Observations of high-frequency internal waves in the southern Taiwan Strait

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ABSTRACT

Based on in situ hydrographic measurements at a station of about 60 m depth near the local shelf break in July 2011 and a satellite image of the sea surface roughness, we present the evidence of existence and characteristics of high-frequency internal waves (HIWs) in the southern Taiwan Strait. Tidal variations of the thermohaline structure at the observational site were revealed by repeating Conductivity-Temperature-Depth (CTD) profiling measurements of every 2 hours, while fluctuations of the isothermals due to the passage of HIWs were recorded by continuous CTD measurements with a probe positioned approximately in the middle of the pycnocline. A fast sampling frequency of 8 Hz allows the structure of the HIWs being captured in great detail. The waves were depression waves, with a period of about 6.2 min and an amplitude of about 25 m. The propagation speed of the waves is estimated to be 0.56 m/s by solving the KdV equation with the observed background stratification. The frequent occurrence of HIWs in the Taiwan Strait is evidenced by the analysis of a MODIS true color image of the sea surface roughness. The possible generation mechanism of the HIWs is discussed based on a MODIS image and the perturbed KdV equation.

ADDITIONAL INDEX WORDS: high-frequency internal waves, internal tide, CTD data, MODIS true color image, perturbed KdV equation
1. INTRODUCTION

The Taiwan Strait (TWS) is a shallow channel connecting the South China Sea (SCS) and the East China Sea, playing a significant role in their water exchanges. The currents in the TWS include the coastal current, the SCS Warm Current extension and the occasional Kuroshio intrusion (Hu et al., 2010). The changes of these currents induce significant variations of thermohaline structures and water mass distributions.

The Taiwan Bank is located in the southern TWS immediately onshore of the local shelf break. Its topographic characteristics favor generation of high-frequency internal waves (HIWs) by tidal currents flowing over shallow banks in warm seasons as in many other seas with similar bathymetric features (Lee and Beardsley, 1974; Colosi et al., 2001; Duda et al., 2004). Meanwhile, the seasonal pycnocline supports the generation and propagation of HIWs in this area. The HIWs are high-frequency and usually large amplitude waves existing in stratified oceans. They affect both vertical and horizontal exchanges of mass, heat and energy, and they induce dramatic thermohaline structure changes as they propagate through the water column (Cai et al., 2008).

With the advance of satellite remote sensing technology, the HIWs in the coastal and shelf seas of China were frequently observed and reported. In particular, the HIWs were often identified in the northern SCS from Synthetic Aperture Radar (SAR) images (Zheng et al., 2001, 2007; Liu and Hsu, 2004; Zhao and Alford, 2006; Li et al., 2008a) and ocean color images (da Silva et al., 2002; Jackson, 2007; Ho et al., 2009; Cai et al., 2012). In addition, several international experiments, such as the ASIAEX
(Asian Seas International Acoustics Experiment), have concentrated on the generation, propagation and evolution features of the HIWs in the SCS (Liu et al., 2008). Meanwhile, the modeling of the HIWs in the SCS has also been conducted by several authors (see Simmons et al., 2011, for a recent review on the topic). However, to our knowledge, in situ observations of HIWs in the TWS have not been reported in the literatures. To this end, in this study, by using in situ hydrographic measurements at a station of about 60 m depth near the local shelf break in July 2011 and a satellite image of the sea surface roughness, we present the evidence of existence and characteristics of the HIWs in the southern TWS.

This paper is structured as follows. In Section 2, we describe the observational evidences of the HIWs in the southern TWS, which include the in situ hydrographic measurements and satellite observation. The analyses of the in situ measurements and the properties of the waves are presented in Section 3. Section 4 discusses the possible generation mechanism of the HIWs. We summarize our findings in Section 5.

2. OBSERVATIONS

2.1 In Situ Measurements

A group of HIWs was successfully recorded during a research cruise of the Xiamen University in July 2011. As shown in Fig. 1, the black dot is the position of St. A8, where the passage of large amplitude HIWs was captured by in situ hydrographic measurements. The mean water depth is about 60 m at the station. Time-series measurements of temperature and salinity profiles were conducted using a SeaBird
SBE 25 Conductivity-Temperature-Depth (CTD) profiler for about 42 hours. As a rule, one CTD cast was taken every 2 hours, and in total 22 hydrographic profiles were obtained from 01:10 UTC July 11 to 19:00 UTC July 12.

During data collections at St. A8, a photo of the sea surface was taken at 21:21 UTC (local early morning) on July 11, 2011 when a long well-defined heap of water apparently moving toward the research vessel was noticed (Fig. 2). It was judged to be the surface signature of the propagation of HIWs, and we thus immediately started an intensive field campaign by positioning a CTD probe at a depth of about 33 m, roughly in the middle of the pycnocline. The probe was set to work in a continuous mode with a sampling frequency of 8 Hz. The measurements lasted about 1 hour, and ended when there were no noticeable vertical fluctuations of isothermals any more. In addition, temperature and salinity profiles half an hour before the arrival of the HIWs were obtained with an MSS-90L microstructure profiler. These represent the pre-HIWs background stratification at St. A8, and will be used to estimate the propagation speed and amplitude of the HIWs.

Anticipating that HIWs may pass by St. A8 again after a semi-diurnal tidal period, we conducted similar continuous measurements 12 hours later, but no evident HIWs were observed. Hence, the following analysis focuses on the former continuous measurements.

2.2 Satellite Observation

Besides the in situ hydrographic measurements and visual experience on the sea
surface roughness, surface signatures of HIWs in the southern TWS were captured by a MODIS (Moderate Resolution Imaging Spectroradiometer) true color image taken at 05:15 UTC on July 8, 2010, making the analysis of the two-dimensional structure of HIWs possible. The spatial resolution of the image is 250 m.

The principle and application of the detection of HIWs in MODIS true color images have been described by Jackson (2007). Simply speaking, although HIWs are ocean's inner unrests, they modulate sea surface current and wave fields, and thus change the sea surface roughness that can be detected by satellite images (Liu and Hsu, 2004; Jackson, 2007; Li et al., 2008a).

It is a pity that there are no concurrent in situ and satellite observations of the same high-frequency internal wave packet, but this on the other hand suggests that the occurrence of HIWs in the southern TWS is not purely episodic, but may be in a frequent even periodic manner. Further discussions on this issue will be given in the following sections.

3. RESULTS

3.1 Variations of Thermohaline Structures

The temporal variations of the thermohaline structure interpolated from the 22 CTD profiles are shown in Fig. 3. A typical three-layer water column structure is evident: a thin upper mixed layer of about 8 m, a well-mixed bottom boundary layer of about 20 m, and a wide (about 30 m in thickness) pycnocline/thermocline/halocline in between. The surface-bottom temperature and salinity differences are about 9 °C
and 1.8, respectively. High temperature (> 28 °C) and low salinity (< 32.8) water is in the upper layer, while low temperature (< 21 °C) and high salinity (> 34.4) water is in the lower layers. It is evident from Fig. 3a that the thermocline is between 10 and 40 m depth. The half-day periodic fluctuations of the isotherms presumably due to semi-diurnal internal tides are also evident (Hu et al., 1999; Hu et al., 2003). Clearly, the variations of the temperature and salinity are highly correlated; increases in temperature corresponded to decreases in salinity, indicating that they were due to same processes, i.e. internal tides. As a result of the strong internal tides, the 21 °C isotherm elevates more than 20 m during half of a semidiurnal period (e.g., from 02:00 to 09:00) (Fig. 3a), while at the same time the elevation of the 34.4 isohaline was up to 25 m (Fig. 3b). Note that both isothermals and isohalines experienced an abrupt depression during 20:00-22:00 UTC on July 11, which is as shown in detail later due to the passage of a packet of HIWs. The sea surface signature of the waves is shown in Fig. 2.

3.2 Properties of the HIWs

A high sampling frequency of 8 Hz allows the passage of the HIWs being captured by the CTD measurements in details. To visualize local impacts of the internal waves, the time series of temperature and salinity at 33 m depth over the whole observational period are shown in Fig. 4. Data from the 22 regular CTD profiling measurements are labeled in circles and connected by a dashed line (Figs. 4a&b). The high-frequency variations of temperature and salinity from 21:05 to 22:09
UTC on July 11 are shown in Figs. 4c&d. Clearly, both temperature and salinity had dramatic variations during the 1 hour continuous observational period; the temperature ranged from 27 to 21 °C and the salinity ranged from 33.5 to 34.4. Evidently, the variations of temperature and salinity are highly correlated, suggesting that they were both due to the passage of the HIWs. The positive temperature anomaly (Fig. 4a) and corresponding negative salinity anomaly (Fig. 4b) induced by the waves suggest that the HIWs had induced downward displacements of the isothermals and isohalines. This means that the waves were depression internal waves.

Note that the decreasing trend of temperature (from 24 °C to about 21 °C) and increasing trend of salinity (from 34.0 to about 34.4) over the 1-hour period are presumably due to the upward recovery of the isothermals/isohalines after the passing of the trough of the leading big depression wave; the first half of the wave had already passed by the observational site before we started the continuous measurements.

\textit{a. Period of the HIWs}

From Figs. 4c&d, one can easily identify that there were 4 crests of the HIWs observed in the first 25 minutes of the 1 hour continuous measurements. Hence, the period of the HIWs is about 6.2 minutes. A more robust estimate from the Fourier-transform based spectral analysis (Emery and Thomson, 2001) gave a value of 6.4 minutes (385 s) (Fig. 5).
**b. Amplitude of the HIWs**

The perturbations of large-amplitude HIWs can induce large fluctuations of temperature and salinity. Therefore, the amplitude (wave height for harmonic waves, i.e. trough to crest distance) of HIWs ($\Delta Z$) can be calculated from CTD measurements at a fixed depth as (Apel et al., 1997)

$$\Delta Z_T = \frac{\Delta T}{R_T},$$  \hspace{1cm} (1-a)

$$\Delta Z_S = \frac{\Delta S}{R_S},$$  \hspace{1cm} (1-b)

where $R_T$ and $R_S$ are the vertical gradients of temperature ($T$) and salinity ($S$) at the measurement depth, i.e. $R_T = \frac{\partial T}{\partial z}$ and $R_S = \frac{\partial S}{\partial z}$, and $\Delta T$ and $\Delta S$ are the amplitudes of temperature and salinity fluctuations.

To get an accurate estimate of $\Delta T$ and $\Delta S$ from the continuous CTD measurements by the probe positioned nominally at a fixed depth (about 33 m), we need first to remove the temperature and salinity fluctuations due to depth changes of the probe. As expected, the depth changes were found to be pretty small (about 2 m), and their contributions to the observed temperature and salinity fluctuations were removed by a linear approximation of CTD profiles around the probe's mean depth. In addition, the decreasing trend of temperature and the corresponding increasing trend of salinity presumably due to the recovery process of the passed leading wave need also to be filtered out (Fig. 4). The maximum fluctuations $\Delta T$ and $\Delta S$ were then estimated as 4.5 °C and 0.6, respectively. On the other hand, based on the background thermohaline structures shown in Fig. 6, the vertical gradients of temperature and
salinity $R_T$ and $R_S$ were estimated as 0.2 °C/m and -0.026 /m, respectively, with a linear approximation of the CTD profiles. Taken together, the amplitude of the HIWs $\Delta Z$ was estimated to be about 25 m.

c. Propagation Speed of the HIWs

To estimate propagation speed of the HIWs, we solve the KdV equation with the observed background stratification. To do this, the realistic density profile was approximated by an equivalent two-layer water column structure following the methodology of Li et al. (2008b). Let $h_1$ and $h_2$ be the thickness of the upper and lower layers of the water column, respectively, the quadratic one-dimensional KdV equation has the following form (Jackson, 2009)

$$\eta_t + c_0 \eta_x + \alpha \eta \eta_x + \beta \eta_{xx} = 0, \quad (2)$$

where $\eta(x, t)$ is the vertical waveform, $c_0$ is linear long-wave phase speed, and $\alpha$ and $\beta$ are the coefficients of nonlinearity and dispersion, respectively. Expressing with the layer thickness $h_1$ and $h_2$ and the density, these parameters are given by

$$c_0 = \left(\frac{g \Delta \rho}{\rho h_1 h_2}\right)^{1/2}, \quad (3)$$

$$\alpha = \frac{3}{2} \frac{c_0 (h_1 - h_2)}{h_1 h_2}, \quad (4)$$

$$\beta = \frac{c_0 h_1 h_2}{6}, \quad (5)$$

where $g$ is the acceleration due to gravity, $\rho$ is the averaged density and $\Delta \rho$ is the density difference between the two layers. The propagation speed of the solitary internal waves is
Here, the CTD data collected half an hour before the arrival of the HIWs were used for the calculation. The background thermohaline structures are shown in Fig. 6, based on which the upper and lower layer thickness of the equivalent two-layer water column was estimated to be 10 m and 50 m, respectively. The corresponding densities were 1020.5 kg/m$^3$ and 1023.0 kg/m$^3$, respectively. Substituting these values into the above equations, the linear long-wave phase speed was estimated to be 0.45 m/s, and the propagation speed of the HIWs was 0.56 m/s. The eigen-solutions of the Strum-Liouville equation (Phillips, 1977), which is valid for weakly nonlinear waves, gave an almost identical value of 0.55 m/s.

4. DISCUSSION

In the last section, we have described the \textit{in situ} observations of internal tides and HIWs at a station of about 60 m depth near the local shelf break in the southern TWS. In particular, the properties of the HIWs were estimated based on the continuous CTD measurements at a fixed point in the pycnocline. The following questions naturally emerge: where were these waves from? How were they generated? Are they related to the observed internal tides? Here below we try to answer these questions by analyzing a MODIS true color image and conducting a dynamical analysis on the generation mechanism of HIWs based on the perturbed KdV equation (Newell, 1985; Zheng et al., 2007).
4.1 Insights from a MODIS True Color Image

As mentioned in Section 2, surface signatures of HIWs in the southern TWS were captured by a MODIS true color image taken at 05:15 UTC on July 18, 2010 (Fig. 7a). In Fig. 7b, the internal wave packets evident in the Fig. 7a are shown by red lines, which are very close to the observational site A8 represented by a red dot. This coincidence of location means that they should be the same phenomenon at different time. To have a look at the detailed structure of the internal wave packets in the MODIS image, in Fig. 7c we plot the variations of gray scale along the cross-topography red line shown in Fig. 7a. It can be seen that the wave packet consists of a leading wave with the largest amplitude followed by trailing waves with decreasing amplitudes. With respect to the in situ observations at St. A8 (Figs. 3&4), it is plausible to presume that the observed HIWs are the trailing waves with smaller amplitudes, while the upward movement trend of isothermals and isohalines was due to the passage of the leading wave. It seems from Fig. 3 that only the second half (or even less) of the leading wave was captured by the continuous CTD measurements. The upward movement trend of the isothermals and isohalines that is evident in Fig. 4 was in fact a result of the recovery process after the passage of the leading wave trough.

4.2 Dynamical Analysis on the Generation of HIWs

Following the work of Zheng et al. (2007), a dynamical analysis on the generation of the HIWs may be conducted based on the perturbed KdV (PKdV)
equation,

$$q_t + 6q q_x + q_{xxx} = -\frac{9}{4} \frac{D}{D} q,$$

(7)

where $q$ is the amplitude of the soliton, $\tau$ is a related distance coordinate, and $\theta$ is the retarded time. $D = l + H(x)/h_0$ is a nondimensional depth, where $h_0$ is the maximum water depth and $-H(x)$ is the height of topography. The subscripts represent partial differentials.

The solutions of (7) can be expressed as

$$q(\theta, \tau) = q^{(0)} + \sigma q^{(1)} + \ldots$$

(8)

which represents a leading soliton (the zero-order solution $q^{(0)}$) with a smaller oscillatory tail (the first-order solution $q^{(1)}$). More details on the equations can be found in Zheng et al. (2007).

To study the generation of HIWs due to the shoaling of bottom topography, similar to the case of Zheng et al. (2007) for the shoaling of pycnocline in the open ocean, we have configured a physical model as shown in Fig. 8, where the location of St. A8 is shown with a red dot. Noticing that the depth of pycnocline is about 40 m, the maximum water depth was chosen as 160 m. The parameters determine the solution of the PKdV equation adopted the following values, $\epsilon = 0.01$, $t = 0$, $\theta = 3$, $\bar{\theta} = 15$, $\sigma = 0.5$, $\eta = 0.4$, $\Gamma = 0.36$, which were chosen to best represent realistic conditions at St. A8 and the adjacent regions.

The solution of the PKdV equation under the above conditions is shown in Fig. 9 in the form of spatial wave structure. For comparison, the time series of the isopycnal fluctuations at St. A8 were transformed to spatial structures with the propagation
speed estimated in Section 3.2. It can be seen that in general the theoretical model can reproduce the main structure of the observations, suggesting that the observed HIWs may have been generated from the interactions of internal tides and the shoaling bottom topography. However, the validity of this hypothesis needs further observational evidence.

5. SUMMARY

In this paper, we reported the *in situ* document of high-frequency internal wave activities in the southern TWS. The measurements were conducted at a station about 60 m depth near the local shelf break in July 2011. Twenty two CTD casts separated by 2 hours from each other were taken to obtain the mean and temporal variations of the thermohaline structure due to internal tides, while 1-hour continuous CTD measurements with a probe mounted at a fixed depth in the pycnocline were conducted to study properties of the HIWs. A fast sampling frequency of 8 Hz allows the structure of the HIWs being captured in great detail. The waves were found to be depression waves, with a period of about 6.2 min, an amplitude of about 25 m, and a propagation speed of about 0.56 m/s. The HIWs are thought to occur frequently (and maybe in a periodic manner) and presumably generated by the interactions of the internal tides and the shoaling of bottom topography, based on an analysis of a MODIS true color image and dynamical analysis with the PKdV equation.
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LITERATURE CITED


Figure Captions:

Fig. 1. The location of the observational station. The St. A8 is shown with a black dot.

Fig. 2. A snapshot of the sea surface at St. A8. The red arrow points to the observed heap of water. (Photo taken on R/V Yanping 2 by the second author)

Fig. 3. Time-depth variations of temperature (a) and salinity (b) at St. A8. The temperature is shown in °C.

Fig. 4. The time series of temperature (a&c) and salinity (b&d) at 33 m depth at St. A8.

Fig. 5. Power spectrum of the temperature (a) and salinity (b) during 21:05-22:09 UTC on July 11. The data were collected from the continuous CTD measurements at 33 m depth, with a sampling frequency of 8 Hz. The dashed line shows the 95% confidence level.

Fig. 6. Background thermohaline structures at St. A8 before arrival of the HIWs (a) Temperature (T) and salinity (S), (b) specific potential density (σθ) and buoyancy frequency (N).

Fig. 7. (a) A part of a MODIS true color image in the Taiwan Strait acquired on 18 July 2010 at 05:15 UTC (the region is shown with a red box in Fig. 1). Internal wave packets are visible in the middle of the image. (b) Bathymetry of the image region. The internal wave packets are shown with red lines. (c) The variations of gray scale along the red line shown in (a).

Fig. 8. A schematic of the physical model for the generation of HIWs on the continental shelf of the Taiwan Strait. The y-axis is upward positive, and the x-axis is cross-isobath positive from the deeper region to the shallower region. The location of St. A8 is shown with a red dot.

Fig. 9. A comparison of the PKdV equation solutions with the in situ observations at St. A8. The red line represents theoretical solutions, the blue line is the 1-hour high frequency continuous measurements, and the blue open circles are the CTD profiling data collected about half an hour before arrival of the HIWs.
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Fig. 2 A snapshot of the sea surface at St. A8. The red arrow points to the observed heap of water. (Photo taken on R/V Yanping 2 by the second author)
Fig. 3 Time-depth variations of temperature (a) and salinity (b) at St. A8. The temperature is shown in °C.
Fig. 4 The time series of temperature (a&c) and salinity (b&d) at 33 m depth at St. A8.
Fig. 5 Power spectrum of the temperature (a) and salinity (b) during 21:05-22:09 UTC on July 11. The data were collected from the continuous CTD measurements at 33 m depth, with a sampling frequency of 8 Hz. The dashed line shows the 95% confidence level.
Fig. 6 Background thermohaline structures at St. A8 before arrival of the HIWs. (a) Temperature ($T$) and salinity ($S$), (b) specific potential density ($\sigma_\theta$) and buoyancy frequency ($N$).
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