Oceanic Pycnocline Depth Estimation from SAR Imagery*

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Abstract: Oceanic pycnocline depth is usually obtained from in situ measurements. As ocean internal waves occur on and propagate along oceanic pycnocline, it is possible to estimate the depth remotely. This paper presents a method for retrieving pycnocline depth from synthetic aperture radar (SAR) imagery where internal waves are visible. This model is constructed by combining a two-layer ocean model and a nonlinear internal wave model. It is also assumed that the observed groups of internal wave packets on SAR imagery are generated by local semidiurnal tides. Case study in East China Sea shows a good agreement with in situ CTD data.
Keywords: SAR, Pycnocline depth, Internal waves

1. Introduction

Nonlinear internal waves are frequently observed on SAR images in the continental shelf waters of the northeast of Taiwan during late spring, summer and early fall seasons when the ocean is fully stratified (Liang, et al., 1995; Liu, et al., 1998; Hsu, et al., 2000). These waves which propagate along the pycnocline are usually generated by the interaction between tidal currents and sea bottom topography.

Since 1970s, a lot of internal wave images have been acquired by SARs. The SAR imaging mechanism of ocean internal waves is related to following three physical processes (Alpers, 1985):

(1) surface current variation by propagation of internal waves;

(2) short-scale surface roughness variation induced by surface currents;

(3) radar backscattering processes between microwaves and short-scale surface waves.

Ocean internal waves observed on SAR imagery usually have wavelengths in the order of a few hundred meters, with several internal wave packets being separated by several kilometers. Oceanic pycnocline depth is the depth of the upper mixed layer of the ocean, which is usually of the order of a few tens of meters thick during the summer. The objective of this paper is to investigate the possibility of estimating this depth from SAR imagery.

2. Methodology

The evolution of nonlinear internal waves is described by Korteweg-de Vries (KdV) equation (Liu, et al., 1998)

$$\frac{\partial \eta}{\partial t} + (C_0 + \alpha\eta)\frac{\partial \eta}{\partial x} + \beta \frac{\partial^3 \eta}{\partial x^3} = 0 \qquad (1)$$

where η the wave elevation, C_0 the linear wave speed, parameters α and β the coefficients for the nonlinear and dispersion effects respectively.

For a two-layer ocean system with upper layer depth h_1 and bottom layer depth h_2, we have,

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$$\alpha = \frac{3C_0(h_1 - h_2)}{2h_1h_2} \quad (2)$$

$$\beta = \frac{C_0h_1h_2}{6} \quad (3)$$

And the linear wave speed C_0 given by dispersion relation of internal wave reads,

$$C_0 = \left[\frac{g\Delta\rho h_1h_2}{\rho(h_1 + h_2)}\right]^{1/2} \quad (4)$$

where $g = 9.8\,\mathrm{m/s^2}$ the gravity acceleration, ρ the mean density of sea water, $\Delta\rho = \rho_2 - \rho_1$ the difference of water density between bottom and upper layer.

When (1) is solved, we obtained following solution,

$$\eta(x,t) = \mp\eta_0\,\mathrm{sech}^2\left(\frac{x - C_p\,t}{l}\right) \quad (5)$$

where η_0, l and C_p the maximum amplitude, the half-width and the phase speed of internal wave, respectively. The minus/plus sign is for depression/elevation type internal wave.

$$C_p = C_0\left[1 + \frac{\eta_0\,|\,h_2 - h_1\,|}{2h_1h_2}\right] \approx C_0 \quad (6)$$

From above, the methodology to derive pycnocline depth can be illustrated as following steps.

First, the distance (Λ) between two internal wave packets generated from semi-diurnal tides with the same source but 12.5 hours apart is measured from SAR image.

Second, the speed (C_g) of internal wave packets is calculated from,

$$C_g = \Lambda / T \quad (7)$$

where $T = 12.5$ h the periods of semi-diurnal tides.

Third, the phase speed of internal wave equals the speed of internal wave packets, or

$$C_p = C_g \quad (8)$$

Fourth, the pycnocline depth h_1 obtained from (8), (10), (11) and (12) reads,

$$h_1 = \frac{g'h \pm \left(g'^2h^2 - 4g'h(\Lambda / T)^2\right)^{1/2}}{2g'} \quad (9)$$

where plus/minus sign for elevation/depression type internal wave, $g' = g\Delta\rho / \rho$ the reduced gravity acceleration, $h = h_1 + h_2$ the water depth.

Thus, when h, $\Delta\rho / \rho$ and Λ are known, the pycnocline depth can be derived from (9).

3. Data

An ERS-1 SAR image covering northeast coastal waters of Taiwan with a spatial resolution of 25 m are selected for case study. It was taken at 2:27 GMT on 23 July 1994 (see Fig. 1).

A CTD data in the same season as SAR data is used for verification. It was located in the northern coastal waters of Taiwan (see Table 1).

Table 1. Time and location of CTD, and measured pycnocline depth

	time	location	pycnocline depth (m)
CTD	3 July 1996	26°19′N, 121°15′E	25

The water depths of locations of nonlinear internal wave packets I and II are 200 m and 500 m, respectively. The relative difference of water density $\Delta\rho / \rho$ is known to be 0.001854 (Liang, et al., 1995).

4. Results

The distance $\Lambda = 2.9\times10^4$ m between leading waves of

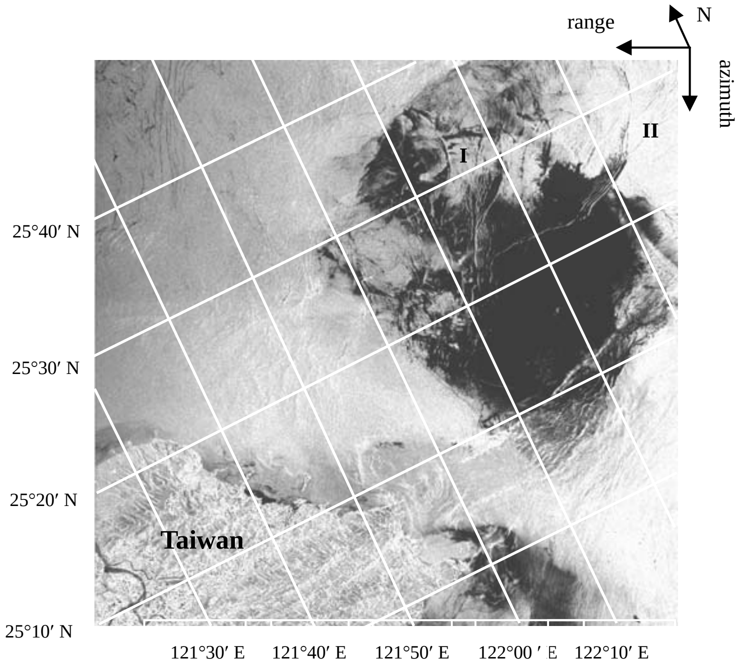

Fig. 1 ERS-1 SAR image showing internal waves in the northeast coastal waters of Taiwan on 23 July 1994. I and II are internal wave packets.

internal wave packets I and II is measured from SAR imagery. The pycnocline depth (h_1) in the position where internal wave packets I and II located are estimated from equations (9). They are listed in Table 2.

Table 2. Estimated pycnocline depth

	I	II	average
pycnocline depth (m)	26.3	24.0	25.2

The comparison between Table 1 and Table 2 shows that the estimated pycnocline depth (26.3 m and 24.0 m) of wave packets I and II and its average (25.2) agrees well to the measured pycnocline depth (25 m) in the same season.

5. Conclusion

It is possible to retrieve pycnocline depth remotely from SAR imagery when internal waves are visible, by using a model which is constructed by combining nonlinear internal wave model and two-layer ocean model and in the assumption of the internal wave packets on SAR imagery are generated by local semidiurnal tides with the same source.

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