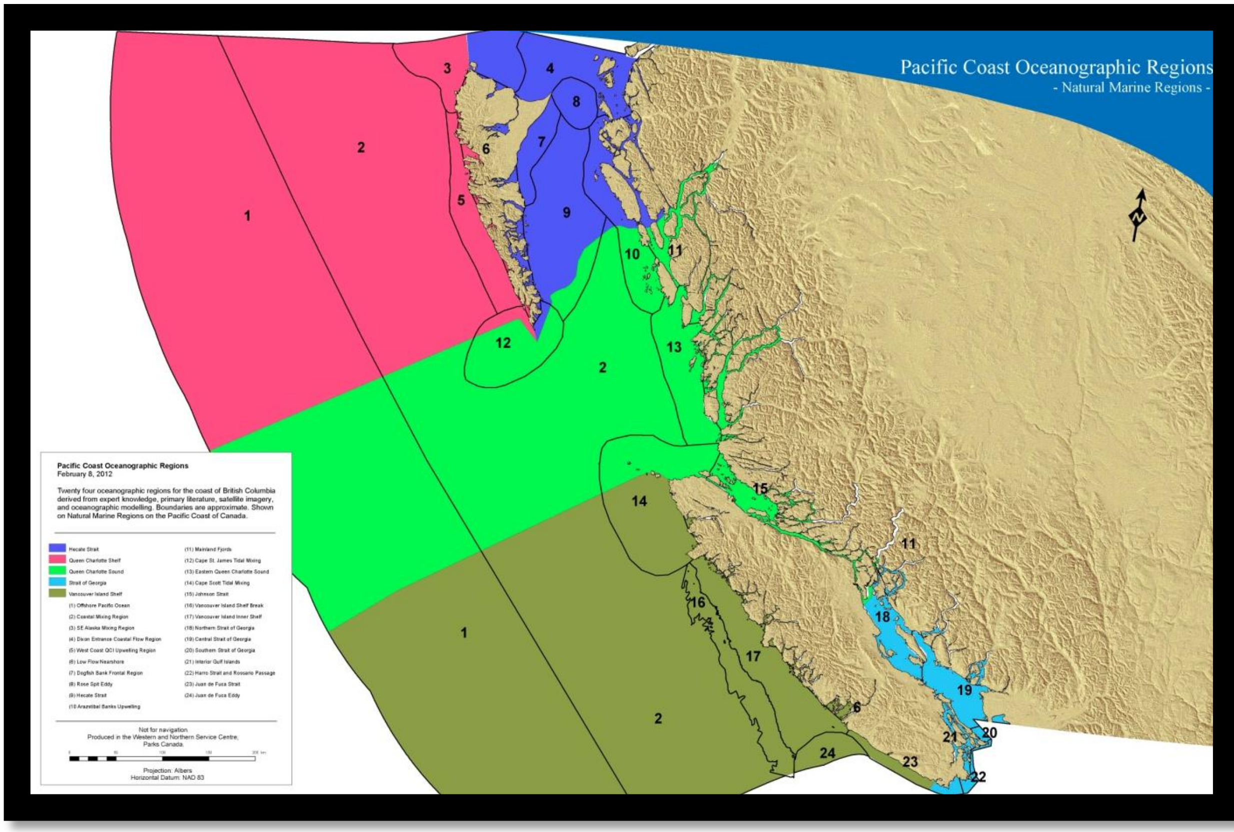

Figure 10. The 24 upper ocean sub regions overlaid on the 5 Natural Marine Regions (NMRs) along the Pacific coast of Canada.

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