United States – Pacific Northwest

based in part on the article *Observations of highly nonlinear internal solitons over the continental shelf.* by T. P. Stanton and L.A. Ostrovsky [1998] with permission of the authors.

Overview

The United States Pacific Northwest covers approximately 750 km of coast between Northern California (42°N, 124°W) to Cape Flattery (48°N, 125°W) (Figure 1). A roughly 100 km wide continental shelf exists along the length of the Pacific Northwest coast. The region is influenced by the California Current and the outflow of the Colombia River.

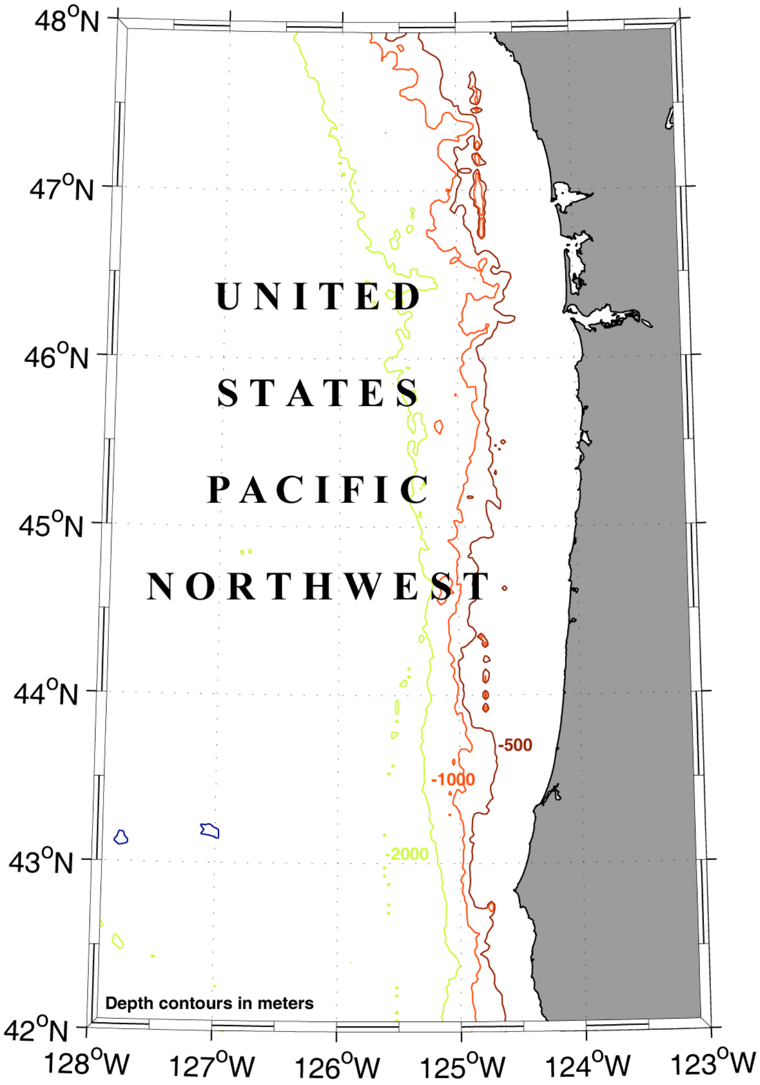


Figure 1. Bathymetry of Northwest coast of the United States [Smith and Sandwell, 1997].

Observations

There has been some scientific study of internal waves along the Pacific Northwest [Fu and Holt, 1982; Stanton and Ostrovsky, 1998; Kropfli et al., 1999]. Satellite imagery shows very strong internal wave signatures occurring relatively close to shore and similar in characteristic to those of Northern California. Ocean profile observations collected during the Coastal Ocean Probing Experiment (COPE) in October 1995 revealed the extreme nonlinearity of the internal wave packets as characterized by a ratio of the maximum isotherm displacement to their initial depth. [Stanton and Ostrovsky, 1998].

The waves are expected to occur primarily during the summer through mid-autumn (June though September) when a well-developed thermocline is present. Table 1 shows the months of the year when internal wave observations have been made.

Table 1 - Months when internal waves have been observed along the United States Pacific Northwest coast. (Numbers indicate unique dates in that month when waves have been noted)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
							2	X	X		

COPE Experiment: COPE was performed off the coast of northern Oregon from 12 September through 7 October 1995. The site, offshore from Tillamook Oregon, was chosen for the strong near surface pycnocline. Measurements included high powered Ka and X band Doppler radars located on a 750 m high coastal mountain top to study radar backscatter properties and produce time series of 150 m horizontal resolution maps showing surface backscatter levels and scatterer velocity spanning an 50 Km radius offshore from the radar site [Kropfli et al, 1999]. Detailed measurements of the near-surface ocean and atmosphere structure were made from FLIP, a 108 m long research platform which was tri-moored in 140 m of water. FLIP recorded upper ocean current measurements with continuous upper ocean profiling by the Loose-tethered Microstructure Profiler (LMP), which was raised and then allowed to free-fall through the water column every 80 seconds This rapid cycling provided 0.1m vertical resolution temperature and salinity profiles from both upward and downward profiles every 40 seconds from the surface to a depth of 35m.

Figure 2 shows a twenty-four hour period near the monthly maximum in tidal amplitude has been selected from the three weeks of observations to illustrate the internal tide characteristics. Figure 2 (Top) is an isotherm profile time series from the surface to 35m depth measured by the LMP. Two cycles of a steep leading edged, smooth displacement of the thermocline, with an amplitude of approximately 10-m, can be seen in the low frequency part of the time series. These two bore-like displacements (seen best in the depth of the yellow, 13.8°C contour) are evidence of a strong, semidiurnal (~12 hour period) internal tidal wave propagating past FLIP from a nearby, offshore generation site over the shelf break.

Equally striking in Figure 2 are the rapid vertical displacements (barely resolved at this time scale) extending down from the leading edge of the low frequency wave displacement by up to 25 m. An enlargement of a 1.7 hour profile time series (Bottom) from the start of the first soliton displacement, shows the extreme nonlinearity of these solitary waves, when the very shallow pycnocline depth of approximately 7m seen at the start of the time series, and the 15-25 m downward displacement amplitudes are considered.

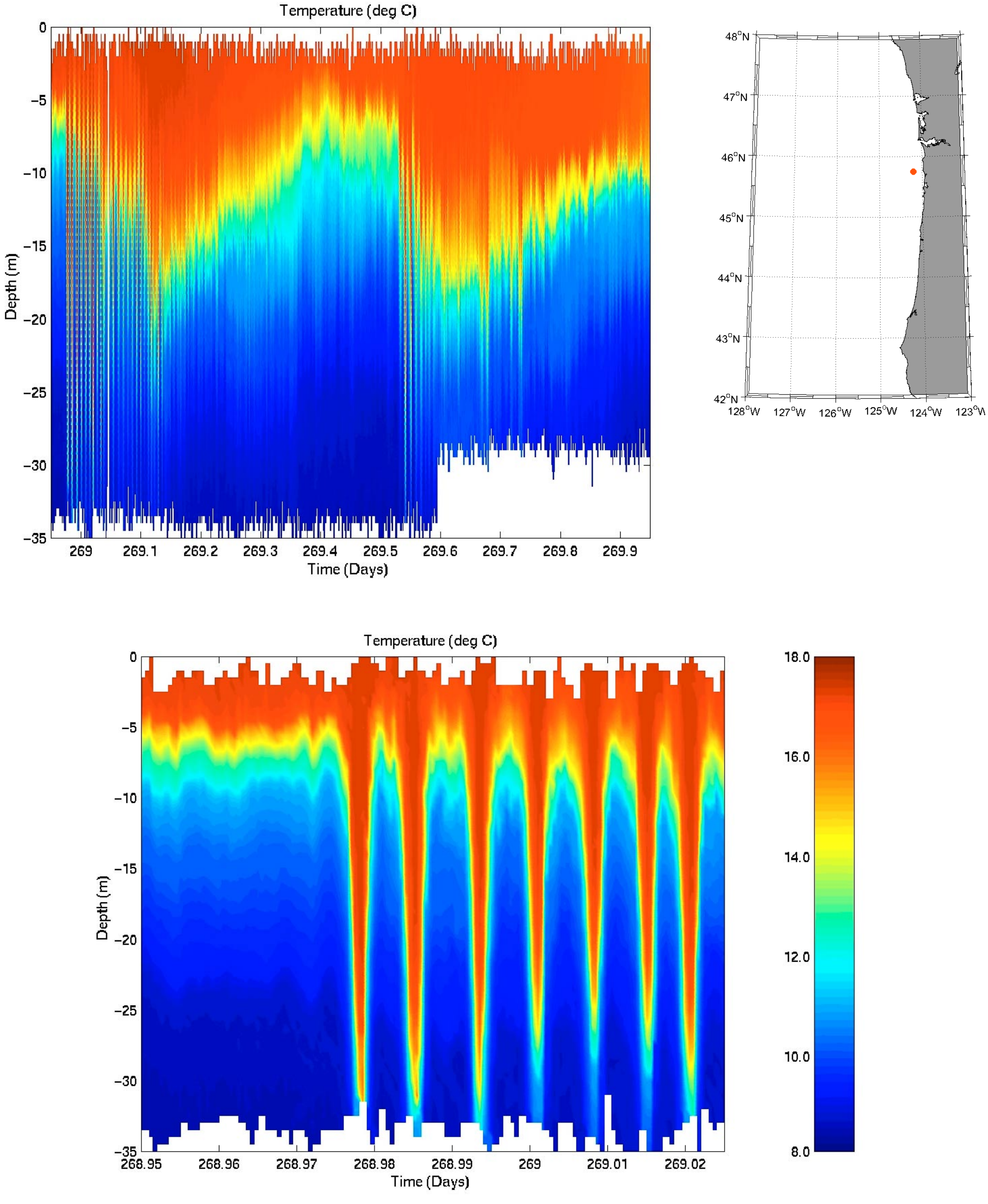


Figure 2. (Top) A color contour time series of temperature profiles from the surface to 35m depth measured by the LMP over a one-day period (26 September 1995). The 10°C span color contour scale is shown the right of the time series panel. The low frequency, semidiurnal internal tide displacement can clearly be seen along the yellow isotherm. (Bottom) A profile time series of the first 1.7 hours of the time series shown in the top figure. White areas indicate times with no data. [After Stanton and Ostrovsky, 1998]

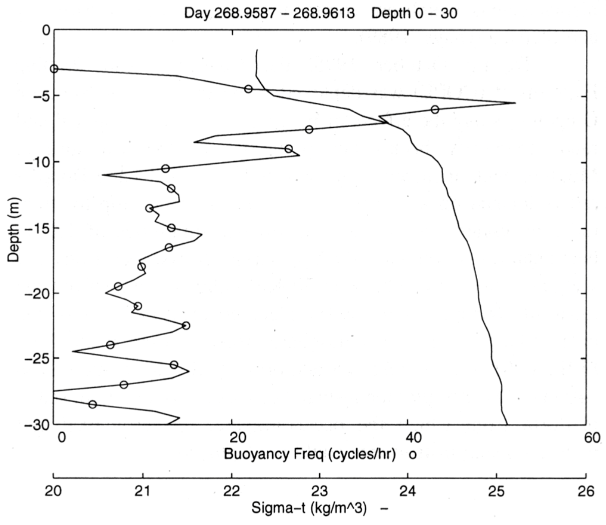


Figure 3. Typical 10-minute average profile of density (solid line) and buoyancy frequency (solid line with o symbols) just prior to the arrival of the SIW packet at the start of yearday 269.

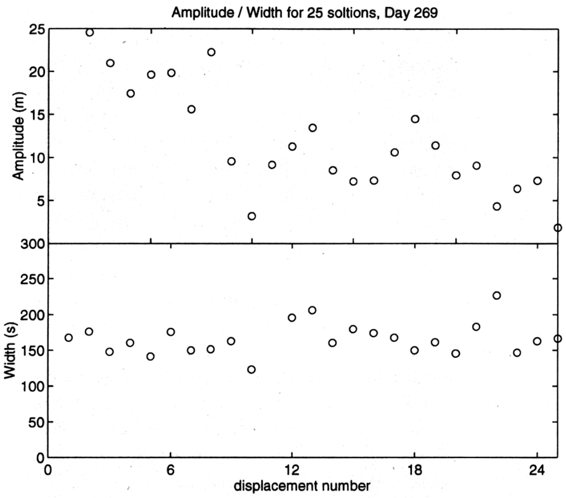


Figure 4. (Top) Maximum displacement for the first 25 solitons in the wave packet shown at the start of Figure 2. (Bottom) Soliton width (defined as the time interval between displacements at half the maximum amplitude) corresponding to waves in the top figure.

A 15-minute average profile of density and the natural buoyancy frequency of a displaced element of water, N, prior to the arrival of the tidal bore in Figure 3 shows the remarkably shallow depth of the very strong stratification, with N up to 45 cph at 5m depth. This shallow, strong stratification arises from a combination of the high temperature and low salinity of the surface layer due to the presence of strongly solar heated, turbid, fresh river runoff which forms a surface plume extending south from the Columbia River at this time of the year. The profiles also indicate that wind mixing due to the 5-8 ms-1 winds at this time was confined by the sharp pycnocline to a very shallow, 4m deep surface mixed layer. As the displacement amplitude is 2 - 4 times greater than the quiescent pycnocline depth, these solitons are clearly extremely nonlinear.

The width and amplitude of 25 successive soliton displacements observed at the start of day 269 have been estimated from isotherm displacements measured by the LMP. In these and the following data, multiple isotherms are tracked within the sharp, but finite-width pycnocline, to increase the robustness of the soliton displacement estimates beyond those available from a single transition of an isotherm with each profile. Figure 4a shows the maximum amplitude of the 25 SIW displacements. The erratic decrease from 25m to less than 5m for displacement number 10 appears to be associated with superposition of refracted waves from slightly different directions, apparent in the radar images. The corresponding wave widths in Figure 4b, expressed as elapsed time in seconds, (measured as the time between half amplitude displacements), show very little departure from 180 seconds.

Table 2 – CombKdV Parameters

Environmental		CombKdV Model	
h_1 = 7 m	ρ_1 = 1022.2 Kg/m^3	α = -0.086 s^{-1}	c = 0.44 m/s
h_2 = 140 m	ρ_2 = 1025.0 Kg/m^3	α_1 = -0.0042 m^{-1} s^{-1}	V_{max} = 0.72 m/s

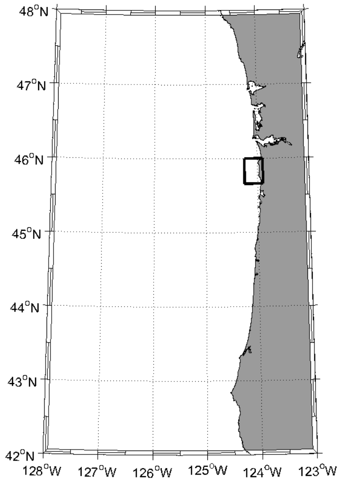
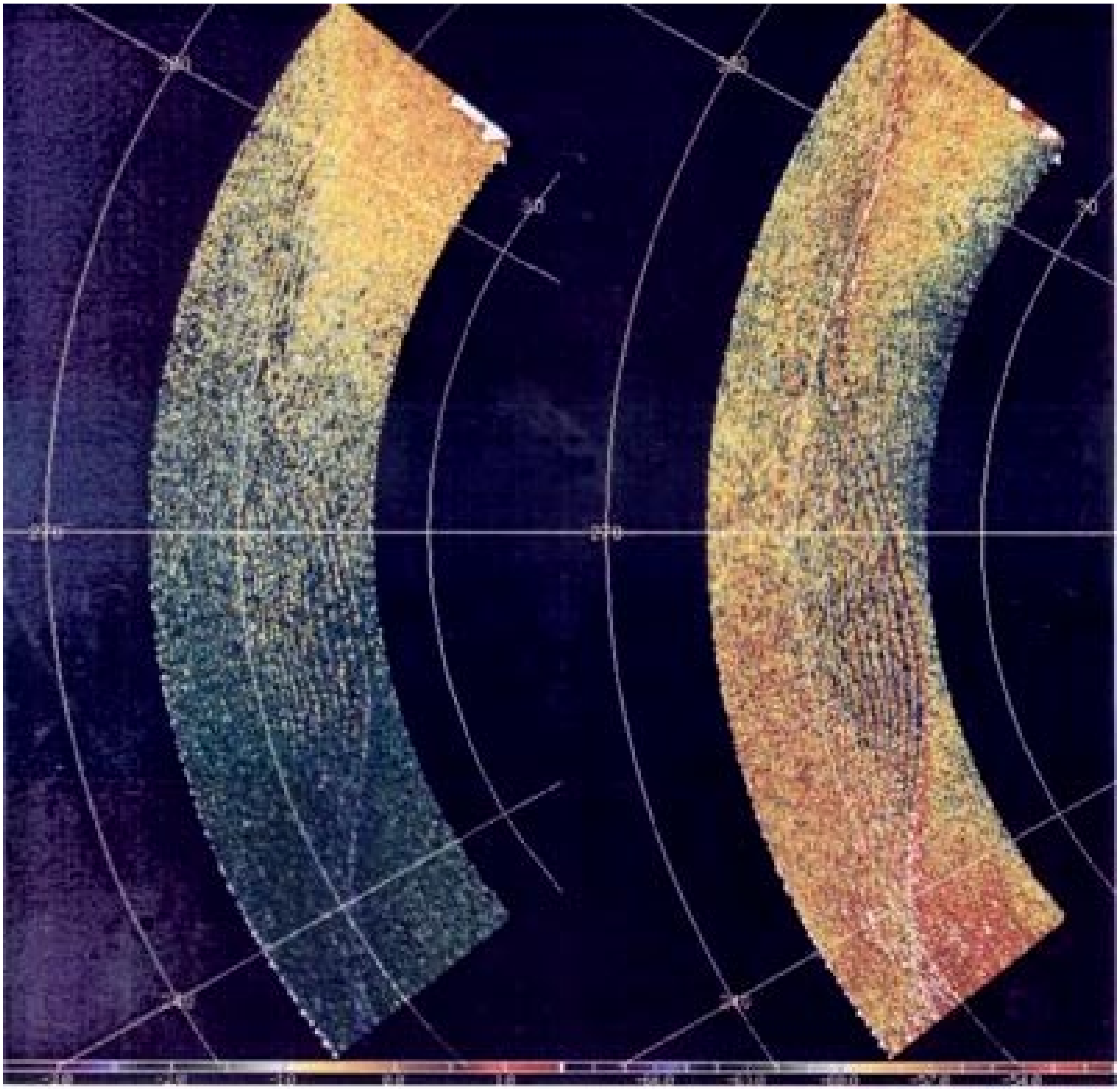


Figure 5. Doppler velocity (left) and normalized radar cross section (right) for the lead wavefront in Figure 2. Data were acquired on 25 September 1995 at 2146 UTC during the COPE experiment using the NOAA ETL scanning Ka band Doppler radar operating at VV polarization. Range marks are at 10-km intervals, Doppler is positive seaward. [After Kropfli et al, 1999]



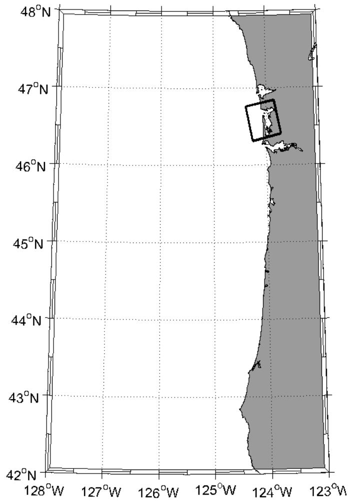
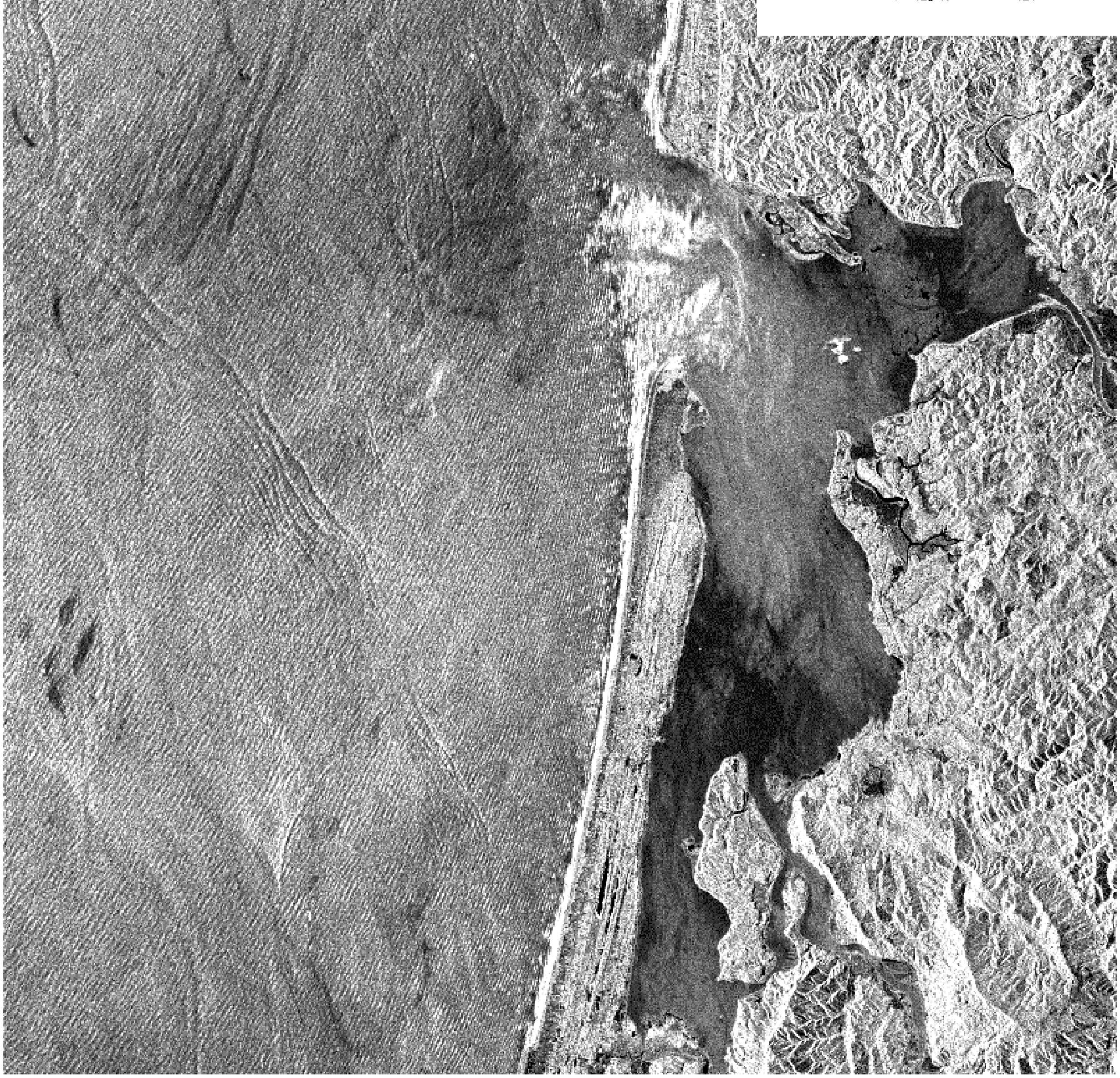


Figure 6. RADARSAT-1 (C-band, HH) SAR image of Willipa Bay along the Washington Coast acquired in 1999. The image shows the signatures of internal waves generated at the coastal shelf break propagating shoreward. Imaged are is 50 km x 50 km. ©CSA 1999



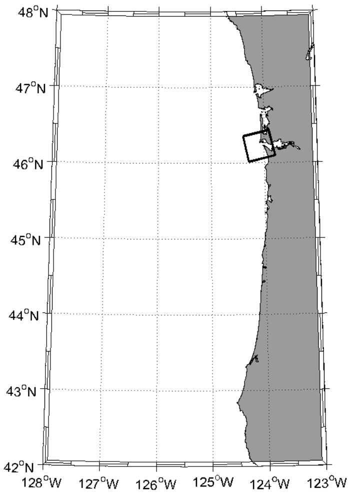
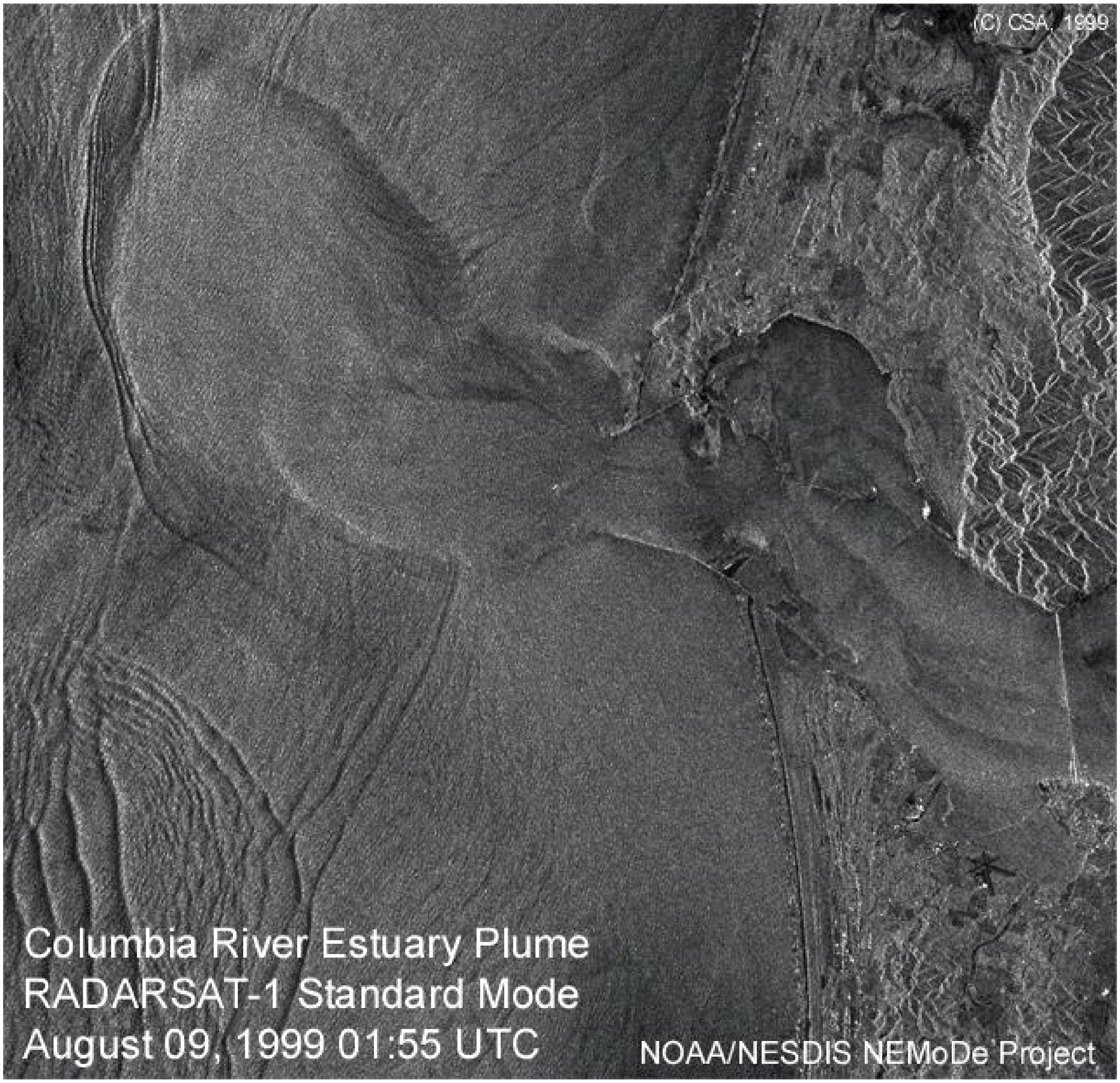


Figure 7. RADARSAT-1 (C-band, HH) SAR image of the Colombia River and Oregon coast acquired on 9 August 1999 at 0155 UTC. The image shows the signatures of both seaward propagating internal waves induced by the Colombia River plume and shoreward propagating waves generated at the coastal shelf break. Imaged area is approximately 45 km x 45 km. ©CSA 1999.



References

Fu, L.L., and B. Holt, 1982, Seasat Views Oceans and Sea Ice with Synthetic Aperture Radar, JPL Publication 81-120, 200pp

Kropfli, R.A., L.A. Ostrovsky, T.P. Stanton, E.A. Skirta, A.N. Keane, and V.A. Irisov, 1999: Relationships between strong internal waves in the coastal zone and their radar and radiometric signatures. *J. Geophys. Re*s., **104 (C2**), 3133-3148.

Stanton, T.P., and L.A. Ostrovsky, 1998: Observations of highly nonlinear internal solitons over the continental shelf. *Geophys. Res. Let*t., **25 (14**), 2695-2698.

Smith, W. H. F., and D. T. Sandwell, Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277, p. 1957-1962, 26 Sept., 1997. http://topex.ucsd.edu/marine_topo/mar_topo.html