Internal wave depiction in Lake Maninjau from high frequency temperature data

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Abstract. Water column of Lake Maninjau has a thermal stratification which sensitive to varying conditions of weather variables, especially to wind forcing. When water column stratified, wind forcing will initiate an internal wave generation in water column. Internal wave has a significant role in physical, chemical and biological processes in lakes. The aim of this study was to illustrate the internal wave in Lake Maninjau. Temperature data and wind speeds were collected from environmental monitoring and warnings system (e-most) device and weather stations of UPT LATPD Maninjau, respectively. The observation periods were conducted for 10 days (April, 1-10 2017). Strong stratification significantly appears in the beginning of observation period. Internal wave drawn from the temperature oscillations at a depth of 1, 9, 14 and 25 m with a vertical V$^2$/H$^1$ mode. Our analysis showed that internal waves resonate with wind speed at the frequency of 6.9 x 10$^{-3}$ cyc/minutes (23.9-h period).

1. Introduction

Internal waves play a significant role in physical, chemical and biological processes in the water column because these are the primary energy source for driving material transport in lakes [1,2]. The presence of internal waves cannot be seen by the naked eyes but can be detected by measurements with an ADCP (Acoustic Doppler Current Profiler), thermistor chains and satellite imagery (SAR image). Internal waves are included in the non linear wave because their propagation speed is affected by amplitude. This wave is commonly known as internal solitary which is found in oceans, estuary, and lakes that are thermally stratified [3]. The amplitude of internal waves is usually greater than surface waves, it can reach up to 10 m high [4].

In stratified water bodies, internal waves are generated by the small part of the mechanical energy of the wind that was transferred to the water body [5,6]. The internal waves set up to oscillate when the wind forcing relaxes. Internal waves are like standing waves that oscillate in a fixed space that has two nodal points, i.e., node and antinode. Figure 1 shows the type of internal wave modes. Internal waves can be divided into different categories, based on the number of nodal points (V,H$_{ij}$), where i and j represent a vertical (V) and horizontal (H) nodal, respectively [7]. The most commonly observed wave mode is V$_1$H$_1$, which this mode represents that both of the nodal vertical and horizontal are one. This kind of mode is commonly generated when the metalimnion layer is thin and the thickness of the metalimnion is assumed...
to remain constant [5]. However, the dynamics of water layers result in the appearance of higher vertical modes. For instance, the second vertical mode ($V_2H_1$) is attributed to a change of thickness of the metalimnion layer, where the epilimnion and hypolimnion oscillate against one other vertically (figure 1.B) [8]. The water column with more layers leads to the appearance of even higher vertical modes [5,8].

Internal wave generation could affect lake ecosystem through mixing processes which can influence nutrient and organisms transport. Previous study has demonstrated that the internal waves could affect the distribution of organisms in the water body [10]. It also contributes to sediment resuspension in the benthic boundary layer [11].

The study of internal waves in Indonesian lakes is rarely carried out. Studying the internal waves provides a better understanding of several processes in the lake, such as the distribution of different organisms, molecules and physical factors that control the water quality in the lake [10,11]. For example, it has been reported that internal waves triggered the internal loading transfer to the epilimnion in stratified lakes which has the potential to increase cyanobacterial blooms [12,13]. This process occurs because internal waves induced the bottom current that contribute to the mixing and resuspension of sediments in the bottom layer [11]. Therefore, characterization of internal waves becomes important, because it has potential to influence the water quality of the lake. This study aimed to provide a general depiction of internal waves in Lake Maninjau, a stratified eutrophic lake in Indonesia. This study is limited to a simple depiction of internal waves derived from temperature profile oscillations and wind speed oscillations.

![Figure 1. Oscillation modes of internal waves](image)

A) first vertical mode $V_1H_1$, B) second vertical mode $V_2H_1$, C) third vertical mode $V_3H_1$ [9].
2. Materials and Methods
The study was conducted in Lake Maninjau, Agam district, West Sumatera Province (0°19’S, 100°12’E) for ten days (1-10th April 2017). The total area of the Lake is 99.5 km² with the length and width are 17 km and 8 km, respectively. The maximum depth is 165 m and the average depth is 105 m. The temperature profile of the water column was measured by a set of thermistor chain placed at a two meter intervals from 0.5 to 62 m depth. The thermistor provides temperature data in ten minutes intervals over ten days measurements. The thermistors were installed on a monitoring buoy; On-Line Monitoring (OLM) at Koto Melintang Station (0°16.373’S, 100° 9.849’E). Wind speed was recorded by a weather station at Loka Alih Teknologi Penyehatan Danau (LATPD), Research Center for Limnology. The distance of the OLM to the weather station is around 5.74 km.

![Figure 2. Lake Maninjau in Sumatra Island of Indonesia. The location of the OnLine Monitoring System (OLM) and weather station (UPT LATPD) are shown by the red dot and blue star, respectively.](image)

We quantified physical indices of the lake, i.e.: thermocline depth, stratification index, wind stress and power spectral density of internal wave. Thermocline depth (m) was defined as the depth of the maximum vertical temperature gradient of the water column [14] Stratification index (Jm⁻²) is a potential energy to prevent the mixing of the water column [15]. When the water column is completely mixed, stratification index is equal to zero (SI = 0), while in the more stratified water column the SI is more positive and the water column is difficult to mix. Wind stress (Nm⁻²) was quantified to identify the effect of wind forcing on
thermal stratification. Power spectral density for wind \((m^2 s^{-2} \text{cycle.min}^{-1})\) and temperature \((\text{°C}^2 \text{.cycle.min}^{-1})\) were calculated to highlight the evolution of periodicities in wind forcing and temperature oscillation. The thermocline depths were computed by \textit{rLakeAnalyzer} [16]. Stratification index and wind stress (eq. 1 and eq. 2) were calculated following [15] and [17]. A Fast Fourier Transform technique [18] was applied to compute power spectral density.

\[
SI = \int_{-h}^{0} \left( \rho - \langle \rho \rangle \right)gzdz,
\]

(eq. 1)

\[
\langle \rho \rangle = \frac{1}{h} \int_{-h}^{0} \rho dz
\]

\[
\tau = \rho_a C_{10} v_{10}^2
\]

(eq. 2)

Where:
- \(SI\): Stratification index \((\text{J.m}^{-2})\)
- \(\rho\): water density \((\text{Kg.m}^{-3})\)
- \(h\): depth of water column \((\text{m})\)
- \(g\): gravity acceleration \((9.8 \text{ m.s}^{-2})\)
- \(\tau\): wind stress \((\text{N.m}^{-2})\)
- \(\rho_a\): air density \((\text{Kg.m}^{-3})\)
- \(C_{10}\): drag coefficient
- \(v_{10}\): wind speed at a height of 10 m \((\text{m.s}^{-1})\)

3. Results and Discussion

3.1. Temperature profiles of water column

Figure 3A shows that the water column of Lake Maninjau has diurnal stratifications during the observation period with vertical temperature of upper layer at the beginning was higher than that at the end period. This is consistent with the previous studies that the water column has a diurnal stratification [19]. The water column stratification is characterized by the configuration of isotherm layers that appears to a depth of 30 m, meanwhile, the water column temperature below 30 m becomes homogeneous. Figure 3A shows that the number of isotherm layers in the last five days are less than in the first five days. This indicates that the water column in the last five days was less stratified than the first five days. These conditions were triggered by the combination of the sensible heat and wind stress that intensively to declined and peaked up in the last observation periods, respectively (figure 4). The increase of wind stress also pushed the thermocline down to a deeper layer in the water column (figure 3.B).
Figure 3. A. Temperature profiles in the water column, B. Daily thermocline depth.

Variation of the absorbed solar radiation and the wind forcing on the water surface lead to the diurnal stratification on the water column [20,21]. The strength of stratification is characterized by stratification index that related to the stability of lake. Figure 4.A indicates the stratification of the water column and wind stress on surface water, while figure 4.B shows the average of sensible heat that characterized the heat exchange between surface water and the air. Our results show that the values of SI vary daily and tend to slightly decrease, while the wind stress started to increase in the last two days observation (figure 4.A). Although the wind stress peaked up at the last two days, the SI has been started to decline since the 7th day. This is due to the heat from the lake being more intensively transferred to the air, which is characterized by the sensible heat that more negative on the 7th and 8th day (figure 4.B). These factors provide a physical force to destratify the lake. Due to the water column is stratified during the observation period, the appropriate wind stress will probably initiate the internal wave in the stratified water layers.
Figure 4. A. Stratification index and wind stress in Lake Maninjau, B. The average of sensible heat into lake

3.2. Oscillation modes of Internal Waves
Vertical structure depiction of the internal waves can be obtained by comparing the temperature data recorded from each thermistor. As each thermistor is fixed with water depth, time series of temperature oscillations at each depth can be depicted (figure 5). We used this information to draw internal wave generation. Thermistors at depth of 1 m, 2 m, 9 m, 14 m, and 24 m were used in this respect.

Based on the maximum and minimum amplitude of temperature oscillations, the temperature oscillation at 1 m and 2 m depth are in the opposite phase compared to the temperature oscillation at 9 m, 14 m, and 25 m depth. These opposite vertical directions indicate vertical displacements of the two interface layers. It is likely that internal wave Lake Maninjau is vertical V2H1 mode (figure 5). However, due to the oscillation amplitude was very small as the temperature at the deeper layers was stable, we were not able to identify the internal wave at the deeper layer.
Figure 5. Oscillation modes of internal waves in Lake Maninjau.

To gain a better understanding of the different temperature oscillation, we performed cross-covariance analysis of temperature time series data of the thermistors at 1 m, 9 m and 14 m (figure 6). The cross-covariance of the temperature at 1 m and 9 m was negative for $t = 1$ day, $t = 2$ day, $t = 3$ day and so on, while at 9 m and 14 m it showed positive results. These indicate that the temperature oscillation at 1 m is in different phases compared to that at 9 and 14 m.

Figure 6. Cross covariances for different time series temperature at 1 and 14 m in depth, temperature at 9 and 14 m in depth.
Figure 7 represents the power spectra of wind speed and temperature resulted from the analysis of time series of wind speed and temperature data at 1 m. Figure 7.A shows that the peak around of $6.9 \times 10^{-3}$ cyc/minutes (period = 23.9-h) and $9.04 \times 10^{-3}$ cyc/minutes (period = 18 h) appear in the oscillation of wind and temperature (figure 7.B). We attribute the peak of 23.9-h period to mode $V_2H_1$ and correspond with figure 5 and 1.B. However, the peak around 18 h that also appears in those of two power spectra does not correspond with the oscillation modes in figure 5. This peak is probably the $V_1H_1$ mode. Whereas, the peak around 12 h at temperature oscillation does not have a corresponding peak in the wind; this peak is probably the water column’s response to a subdaily wind pattern [5]. The peak energy in the mode $V_1H_1$ is lower than the peak energy in the mode $V_2H_1$, this is likely due to the mode $V_1H_1$ is damped by the mode $V_2H_1$ that resonates with the highest energy of wind [5]. However, a further detailed research needs to be done to explain other internal wave modes at Lake Maninjau.

4. Conclusion
Internal waves at Lake Maninjau are drawn from temperature oscillations in stratified layers of water columns. The formed internal wave has a vertical $V_2H_1$ mode with a frequency that resonates with the frequency of the wind.

5. References
[1] Sakai T and Redekopp L G 2009 A Nonlin. Process. Geophys. 16 487–502
[2] Fricker P D and Nepf H M 2000 J. Geophys. Res. 105 14273–14251
[3] Febrianto Y, Akman and Hidayati 2014 Pillar Phys. 4 41–48
[4] C. R. Goldman and A. J. Horne 1983 Limnology United States of America: McGraw-Hill, Inc,
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