1. INTRODUCTION AND BACKGROUND

In January 2007, the Center for Coastal Monitoring and Assessment (CCMA), Office of National Marine Sanctuaries (ONMS), and Federal/Regional Integrated Ocean Observation System (IOOS) Associations initiated discussions on the importance of broad-scale use of satellite-based oceanographic data to support the Olympic Coast National Marine Sanctuary (OCNMS). Satellite data requirements were identified to: (1) fill existing gaps in baseline environmental data, (2) enhance the understanding of ecological patterns and processes for the Olympic Coast region, and (3) provide information and insights to support the Olympic Coast Sanctuary Management Plan Review process (http://olympiccoast.noaa.gov/). To support these requirements, CCMA conducted a two-year investigation and summary of ocean climate, character, and color for the Pacific Northwest (PNW) region through satellite remote sensing.

This oceanographic summary represents a unique regional synthesis, interpretation, and characterization of multiple long-term satellite observational datasets made available through the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and other worldwide operational data centers (see data products and sources). Observational monitoring emphasizes real-time data collection and archiving, product generation, and distribution of information vital for improved understanding of physical and biological characteristics in a regional context. A key benefit of sustained data collection is the potential to provide a clear synoptic-scale vision of important temporal and spatial oceanic events, useful for developing environmental indicators of perturbation and for identifying long-term trends within U.S. (and its associated territories') marine protected areas, including sanctuaries.

The objectives of the characterization were to:

(1) Identify, obtain, and perform regional syntheses on pertinent long-term satellite data to characterize the physical and oceanographic conditions within the PNW, and specifically the OCNMS; and

(2) Summarize surface patterns, features, and underlying processes governing oceanographic variability and climate as depicted through satellite remote sensing for consideration in National Marine Sanctuary biodiversity/conservation evaluations, management plan reviews, ecosystem assessments, and other decision-support initiatives.

Herein, seasonal and interannual variability (and co-variability) of surface water properties and features were characterized with reference to dominant physical processes for the region. Seasonal surface patterns and changes over a typical annual cycle were analyzed and documented. Specific spatial-temporal linkages among water properties were analyzed to provide insights on ocean behavior and timing of seasonal transitions. Ocean temperature fronts and chlorophyll variability measures were used to reveal spatial-temporal aspects of phytoplankton (biological) activity for the region. In addition, oceanographic anomalies of key surface properties were documented as potential indicators of environmental perturbation, and for evaluating future trends for the sanctuary.

This study complements prior oceanographic investigations through the use of temporally and spatially robust remote sensing datasets. A characterization of oceanographic baseline conditions for the OCNMS is among the most important components in management decision support because it sets the context for describing the distribution of biological resources and for defining management alternatives. Ultimately, the goal is to link long-term synoptic imagery with direct observational and interpolated data to improve the understanding of environmental variability and perturbations affecting the sanctuary, and to monitor changes occurring in the sanctuary.

The OCNMS was established in 1994 in recognition of its nationally significant and unique marine environment. The sanctuary resides in a dynamic oceanographic setting with broad scale (> 500 km) variability dominated by seasonal upwelling and downwelling. As a result, the PNW and OCNMS support rich marine mammal and seabird faunas, abundant populations of kelp and intertidal algae, and productive fish and invertebrate communities (ONMS 2008, Sydeman and Elliot 2008). Due to the dynamic nature and harsh

oceanographic conditions along the PNW, collecting physical and biological monitoring data poses a significant challenge when using shipboard *in situ* and/or moored buoy monitoring. The satellite-derived proxies developed as fully georeferenced map layers were used to fill existing data gaps in baseline environmental information, and to provide key insights on local variability for the PNW region.

1.1 Regional Setting and Study Area

The study area lies in the northern portion of the Oregonian biogeographic province that extends from Pt. Conception, California, to Cape Flattery, Washington (Airame et al. 2003). The province is characterized by a narrow continental shelf, mountainous shoreline, steep rocky headlands, sandy pocket beaches with sea stack islands, many small and a few large rivers, and small estuaries with barrier islands. The province is also noted as exhibiting the greatest volume of upwelling in North America. The study region resides within the California Current System (CCS) and represents one of North America's most productive marine ecosystems.

The OCNMS, located in the northern portion of the study area off the coast of Washington, encompasses approximately 8,572 km^2 (3,310 mi^2) of coastal and oceanic waters, or approximately 10% of the study area for this assessment (Figure 1). The sanctuary boundary extends from Koitlah Pt. due north to the U.S.-Canada border seaward to the 100 fm isobath. Following the 100 fm (~183 m) isobath southward, the boundary extends approximately 145 km, cutting across the heads of Nitnat, Juan de Fuca, and Quinault Canyons to a point due west of the Copalis River. The shoreward boundary is the mean lower low water line when adjacent to Indian reservations and state and county lands. When adjacent to federally managed lands, the boundary extends to the mean higher high water line.

1.2 Regional Oceanographic Summary

The dominant physical broad-scale processes influencing PNW oceanography have been summarized by Hickey (1979, 1989, 1998), Hickey and Banas (2003), Strub et al. (1987), and Strub and James (1988, 2002). The PNW region is characterized by distinct patterns in oceanographic circulation, winter storms, flow-topography interactions, and land-sea influences. Large- scale processes are the predominant influence on seasonal upwelling-downwelling fluctuations, resulting in a highly dynamic oceanographic environment.

PNW oceanography is dominated by the CCS, a broad, meandering system of currents with strong interannual, seasonal and weekly variability (Hickey 1998). The CCS forms the southerly flowing segment of the greater North Pacific Gyre and extends from British Columbia, Canada to Baja California, Mexico (Figure 2). The dominant scales of circulation over much of the CCS are set up by strong alongshore winds, bottom topography, and shelf influences (Halliwell and Allen 1987). Because of these characteristics, coastal trapped waves are efficiently gener-

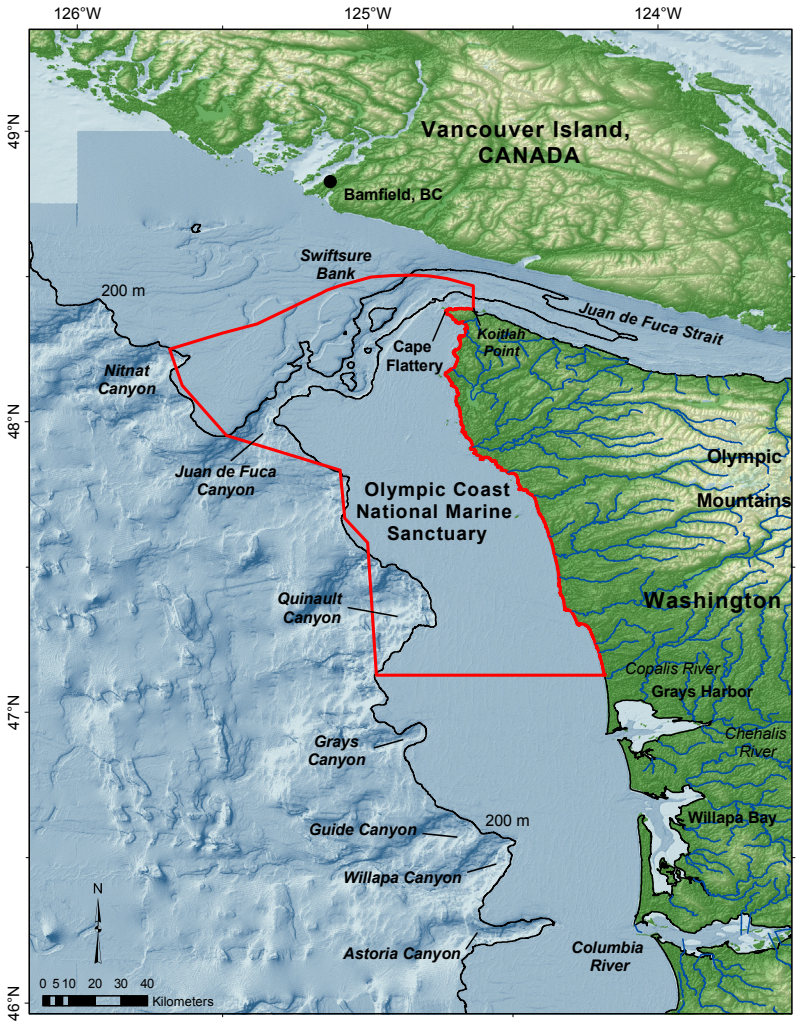

Figure 1. Physiographic features off Washington coast and within the Olympic Coast NMS.

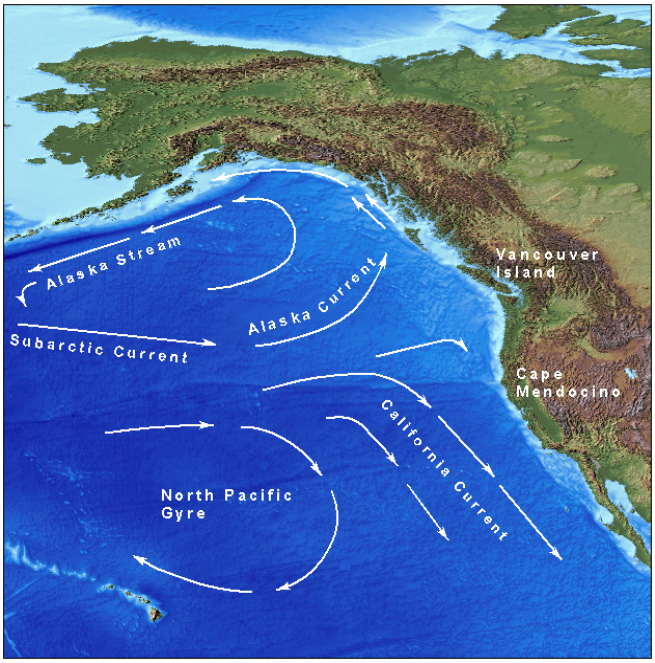

Figure 2. General schematic of the California Current System and North Pacific Gyre. Adapted from NOAA/NCCOS.

ated and propagate long distances along the continental margins of much of western North America (Hickey and Banas 2003).

The CCS includes the slow, southward-moving California Current, the wintertime, northward-flowing Davidson Current, California Undercurrent, and other shelf and slope currents with primarily shorter-than-seasonal time scales. The southward-flowing California Coastal Jet Current and northward Davidson current are commonly observed on the continental shelf during the summer and winter, respectively (Figure 3). The California Current flows southward year round offshore from the shelf break to a distance of 1,000 km from the coast (Hickey 1979, 1998).

Topographic features of the continental shelf interact with and influence flows and circulation in the region. The surface outflow patterns from the Juan de Fuca Strait, and interactions with bottom topography, affect chemical and biological processes, including transport mechanisms for nutrients, larvae, plankton, and even toxicants (domoic acid) associated with the Juan de Fuca eddy (Trainer et al. 2002, Trainer and Suddleson 2005, Trainer et al. 2009).

The PNW includes one major river plume (the Columbia River), and several smaller estuaries and plumes, particularly evident south of the Juan de Fuca Strait. The Columbia River plume is highly dynamic with variation in direction, depth, and width in response to wind strength and direction (Thomas and Weatherbee, 2006). The plume flows northward over the shelf and slope in the fall and winter. In the spring and summer it flows southward, well offshore of the Oregon shelf.

1.3 Seasonal Cycles

Seasonal oceanographic cycles influencing the PNW have been described in detail by Hickey and Banas (2003) and are defined by the dominant circulation patterns in the PNW region. Generally, oceanographic seasons can be characterized as (1) Winter (November-mid-February), (2) Spring (late February-March), (3) Early summer (April-June), (4) Late summer-early fall (July-September), and (5) Fall (October-November), including spring and fall periods of transition.

Coastal upwelling is the dominant process controlling Olympic Coast water property variability over several-day to seasonal time scales. Upwelling along the Olympic Coast typically exemplifies colder, denser, saltier, and nutrient-rich waters that are being forced upward adjacent to the coast, typified by southward winds driving an offshore surface water movement known as Ekman transport. This occurs along the entire U.S. West Coast, but the strength and duration of upwelling increases to the south. With the exception of regions affected by the Columbia plume, stratification in the CCS is remarkably similar at most locations and is largely controlled by seasonal changes in large-scale advection (transport) and upwelling of water masses. Increases in chlorophyll production and biomass are evident during the heightened upwelling season. The region experiences periods of wind relaxation when seas are intermittently calm and winds are variable.

Coastal downwelling generally occurs during the fall and winter, where a marked reversal from the summer pattern is evident along the Olympic Coast. The strong Davidson Current affecting the region is driven not only by the large-scale north-south pressure gradient, but also by strong winds from the south associated with storms entering the region. Wind stress combining with the Coriolis force is especially strong in winter, driving an onshore Ekman transport of water (Thomas, Strub, and Brickley 2003). Downwelled wa-

ter along the coast is typically warmer, less saline, and nutrient reduced. The region can undergo diminishing cross-shelf and alongshore currents, causing a decrease in onshore Ekman transport at times during the winter season (Allen and Newberger, 1996; Austin and Barth, 2002).

For this report, seasonal oceanographic cycles and transition periods will be characterized by surface patterns, and changes in response to the dominant circulation drivers affecting the Olympic Coast region. Seasonal cycles will be documented to better understand expected conditions of each variable and to provide insights on dominant processes influencing variable response. General lags associated with surface characteristics in response to ocean processes also will be documented.

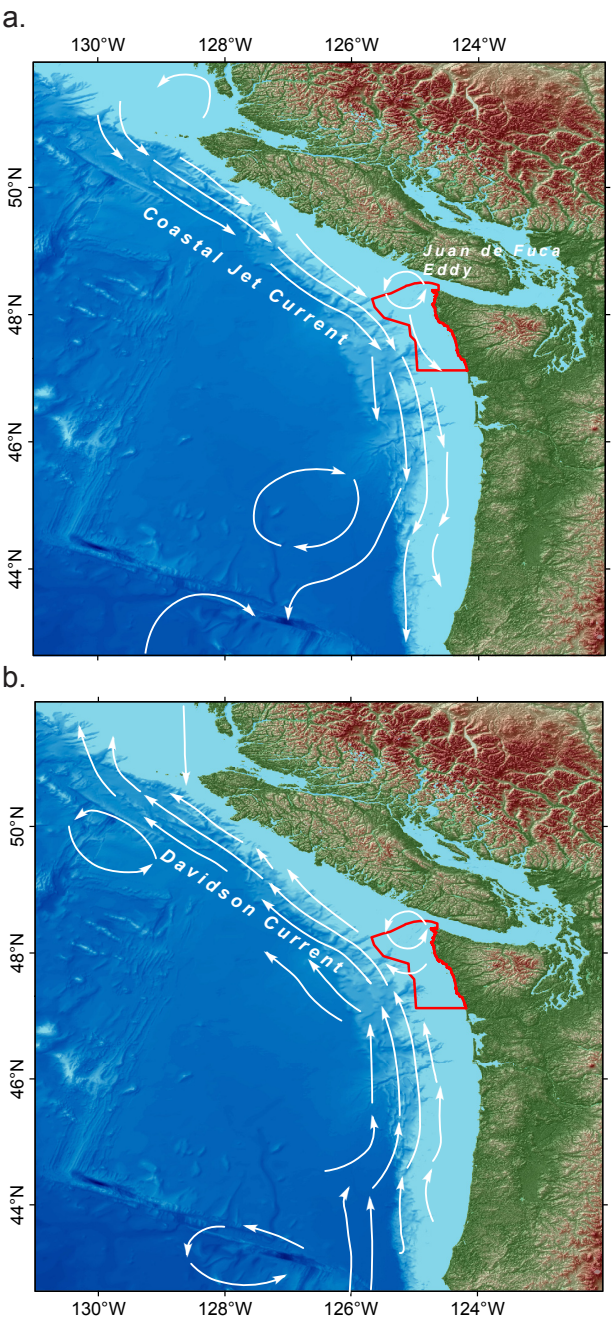

Figure 3. Generalized surface flow of the California Current System in the PNW during typical (a) summer and (b) winter conditions. Source: NOAA.

1.4 Interannual Cycles

Interannual and decadal-scale variability of the CCS involves complex atmospheric interconnections associated with El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) (Halpin et al. 2004, Di Lorenzo et al. 2008). These cycles promote significant long-term variability in the region that can yield extreme oceanographic anomalies on interannual to decadal time scales (Schwing et al. 1996). ENSO conditions are a result of interannual changes in sea level pressure between the eastern and western hemispheres of the tropical Pacific (Conlan and Service 2000). PDO is a long-term climatic pattern that is expressed by altering sea surface temperatures, surface winds, and sea level pressure (Mantua and Hare 2002). PDO shifts generally occur every 20-30 years and have occurred five times in the last century. (Airamé et al. 2003). The PDO can be described as an extensive El Niño-like pattern of Pacific climate variability with warm (positive) and cool (negative) phases. The most recent shifts from warm/cool and cool/warm occurred in 1998 and 2003, (Airamé et al. 2003; Peterson and Schwing 2003). During warm PDO, cold surface water temperature anomalies are observed in the western and central North Pacific Ocean, while the eastern Pacific exhibits above-average temperatures. The opposite patterns occur during cool phases. The NPGO is a climate pattern driven by broad-scale variations in ocean upwelling and transport processes. The NPGO shows strong interannual patterns of association with key physical-biological ocean variables, including salinity, nutrients, and chlorophyll *a* (Di Lorenzo et al. 2008).

For this report, interannual patterns of surface variable response will be presented as climatological anomalies (deviations) to highlight spatial-temporal characteristics of those deviations from expected conditions. Variable response will also be visually compared with documented shifts in ENSO.