2. DATA AND METHODS

2.1 Data Synthesis

Remote sensing data provide key information to understand ocean environments by characterizing the distribution and variability of oceanic surface features. These include ocean fronts, chlorophyll production and transition zones, cold and warm core eddies, convergence zones, and river plumes. Optical observations of physical, biological, and sediment characteristics provide valuable quantitative information on localized transport processes, meso-scale circulation features, and even large-scale water mass characteristics. Radar altimetry estimates of sea surface heights and roughness readily depict ocean surface characteristics including mean sea level, marine currents, winds, and waves. The remote sensing data presented herein were synthesized based on 8+ years of operational coverage, and include weekly to monthly averaged, and climatological anomaly data, for satellite-derived sea surface temperature (SST), sea surface height anomaly (SSHA), geostrophic currents, ocean color products, and winds. In addition to remote sensing data, gridded monthly land precipitation and Columbia River discharge data were used for comparison with remote sensing data, where appropriate. A complete product index for the data used throughout this report can be found in Table1.

Sea Surface Temperature (SST)

The Coral Reef Temperature Anomaly Database (CoRTAD) SST estimates were obtained from the NOAA/NASA Advanced Very High Resolution Radiometer (AVHRR) Oceans Pathfinder Version 5.0 Program, developed by the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS) and the NOAA National Oceanographic Data Center (NODC). The Pathfinder V. 5.0 Program measures global cloud cover, sea surface temperature, and ice, snow, and vegetation cover and characteristics. Weekly (7-day) and monthly averaged data for both the ascending pass (daytime) and descending pass (nighttime) are available on equal-angle grids of 8,192 elements in longitude and 4,096 in latitude (4 km resolution). Gap-filled weekly averaged 4km data were used to achieve the greatest possible spatial coverage over a 7-day cycle. The CoRTAD SST "baseline" temporal resolution encompasses 1,096 weeks for the period January 1985 to December 2005. CoRTAD data were then subset to include the entire West Coast, and weekly data were then binned to monthly averages. CoRTAD SST data series are useful for a range of applications including climatological (1985-2005) baseline and trend determination, ocean frontal boundary delineation, thermal stress detection in coral reefs, and climate indicator development (Halpern et al. 2008, Bruno et al. 2007).

SST Fronts

SST fronts were detected using CoRTAD data as described above, but also from NOAA/NESDIS/STAR Office holdings of the NOAA Geostationary Operational Environmental Satellites (GOES-10/11) SST and SST fronts data. SST fronts typically occur at the boundaries between various surface water types characterized by different physical, biological and optical properties. Frontal probabilities were calculated from daily-averaged SST fields based on 24-hourly observations. SST fields were processed at NOAA/STAR and CCMA by applying an edge-detection algorithm to identify SST fronts. The probability of detecting fronts (PDF) was calculated based on number of times a particular pixel qualifies as a front divided by the number of clear pixels (following Castelao et al. 2006).

Sea Surface Height Anomaly (SSHA)

SSHA data from altimetry reflect vertical changes from mean sea level and were obtained from the Archiving, Validation and Interpretation of Satellite Data in Oceanography (AVISO) Program. AVISO delayed time products of sea surface height generated from merged Topex/Poseidon (T/P), Jason-1/2, ERS-1/2 and ENVISAT missions. Delayed time (DT) Reference series products were used to provide accurate, homogeneous measurements across time. Weekly (7-day) and monthly averaged data are available on equal-angle grids of 1080 elements in longitude and 720 in latitude (referred to as 1/4° grid size). In the derivation of SSHA, an estimate of mean sea level (referred to as the mean profile from T/P data for the period January 1993 to December 1999) was applied to develop one merged vertical anomaly map combining measurements from available altimeter missions. SSHA data used in this report encompassed 729 weeks from October 1992 to September 2006. Monthly estimates of vertical sea surface height from mean sea level were

Table 1. Remote sensing data products and source specifications for the Olympic Coast National Marine Sanctuary Oceanographic Characterization.

Product Type	Data Source	Frame	Resolution	Summary	Units
Pathfinder SST and SST Anomaly (CoRTAD)	NOAA/NESDIS/NODC	1985-2005	4km	Weekly/ Monthly	°C
SST gradients (CoRTAD)	NOAA/NESDIS/NODC	1985-2005	4km	Weekly/ Monthly	(°C/12km)
GOES-10/11SST and SST fronts	NESDIS/NODC/STAR	2000-2007	4km	Daily/ Monthly	°C
SeaWiFS Ocean Color Chlorophyll and Anomalies	NASA	1997-2007	1km	Daily/ Monthly	µg L-1, Steradian -1
SeaWiFS Ocean Color Turbidity; Remote Sensing Reflectance at 670nm)	NASA	1997-2007	1km	Daily/ Monthly	Steradian -1
Jason-1, Topex/Poseidon, ERS-1/2ENVISAT Sea Surface Height Anomalies	AVISO, SSALTO/DUACS & CNES	1992-2006	1/4° grids	Weekly/ Monthly	cm
Jason-1, Topex/Poseidon, ERS-1/2ENVISAT Geostrophic Surface Currents	AVISO, SSALTO/DUACS & CNES	1992-2006	1/3° grids	Weekly/ Monthly	cm/s, degrees from north
QuikSCAT Sea Surface Winds	Remote Sensing Systems	1999-2007	25km	Weekly/ Monthly	m/s, degrees from north
Land Precipitation Totals and Anomalies	GPCC	1986-2006	1° grids	Monthly	mm
Columbia River Streamflow Totals	USGS	1986-2006	watershed	Monthly	cfs

obtained following a simple bin averaging technique. Merged SSHA data series provide information on sea level trends, density-driven changes, geostrophic current intensity and direction, and subsurface layers, i.e., mixed and thermocline depths (Strub and James 2002, Wilson and Coles 2004, Gordon and Giulivi 2004).

Geostrophic Currents

Estimates of geostrophic currents were obtained from merged Jason-1, Topex/Poseidon, ERS-1/2, and ENVISAT missions provided by the AVISO Program. Delayed time Mean Sea Level Anomaly (MSLA) products of geostrophic currents were used. Using oceanographic convention, weekly (7-day) Easterly-toward the East (U) and Northerly-toward the North (V) components, and monthly averaged U-V data, were

made available on a Mercator grid projection with a resolution of 1/3° grid size, encompassing 729 weeks from October 1992 to September 2006. Geostrophic currents result from the balance between Coriolis force and horizontal pressure gradients. Geostrophy implies that the slope of SSHA measured from satellites is directly related to the pressure gradient at the sea surface, and thus, to a geostrophic velocity at the surface.

Ocean Color

The ocean color dataset from Sea-viewing Wide Field-of-View Sensor (SeaWiFS) provided a 10-year (September 1997 to October 2007), near daily set of chlorophyll and light attenuation data, i.e., turbidity, at 1-km spatial resolution. SeaWiFS Ocean Color Level-2 archive products produced and distributed by the NASA Goddard Space Flight Center's Ocean Color Data Processing System (OCDPS) include the geophysical values for chlorophyll *a* using the OC4v5 algorithm. Chlorophyll *a* is the dominant pigment in marine photosynthetic organisms, and is referred to simply as chlorophyll within this report. Light availability, or turbidity, is estimated using the remote sensing reflectance at 670nm Rrs(670) in units of Steradian-1, which is a proxy for light scattering due to inorganic sediments in the water. SeaWiFS data are useful for investigating patterns, trends, and episodic events of near-surface ocean phytoplankton variability over a multitude of spatial domains (Sackman et al. 2004, Thomas, Townsend, and Weatherbee 2003).

Winds

QuikSCAT scatterometer wind products derived from Remote Sensing Systems, Inc. (RSS) provided a 7-year (July 1999 to September 2006), weekly set of wind magnitude and direction data at 25km spatial resolution. Winds were calculated using a microwave scatterometer to estimate sea surface roughness and radiometer measurements for rain flagging and sea ice detection. Weekly and monthly averaged data were derived from all data within the calendar month. Wind speeds are scalar averaged and directions are vector averaged.

Land Precipitation and PNW Drainage Boundaries

Regional precipitation data used for spatial comparisons were obtained via the Global Precipitation Climatology Centre (GPCC) real-time precipitation data product based on the complete GPCC monthly rainfall station database in 1° x 1° resolution (Adler et al. 2003). GPCC land precipitation monitoring data products were processed using area-averaged and time-integrated precipitation fields, based on surface rain gauge measurements collected nationally. The geographic framework (taken from NOAA/NOS/SPO 1999) depicts the boundaries of basins that would include the majority of runoff entering the shelf area of the Olympic Coast, including those from river systems and coastal drainages. Only portions of GPCC grid cells that fell within the coastal drainage basins were used. Monthly precipitation totals were combined as a mean value for the entire coastal basin.

Climatological Summaries

Seasonal to inter-annual shifts in oceanic and atmospheric conditions off the Olympic Coast can significantly influence the persistence, location, and spatial orientation of surface layer features and spatial patterns. The satellite image data series allowed for the extraction of weekly to monthly surface data and for the development of long-term (climatological) weekly to monthly data summaries of average (expected) conditions for each variable presented. In addition, monthly temporal deviation (climatological anomalies) and variability (standard deviation or index) terms were calculated for each variable (V). The general formula used in the determination of expected conditions and anomalies follows:

$$V_1'(m,y) = V_1(m,y) - \overline{V_1(m)}$$

where, V_1 represents the monthly average (or median) for month m of year y, $\overline{V_1}$ is the long-term (grand) mean for month m of all years, and V_1' is the climatological anomaly for month m of year y. This calculation was performed on all overlapping pixels in the monthly and weekly image databases to create image climatologies for each variable. These climatological images and anomalies will be used to summarize water properties for the upwelling, downwelling, and transition periods, and over interannual cycles.

Assessing variability of surface water properties from satellite provides added spatial and temporal context into the physical processes that limit or enhance phytoplankton production at the surface and at depth.

To address chlorophyll variability, the range (spread) around the monthly and climatological monthly median (50th percentile) values were calculated using the difference between the 75th and 25th quantiles for each overlapping pixel in each month of the calendar year. Quantiling is used to eliminate questionable values in the SeaWiFS dataset. Resulting maps show the spatial distribution of months with the highest variability, revealing chlorophyll "patches" with shape, size, and position occurring at different months of the year.

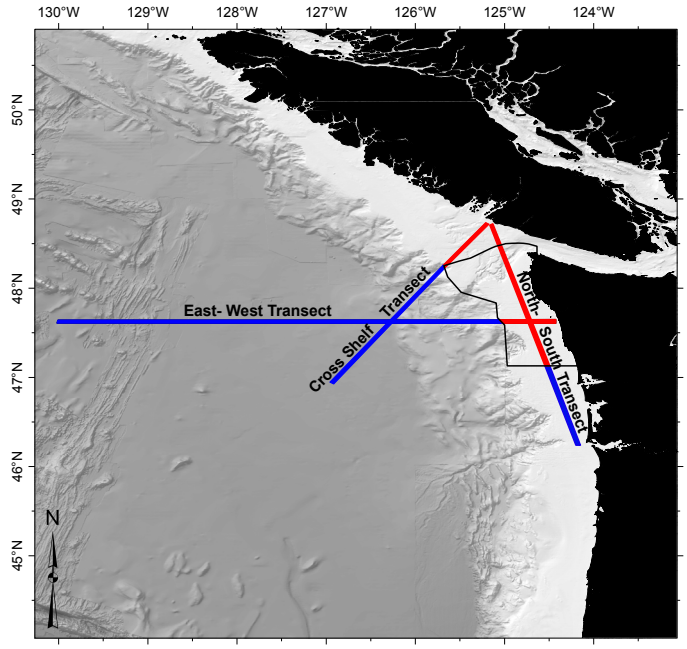

Figure 4. Transects used for seasonal satellite oceanographic data extractions.

2.2 Visual Representation of Data

The development of consistent daily and weekly time series of multiple image datasets allowed for visual representation and interpretation across variables. Since monthly averaged images are essentially snapshots of expected or average conditions over time, and are not representative of within month variability, extractions of weekly data were performed to help explain temporal patterns of variability important to ocean climate and character within and adjacent to the sanctuary. Data were extracted along three transect lines in the study area, following a general longitudinal (E-W), cross-shelf, and longshore (N-S) orientation (Figure 4). The longitudinal E-W transect was used to compare patterns of variability inside the sanctuary versus the open ocean environment; the diagonal cross-shelf transect was used to compare shelf patterns influenced by Juan de Fuca Strait outflow and eddy circulation versus shelf slope and open ocean; and the latitudinal N-S transect was used to compare longshore patterns inside the sanctuary versus areas influenced by estuarine and river plumes to the south.

Long-term weekly averaged SST (Figure 5), SSHA, chlorophyll, and turbidity data were extracted along the three transect lines to evaluate spatial-temporal patterns of variability and linkages with complementary satellite datasets. Vector quantities of SSHA-derived geostrophic currents extracted into northerly (toward the north) and easterly (toward the east) components were temporally averaged and plotted as conventional stick plots, depicting magnitude and direction of surface currents (Figure 5, bottom). Weekly (instantaneous) and anomaly data were extracted using time-series color plots (Hovmöller diagrams) and line plots to reveal interannual characteristics of variables (Figure 6). A Hovmöller diagram maps a scalar quantity (e.g., SST in °C) over a span of latitude or longitude through time. The scalar quantities were extracted in the longitudinal, cross-shelf, and longshore directions to depict spatial-temporal variability and episodic (anomalous) events for the period.

2.3 Quantitative Representation of Data

Statistical measures of association between remote sensing data types were used to highlight physical and biological coupling, and to infer the nature of oceanographic processes along the Olympic coast. Because these large data sources represent co-located and broad-ranging surfaces (e.g., maps of sea surface temperature, chlorophyll concentration), correlation was used to assess the magnitude and direction (positive/negative) of association among oceanographic variables. Because many of these variables were not normally distributed, Spearman's nonparametric distribution-free rank correlation was used (Lehmann and D'Abrera 1998). This technique provides a measure of monotone (linear) association, and is often used when the distribution of the data make Pearson's correlation coefficient undesirable or misleading. Correlation coefficients (ρ – rho) were computed and mapped among monthly mean/median data, and for climatological anomaly data. Correlation matrices describing spatial and temporal associations of all variables, as well as inferred mechanisms influencing variable associations were assessed and documented.

Data Disclaimer

All remote sensing data, particularly near the coast, should be treated with caution. Near-shore altimetry data that are extrapolated from offshore data typically result in poor sea surface height estimates and subsequently poor geostrophic velocity calculations (Saraceno et al. 2008). Ocean color chlorophyll signals may be biased in some cases due to the presence of color-dissolved organic materials (CDOM) and particulate matter in coastal regions (Gregg and Casey 2004). Turbidity reflectance fields also can be affected by the presence of algal pigments in the water column due to absorption of chlorophyll in the red wavelengths (Dall'Olmo and Gitelson 2005).

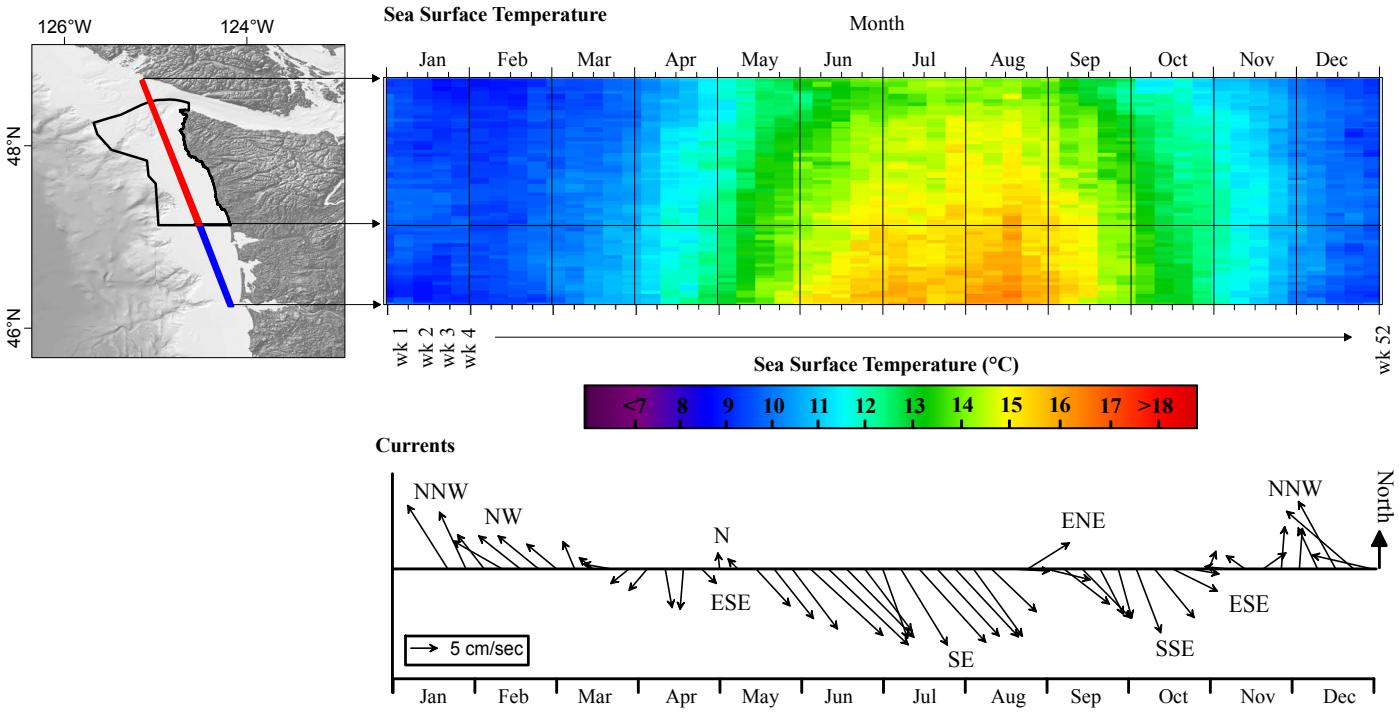

Figure 5. Example plot showing long-term weekly averaged (expected) SST conditions along a North-South transect line for Olympic Coast shelf waters (red line) and Washington Coast shelf waters (blue line), and SSHA-derived surface currents depicting magnitude and direction along the southern portion of the transect. Time period for CoRTAD SST: 1985-2005; AVISO geostrophic currents:1992-2006.

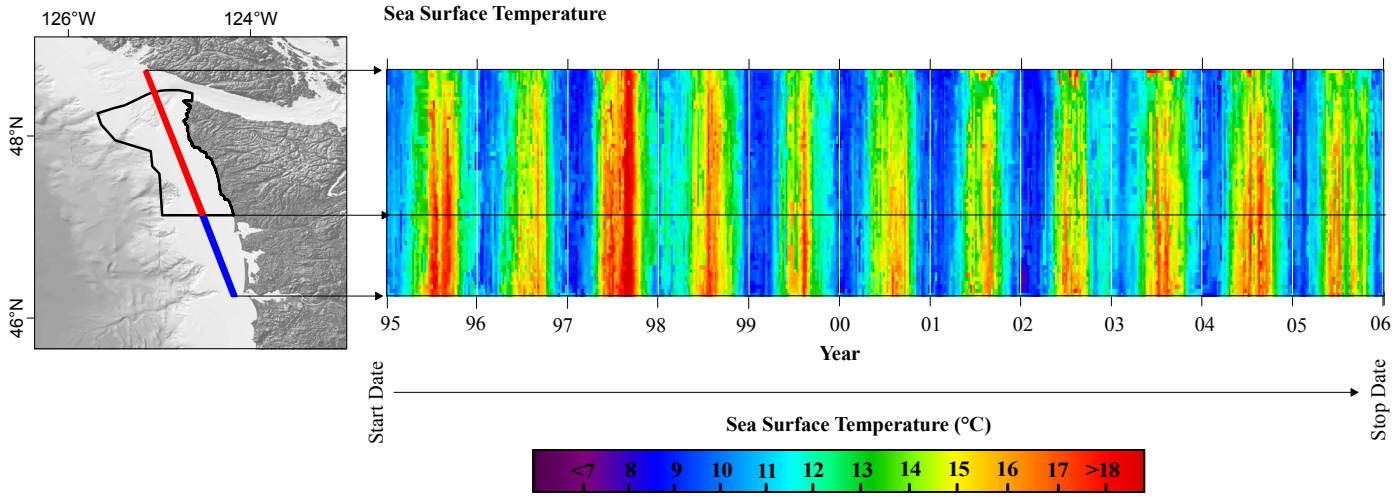

Figure 6. Example time-series plot (Hovmöller) of weekly gap-filled CoRTAD SST (C°) revealing SST along a North-South transect line for Olympic Coast shelf waters (red line) and Washington Coast shelf waters (blue line). Time period: January1995-December 2005.