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Analyzing Dynamic Characteristics of Internal Solitons Generated at the Columbia River Plume Front with SAR Images

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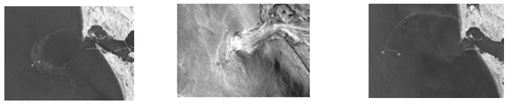
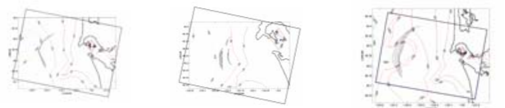
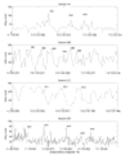
1. Introduction

The Columbia River plume transports dissolved and particulate load, phyto- and zooplankton, and larvae across the shelf. It also facilitates primary production and influences food-web structure through its supply of silicate and micronutrients. Small-scale phenomena such as plume fronts and internal waves generated by the plume can greatly affect vertical mixing between the plume and ocean waters. Internal waves that are generated at the front of the river plume and propagate off shoreward [Nash and Moum 2005; Orton and Jay 2005] both cause mixing and transport plume water into the adjacent coastal ocean. We use Synthetic Aperture Radar (SAR) images and vessel data to obtain the dynamic parameters of the internal waves generated at the Columbia River plume front, analyze effects of the internal waves on the vertical mixing, and estimate horizontal transport in theplume water layer.







RISE (River Influences on Shelf Ecosystem) project studies the effects of the Columbia River plume on the ecosystem of the Northwest coastal waters. The first and second cruises were carried out in July, 2004 and June 2005. Using these in-situ data, we derived the upper and lower layer densities and depths in the areas where the internal waves were observed.

3. Theoretical analyses

The above soliton have the following properties:

$$\frac{L}{h_1} >> 1, \quad \frac{h_1}{H} << 1, \quad \frac{L}{H} \approx O(1), \quad \frac{\eta_0 L}{h_1{}^2} \approx O(1)$$

A theoretical model for finite-depth internal soliton [Joseph 1977] provides:

Amplitude: $\eta(\xi;a,b) = \frac{-\eta_0}{\cosh^2 a\xi + (\sinh^2 a\xi)/(a^2b^2)}$ $\quad ab\tan(aH) = 1 \quad b = \frac{4h_1{}^2}{3\eta_0}$

Phase Speed: $c = c_0\left\{1 + \frac{h_1}{2H}\left[1 + \frac{H}{b}\left(1 - a^2b^2\right)\right]\right\} \quad c_0 = \left(\frac{\delta\rho}{\rho}\frac{g}{k}\right)^{\frac{1}{2}}[\coth kh_1 + \coth k(H-h_1)]^{-\frac{1}{2}}$

Upper Layer Vel: $u_1 = \frac{\eta_0 c_0}{h}\frac{1}{\cosh^2 a\xi + (\sinh^2 a\xi)/(a^2b^2)}$ Lower Layer Vel: $u_2 = -\frac{\eta_0 c_0}{(H-h)}\frac{1}{\cosh^2 a\xi + (\sinh^2 a\xi)/(a^2b^2)}$

Where H is the water depth; h is the upper layer depth; ρ is the density; and k is the wavenumber.

Zheng et al. [2001] developed a theoretical model of the Radar backscatter cross section for internal waves in shallow water regime. Based on their study, we derived an analytic expression for finite-depth internal soliton cases. The Radar backscatter cross section per unite area caused by an internal soliton is written as:

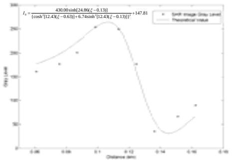
$$\hat{\sigma}_{0IS}(\theta)_{ij} = \frac{1}{M}\frac{\sinh 2a\xi}{(\cosh^2 a\xi + \frac{1}{a^2b^2}\sinh^2 a\xi)^2}$$

where M is the maximum value of the function $\frac{\sinh 2a\xi}{(\cosh^2 a\xi + \frac{1}{a^2b^2}\sinh^2 a\xi)^2}$

In SAR image, the soliton induced gray level is given by

$$I_0 = \frac{A\sinh 2a(\xi-\xi_0)}{[\cosh^2 a(\xi-\xi_0) + \tan^2 aH\sinh^2 a(\xi-\xi_0)]^2} + B$$

The parameters A, a, ξ_o, and B are determined by using non-linear least squares curve fit of the theoretical mode to SAR image data:



Soliton half-width $\quad D_{half} = \frac{2}{a}\text{asinh}\left[\frac{1}{\sqrt{1+\tan^2(aH)}}\right]$

Amplitude $\quad D_{half} = \frac{2}{a}\text{asinh}\left[\frac{1}{\sqrt{1+\tan^2(aH)}}\right]$

Energy $\quad E = (\rho_2 - \rho_1)g\eta_0{}^2\int_{-\infty}^{\infty}\left[\frac{1}{\cosh^2 ax + \sinh^2 ax/(a^2b^2)}\right]^2 dx$

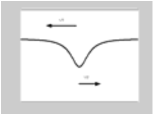
The Soliton dynamic parameters are derived and listed in the table

Dynamic Parameters	D_{half} (m)	η_0 (m)	c (m)	U_1 (m/s)	U_2 (m/s)	E (J/m)
Sec AA' SA1	47.9	15.02	0.68	0.439	0.068	1.9×10^5
SA2	69.0	10.03	0.62	0.292	0.047	1.2×10^5
SA3	80.0	8.35	0.60	0.244	0.039	1.0×10^5
Sec BB' SB1	56.6	5.66	0.52	0.202	0.026	3.0×10^4
SB2	95.2	2.72	0.48	0.107	0.014	1.4×10^4
SB3	78.0	3.50	0.49	0.138	0.018	1.9×10^4
SB4	100.3	2.54	0.48	0.100	0.013	1.3×10^4
SB5	86.5	3.08	0.48	0.121	0.016	1.7×10^4
SB6	88.9	2.97	0.48	0.112	0.015	1.6×10^4
Sec CC' SC1	90.4	2.74	0.47	0.106	0.017	1.4×10^4
SC2	94.4	2.58	0.47	0.100	0.016	1.3×10^4
SC3	111.9	2.03	0.46	0.078	0.013	0.9×10^4
Sec DD' SD1	234.6	6.85	0.72	0.172	0.013	1.7×10^5
SD2	260.4	6.05	0.72	0.152	0.011	1.4×10^5
SD3	254.6	6.22	0.72	0.156	0.012	1.5×10^5
SD4	251.7	6.30	0.72	0.159	0.012	1.5×10^5
SD5	302.7	5.05	0.71	0.127	0.009	1.2×10^5

4. Effects of the internal solitions on vertical mixing

The turbulent vertical mixing can be described by the gradient Richardson number $Ri = \frac{N^2}{\left|\frac{\partial \mathbf{U}}{\partial z}\right|^2} = \frac{\frac{-g}{\rho}\frac{\partial\rho}{\partial z}}{\left|\frac{\partial \mathbf{U}}{\partial z}\right|^2}$

Vertical turbulent mixing develops when Ri<0.25 (turbulent critical value). Internal solitions can increase the vertical velocity shear, and decrease the Ri, allowing vertical turbulent mixing to occur.



Shear increase: $\left|\frac{U1+U2}{\Delta D}\right|$

Velocity Shear caused by an internal solition [Sandstrom and Oakey, 1995] $\quad \frac{\partial u}{\partial z} = c(\frac{N^2}{c^2} + 2a^2)\eta_0$

The background Richardson number (in absent of internal waves) in the SA1 case

$$Ri_b = \frac{N^2}{(\frac{\partial U}{\partial z})^2 + (\frac{\partial V}{\partial z})^2} = 2.98$$

Under soliton SA1 influence $\quad Ri = \frac{N^2}{\left|\frac{\partial \mathbf{U}}{\partial z} + \frac{\partial \mathbf{u}}{\partial z}\right|^2} = \frac{N^2}{(\frac{\partial U}{\partial z} + \frac{\partial u}{\partial z}\cos\alpha_1)^2 + (\frac{\partial V}{\partial z} + \frac{\partial u}{\partial z}\cos\alpha_2)^2} = 0.24 < 0.25$

Thus, the internal soliton caused the turbulent mixing

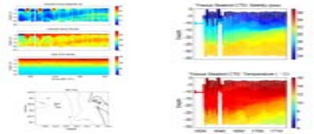
5. The horizontal transport in upper layer (plume layer) induced by internal solitons

This net horizontal transport results from the non-linearity of the internal soltion. For a linear internal wave, the velocity field is harmonic, and no net transport is expected. The net horizontal transport can help to spread the plume water out.

$$Q = \int_{-\infty}^{\infty}\frac{\eta_0 c_0}{\cosh^2 a(x-ct) + \tan^2 aH\sinh^2 a(x-ct)}dt = \frac{\eta_0 c_0}{ac}\int_{-\infty}^{\infty}\frac{1}{\cosh^2\beta + \tan^2 aH\sinh^2\beta}d\beta$$

For SA1 the transport Q=1.23×10^3 m^3/m

6. An internal soliton packet captured in RISE 2005 cruise



TRIAXUS observations allow us to define model parameters and understand soliton properties. The current direction within the solitons is to the northwest, suggesting that the observed solitons are traveling off-shoreward. The echo intensity, and CTD S and T shows that the amplitude of leading soliton is about 15 m, and the low salinity is deeper on the right side than the left side, reflecting that under the influence of the solitons the surface plume water with low salinity can be mixed into a lower level, and also the horizontal transport of the plume water by the internal solitons strengthens this process.

7. Conclusions

1) We have derived dynamic parameters of internal solitons with SAR image based on the backscatter cross section model of internal solitons developed in this study.
2) Using the derived dynamic parameters, we find that vertical turbulent mixing is facilititated by the influence of the internal soliton SA1.
3) The internal solitons, generated at plume front, cause a horizontal transport in the upperlayer, which carry plume water beyond plume area, resulting the horizonta lmixing.

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