Satellite Surface Observations of the 2008 Oregon Coastal Upwelling Season

Sarah Dewey, REU
P. Ted Strub, advisor
Corinne James, computer guru

Abstract

A holistic understanding of upwelling along the Oregon Coast requires many methods for data collection, remote or otherwise. The objective of this study is to optimally combine satellite altimeter data with satellite sea-surface temperature (SST) and in-situ wind data in order to fully describe seasonal coastal upwelling. All of these datasets are widely available, and while they do not describe the vertical water column beyond a superficial depth, their surface information may be combined to show an overturn of the water on the coast. A timeseries of calculated sea-surface height anomalies and satellite-derived temperature composites is used to describe the progression of coastal upwelling in Oregon during 2008. Cold, filament-like intrusions are visible along the coast as the season proceeds, and warm eddy formation from the interaction of this cold water with onshore flow is also visible; both temperature and topographic observations of these phenomena are used to describe upwelling as it occurs.

Introduction

Winds in the eastern Pacific Ocean drive upwelling along the Oregon Coast. Seasonal on-shore winds create pressure gradients, which in turn create equator-ward geostrophic flow. This flow generates Ekman transport away from the coast, and the water transported offshore is replaced with cold, salty, nutrient-rich water from below. Because this upwelled water is of a higher density than the surface water, when it outcrops at the surface it exhibits a lower dynamic height. Satellite-based altimeter measurements of sea level anomaly (SLA) can therefore be used to generate pressure and geostrophic flow fields. Combined with SST information and with wind data, seasonal changes in this height can describe the progression of upwelling. All of these data, satellite and in-situ, are sampled on different time and spatial scales, and are potentially course or sparse in nature. To make optimal use of all of these data sources, they must be combined; together, they can provide a well-rounded description of Oregon coastal upwelling.

Background

The relationship between sea surface height (SSH) and geostrophic flow is governed by pressure gradients. Use of an altimeter to calculate a flow field was fully dissected by Wunsch and Stammer (1998), and since that time has become a refined means of describing large-scale geostrophic flow. The main satellites carrying altimeters are TOPEX/POSEIDON (launched 1992) and JASON-1 (launched 2001; JASON-2 was launched in 2008), each a polar-orbiting system with a ten-day repeat period and nearly global coverage. While ocean altimeter signals can be affected by interaction with the land, use of altimeter and satellite data has been widespread in studying the Oregon Coast and accompanying California Current System (CCS) (Saraceno et. al., 2008; Venegas et. al., 2008).

Coastal upwelling is a seasonal phenomenon, occurring in the CCD in the spring. Barth et. al. (2004, 2005) describe flow-topography interactions of the California Current with the continental shelf, as well as the wind conditions and water properties off of the coast during an upwelling period. Studies such as these outline "typical" upwelling condition; in recent years, such close measurements of these conditions have been useful, especially in 2005 when the Oregon Coast experienced a noticeable temporal shift in the regular upwelling cycle. While the spring upwelling was delayed, late-summer upwelling was "stronger than normal…allowing the CUI [cumulative upwelling index, derived from pressure fields and mass transport data] for 2005 to reach the climatological mean by fall" (Schwing et. al., 2006). In the meantime, however, everything from phytoplankton production and SST (Thomas and Brickley, 2006) to whale feeding (Newell and Cowles, 2006) and auklet survival (Sydeman et. al., 2006) was affected along the Oregon Coast.

The manner in which these parameters were measured during the anomaly period illustrated the need for combined altimeter and in-situ measurements: the change was detected using both remotely-sensed and in-situ data. These data ranged from plankton net tows (Brodeur et. al., 2006) to CTD transects and buoy data (Hickey et. al., 2006; Pierce et. al., 2006). Thomas and Brickley (2006) use satellite observations of chlorophyll and combine them with buoy data. In this manner, a careful combination of superficial and deep measurements will continue to paint a full picture of current seasonal upwelling conditions and to advance understanding of the ramifications of such unusual years as 2005.

Objectives

The primary objective of this study was to use multiple data sources and forms to generate a holistic narrative of the 2008 upwelling season along the Oregon Coast. The data sources used were Jason-1 and -2 satellite altimeter data; continuous winds data from NDBC buoy 46050, moored off of the Newport line; and AVHRR sea-surface temperature imagery from NOAA, by way of OSU's GLOBEC AVHRR archive on the Pisco server. This project's combination of these data can serve as the first step in a multifaceted examination of upwelling; this multi-source approach is necessary not only because of upwelling's surface signature in height and temperature fields, but because of its unseen effects in the deeper vertical water column.

More focused and detailed objectives of this study were to pay attention to the influence of the coast on the altimeter and SST image data. Because the coast is often cloudy, pristine SST images are rare, and because the altimeter is designed to work over water rather than over land, its measurements can become increasingly noisy as it nears the coast. The SSH and SST data were interpreted and calculated to provide the best possible information about coastal upwelling given these conditions.

In addition to assembling an optimal dataset, the careful combination of these data was an important study objective. While all three datasets (SSH, SST, and winds) are limited in vertical scale to the very surface of the ocean, each may be used as a "check" to the others. For example, while the surface SST may not show a cold tongue along the coast associated with upwelling, the Jason-derived SSH anomaly may show a dip. That is, upwelling occurs in otherwise warm-looking water, and the colder, upwelled water lies beneath the surface. The winds, as well, provide a good “big picture” indication of when upwelling starts to occur, based on a transition in wind direction and intensity in early spring.

By both carefully combining datasets and working within those datasets’ limitations, one can assemble a fairly complete picture of the surface processes associated with upwelling; this picture is limited to the surface, however, and full water column data is needed to further this investigation.

Methods

All of the data used in this study was previously archived. Jason-1 and -2 netCDF files were available from Remko Scharroo’s RADS dataset, and continuous winds for buoy 46050 were available from NDBC’s website. SST images were retrieved from OSU Pisco’s GLOBEC AVHRR archive.

The organization of these pieces of data varied by dataset. Jason-1 netCDF files, as well as Jason-2 netCDF files to fill a period of missing Jason-1 data in August 2008, were read into a series of structures in Matlab in order to preserve and to organize all metadata. Continuous winds for 2008 were organized in Matlab as a series of variables rather than as structures, so that the data could be accessed from one source matrix; this slight change in approach was appropriate because the wind information lacked metadata.

SST images were processed in a series of steps. First, GOES images of the area were selected for cloud-free days at approximately two-to-three-week intervals throughout 2008. From these identified study days, specific AVHRR images for GLOBEC North (35.76N-56.23N, 117.76W-138.23W) were selected and organized into one-to-two day composites. These composites were selected to minimize cloud appearance, and also to correspond with Jason pass 28 and 247 coast-crossing times. The composites were then read as a byte array into Matlab, where they were processed as images in conjunction with the SSH data. No cloud mask was used and the median filter width for all of the images was five.

The Jason-1 and -2 along-track SSHs for passes 28 and 247 were calculated using a series of corrections from Remko’s data manual, in addition to the variables included in the Jason-1 and -2 datasets. These variables were subtracted, and data extraneous to appropriate ranges was excluded (Figure 2). In addition to this limiting of data range, “flagged” variables were often excluded. Remko identifies suspect data in his files using a “flag” variable; these flags (ranging in description from land vs. water identification to whether the satellite was on track at the time of measurement) may be used to include or to exclude various pieces of data. For pass 28, some flagged data were excluded; for pass 247, no flags were excluded. In order to collect information as close to the coast as possible, all land flags were ignored for pass 28, but ionospheric corrections and variable estimate quality flags were included.

In order to present this SLA data in combination with the SST data, the SLA was plotted perpendicular to the Zlotnicki-Fu grid tracks for the passes at hand, at a scale of 1:250000. The study window at hand is a grid from 128W to 123W and 41N to 48N, which encompasses the Zlotnicki-Fu grid crossing, as well as the Oregon Coast ranging from north of the mouth of the Columbia river to south of Cape Blanco. The mean for the offshore portion of each track within the study window, from 125.5W to 128W, was subtracted from the along-track SLA values to center the plot around the grid line and to make clearer any marked change in near-coastal SSH.

The one-to-two day SST composites, already selected for their paucity of cloud, were further filtered to eliminate all cloud-based sources of extraneous temperature data. For each image, a box was selected with the greatest possible cloud-free temperature range, and the temperature bar was scaled to that box. This scaling aided in eliminating clouds' influence on the data, and created images with maximal SST color contrast. The color bars on the images are therefore scaled only to maximize contrast, and not to match one another. This pseudo-"cloud mask" is best illustrated in Figure 17, in which the October 11 coastal flow features are shown in high contrast, and the cloud appears as a uniform dark blue area to the northwest.

The winds' role in this visual representation of the data was minimal, as their visual analysis took place somewhat separately. Wind vectors were divided into horizontal and meridional components according to the direction they were blowing (rather than their source direction), and plotted in bar graph form for the months included in the study and for the full year (Figures 3-6). Study days were highlighted, and the plots of the corresponding months have been placed above the SLA-SST comparison images. The winds serve as a helpful contextual illustration to the SLA-SST changes occurring from image to image.

In addition to combined SLA-SST plots with the wind, vertically-stacked plots (Figures 1-2) of calculated SSH were generated for 2008 cycles (~9.9-day intervals) ranging from early June to late October/early November. These plots were generated much as the along-track plots of the SLA were: the SSH was calculated and subtracted from its mean over the axis range, from 126.3W to the coast crossing (123.9766W for pass 28, 124.1392W for pass 247). These data were then scaled to fifteen times their size in order to heighten spatial contrast, and plotted against longitude. Depressions or elevations in the SSH over time are easily seen in this type of plot. For instance, a warm feature is visible in Figure 2 in the pass 247 plot, originating in mid-July at 125.3W and moving westward to 126.3W, its appearance in the figure constrained by the axis of the plot. This kind of timeseries analysis is beneficial to a study of the full upwelling season because it is not limited by the availability of cloud-free satellite temperature data.

Results and Discussion

Wind data from NDBC buoy 46050, when split into meridional and zonal components, shows a distinct shift in the early spring in both wind direction and magnitude that signals the onset of the upwelling season. The meridional winds (Figure 6) experience episodic shifts to southward flow for two six-day periods and one three-day period in April, but the highly oscillatory nature of the winds during that month—both northward and southward winds demonstrate a significant magnitude (about 7 m/s), and alternate in occurrence fairly regularly—indicate that the physical system along the coast has not fully transitioned into a period of upwelling. This transition occurs at May 3, at which point the wind shifts to a predominantly southward direction with moderate speed (7-10 m/s), and remains that way until late September/early October.

The trends in this meridional component are followed by those in the zonal wind component (Figure 5): June 12 marks an abrupt change in the zonal winds from 4 m/s eastward to 1m/s westward. Together with the meridional winds, this zonal trend indicates that the wind has shifted from blowing to the northeast to blowing to the south and slightly to the west: onshore winds have initiated Ekman transport and full physical upwelling after an initial period of relaxation, and the southward winds further enable the development of equatorward coastal flow.

SST images and SSH calculations from the early spring reinforce this assessment of the seasonal wind shift off of the coast. Images from March 5 and April 12 (Figures 7-8) show the pre-upwelling, “base level” conditions. While in both cases, the SST color is slightly mottled due to the presence of cloud, there is no largely visible zonal temperature gradient, and the SLAs do not experience a largely noticeable depression. While the April 12 image hints at a slight depression starting near the coast, it is couched in a noisy piece of nearshore data in which SLAs range from 5 to 20 cm, and there is no temperature data to support it, since the coastal waters appear uniformly to be 9.5C. Data for the full vertical water column would be beneficial in this case, in order to determine whether cold water is starting to intrude near the coast; however, the winds suggest that even if it is, this is an isolated upwelling episode predating the full onset of the upwelling season.

In sync with the wind shifts observed at buoy 46050, the June 12 image (Figure 9) demonstrates a regime shift: the development of a 9.5C cold wedge contrasting with the surrounding 13C water begins along the southern portion of the coastal study area, and a cold filament with a nascent-eddy-like core extends to 126W. While the northwest corner of the image is cloudy, the nearshore pass 28 altimeter measurements demonstrate a drop 30 cm at its extreme associated with the intrusion of this cold wedge. While the cold wedge is not necessarily visible under the altimeter track, the altimeter measurement hints at sub-surface processes and illustrates why these two data sources must always be considered in conjunction with one another. The meridional winds in June are still slightly variable, though after June 9 they all but cease their oscillating and settle into southward motion. Due to a shift at the end of the month, however, the June 27-28 image (Figure 10) is slightly cloudy, as visible in the fragmented pass 247 data and in the 17C “ocean” nearby, though it still shows the presence of an 11C cold wedge and slightly diminished SSH appearing to be about 10 cm lower than the offshore mean.

This end-of-June wind shift is paralleled in a wind shift at the end of September, visible when the uniformly southward ~7m/s late August/early September meridional winds subside to a period of oscillation extending through October (Figure 4). The formerly distinct cold filaments extending westward from the coast beyond 127W (Figures 14-16) lack their defined shape, and eddies either move or their formation is disrupted (Figure 17).

The aid of uniform southward winds in this coastal feature formation can be seen in July (Figures 11-12), when southward wind flow is maintained from the 6th through the 25th , and there is a clear contrast between the offshore cold flow filaments and the warm onshore flow with its inter-filament eddy formation. The pass 247 SSH plays more of a role in this month and subsequent months than it did prior; while the pass 28 height is useful for looking at a nearshore drop to indicate upwelling, pass 247 becomes useful with the development of offshore features between 125W and 128W in the study area.

Dips in SSH associated with the outreach of the filaments beyond 126W are observed, and can be correlated with the surface SST.

A story of the development of upwelling during the 2008 season may be patched together from these images and from wind data. The early spring is notable for its lack of apparent zonal temperature gradients, and a 9.5C wedge is first visible in the June 12 image (Figure 9). This wedge develops throughout the upwelling season, maintaining comparable or slightly higher surface temperatures. This wedge is observable through passes 28 and 247 of the Jason altimeters; the pass 28 nearshore dip reaches almost half a meter at its greatest extent in the July 31 image (Figure 12). Pass 247 shows the development of several cold tongues extending from the coast and responding to local bathymetry: the number of these cold tongues is at a maximum three in the study area, corresponding with bathymetric features such as Stonewall and Heceta Banks (see Barth, Pierce, and Castelao, 2005; and Barth, Pierce, and Cowles, 2005, for an in-depth discussion on the influence of this bathymetry on coastal flow).

In addition to these images of the metamorphic sea surface, vertically-stacked SSH plots (Figures 1-2) show the development of a nearshore drop of 0 to 0.2 m in SSH in pass 28 and of warm-core eddies moving off of the coast in pass 247. A warm feature (that is, one of elevated surface topography) is visible starting at the end of July around 125.3W and moving past 126W in November, reaching approximately 0.2m at its largest extent in early October. The nearshore drop in pass 28 is a little more difficult to quantify, since the altimeter data tends to be noisier near the coast; the tradeoff in ignoring land-flagged data is that while a dip in height is visible, its magnitude is not always reliably represented. In this case, the magnitude of the drop ranges from 0m to about 0.33m. It is visible, though, starting in the beginning of June (the beginning of the plot), and only levels off at the end of September and into October—though it is still present in the October 19 plot, and likely occurs occasionally as the meridional winds oscillate often during the mid- to late fall.

Conclusions and Further Research

The story of the 2008 upwelling season plays out as expected: a cold wedge develops, becoming apparent first towards the south and then farther north as the season progresses. This wedge is accompanied by a depression in the sea surface consistent with a pressure gradient and the resulting southward flow of the California Current; areas of higher temperature correspond with areas of higher sea surface, as expected from a density differential. The surface evidence for upwelling and surface data detailing its progression are strong.

However, further information is needed to investigate the full water column. While often the SST and SSH data provide convenient checks on one another, they do not correspond as exactly as hoped. Investigation of deeper water is possible using remote AUVs, or gliders. These instruments measure various physical water properties at different depths while underway; these measurements can be used to calculate dynamic heights for comparison with satellite-derived SSH, in addition to showing the temperature and salinity of deeper water involved in the upwelling. Such a comparison is underway currently, in a study area off of the Oregon Coast encompassing the Zlotnicki-Fu pass 247 and 28 crossing and the Newport hydrographic line.

Comparing glider-calculated dynamic heights with altimeter-derived SLAs can also provide information about the nature of near-coastal jets flowing southward as part of the CCS. Since geostrophic flow is governed by these heights, flow fields may be generated from height data and jet properties may be calculated.

References

Barth, J. A., S. D. Pierce, and R. M. Castelao, 2005: Time-dependent, wind-driven flow over a shallow midshelf submarine bank. *J. Geophys. Res.*, **110**, C10S05.

Barth, J. A., S. D. Pierce, and T. J. Cowles, 2005: Mesoscale structure and its seasonal evolution in the northern California Current System. *Deep-Sea Research II*, **52**, 5-28.

Brodeur, R. D., S. Ralston, R. L. Emmett, M. Trudel, T. D. Auth, and A. J. Phillips, 2006: Anomalous pelagic nekton abundance, distribution, and apparent recruitment in the northern California Current in 2004 and 2005. *Geophys. Res. Lett*., **33**, L22S08.

Castelao, R. M., J. A. Barth, and T. P. Mavor, 2005: Flow-topography interactions in the northern California Current System observed from geostationary satellite data. *Geophys. Res. Lett.*, **32**, L24612.

Chelton, D. B., J. C. Ries, B. J. Haines, L. Fu, and P. S. Callahan: Satellite altimetry, in *Satellite Altimetry and Earth Sciences*, L. Fu and A. Cazenave, eds. San Diego: Academic Press, 2001.

Hickey, B., A. MacFadyen, W. Cochlan, R. Kudela, K. Bruland, and C. Trick, 2006: Evolution of chemical, biological, and physical water properties in the northern California Current in 2005: Remote or local wind forcing?. *Geophys. Res. Lett*., **33**, L22S02.

Kosro, P. M., W. T. Peterson, B. M. Hickey, R. K. Shearman, and S. D. Price, 2006: Physical versus biological spring transition: 2005. *Geophys. Res. Lett.*, **33**, L22S03.

Leuliette, E., R. Nerem, and T. Mitchum, 2004: Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. *Mar. Geod.*, **27(1)**.

Martin, S. *An Introduction to Ocean Remote Sensing*. New York: Cambridge University Press, 2004.

Newell, C. L., and T. J. Cowles, 2006: Unusual gray whale Eschrichtius robustus feeding in the summer of 2005 off the central Oregon Coast. *Geophys. Res. Lett*., **33**, L22S11.

Pierce, S. D., J. A. Barth, R. E. Thomas, and G. W. Fleischer, 2006: Anomalously warm July 2005 in the northern California Current: Historical context and the significance of cumulative wind stress. *Geophys. Res. Lett.*, **33**, L22S04.

Saraceno, M., P. T. Strub, and P. M. Kosro, 2008: Estimates of sea surface height and near-surface alongshore coastal currents from combinations of altimeters and tide gauges. *J. Geophys. Res*., **113**, C11013.

Schwing, F. B., N. A. Bond, S. J. Bograd, T. Mitchell, M. A. Alexander, and N. Mantua, 2006: Delayed coastal upwelling along the U.S. West Coast in 2005: A historical

Perspective. *Geophys. Res. Lett*., **33**, L22S01.

Strub, P. T. and C. James: Satellite comparisons of eastern boundary currents: resolution of circulation features in “coastal” oceans.

Sydeman, W. J., R. W. Bradley, P. Warzybok, C. L. Abraham, J. Jahncke, K. D. Hyrenbach, V. Kousky, J. M. Hipfner and M. D. Ohman, 2006: Planktivorous auklet Ptychoramphus aleuticus responses to ocean climate, 2005: Unusual atmospheric blocking?. *Geophys. Res. Lett*., **33**, L22S09.

Thomas, A. C., and P. Brickley, 2006: Satellite measurements of chlorophyll distribution during spring 2005 in the California Current. *Geophys. Res. Lett*., **33**, L22S05.

Venegas, R. M., P. T. Strub, E. Beier, R. Letelier, A. C. Thomas, T. Cowles, C. James, L. Soto-Mardones, and C. Cabrera, 2008: Satellite-derived variability in chlorophyll, wind stress, sea surface height, and temperature in the northern California Current System. *J. Geophys. Res.*, **113**, C03015.

Wunsch, C., and D. Stammer, 1998: Satellite altimetry, the marine geoid, and the oceanic general circulation. *Annu. Rev. Earth Planet. Sci.,* **26,** 219–253.