Relationship of mixed layer depth and sea surface temperature on longwave radiation flux up in the west of Sumatra waters

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Abstract. Thermal energy which stored in upper ocean mixed layer will be released in the form of longwave radiation flux up (LWUp). LW Up is a longwave that emitted from sea surface to atmosphere. Variability of upper ocean mixed layer has influence on ocean thermal capacity and then affected LW Up variation. The area of interest of this research was west of Sumatra waters. Vertical temperature profiles, sea surface temperature (SST) and LW Up data from 2000 to 2015 were used. Mixed layer depth (MLD) was computed by Threshold Method based on temperature profiles with 0.31°C temperature criterion. The results show high LW Up flux occur during shallow MLD and low LW Up occur when MLD become deeper. Correlation between SST and LW Up give a fine value about 0.9 in all station. Good correlation coefficient between MLD and LW Up found in station 1 (-0.81) and 9 (-0.77) with 1 month lag. This results suggest that shallow (deep) MLD followed by high (low) SST so that the result is increase (decrease) LW Up by 1 month lag. Small correlation between MLD and LW Up found in area near equator region. Indian Ocean circulation, westerly wind, and Wyrtki jet are possibly causing the small correlation in equator region.

1. Introduction

Solar energy reaching earth surface is stored temporarily in upper ocean layer or ocean mixed layer as thermal energy. Thermal energy released mostly as latent heat by evaporation, followed by net longwave flux radiation (hereafter net LW) and then as sensible heat by conduction [1]. Net LW consists of longwave radiated from ocean surface to the atmosphere called LW Up and longwave radiated from atmosphere to ocean surface called LW Down which is compute as the difference between LW Up and LW Down [2]. Many literatures discuss about longwave in form of net LW even though LW Up has important role and become a main source for atmosphere to emitted LW Down.

The amount of LW Up emitted depend on ocean surface temperature. If strong diurnal cycle of sea surface temperature (hereafter SST) in top few meters of the ocean was neglected, LW up depend on mixed layer temperature. Ocean mixed layer is a layer that have homogenous temperature, salinity, and density vertically. This homogenous layer results from active vertical-mixing near the surface, promote by various processes like wind-stirring, wave, turbulence generation by vertical shear or night time convective mixing [3]. Mixed layer depth (MLD) variability influence ocean heat capacity that will affect SST and LW Up. Shallow MLD exhibits a reduced thermal capacity and can hence promote
large SST anomaly otherwise deep MLD exhibits an increased thermal capacity so that SST will remain stable to some perturbation [4]. Shallow MLD which cause heating of the atmosphere dominated by surface energy flux (latent and longwave flux) whereas the heating dominated by shortwave absorption within the atmospheric column in the deep MLD condition [5].

Considering the linkages between MLD, SST and LW Up, a preliminary research was conducted. The objective of this research is to gain understanding about the relationship between MLD, SST, and LW Up. The paper is organized as follows: a brief description of research and data in section 2. Section 3 deals with methodology used to compute MLD and cross correlation. Section 4 deals with results and discussion. Conclusions are presented in section 5.

2. Research area and data source

The research area of interest was west of Sumatra waters from 79°E to 101°E and 16°N and 9°S which divided into 10 study areas (see figure 1). All study areas located in a tropical basin and forced by semi-annually reversing wind system, the monsoon. The surface circulation also reverse semi-annually like wind, however it is not strictly but appears to lead it.

![Figure 1. Research area and data positions.](image)

For the purpose of these research, 79,709 observation vertical temperature profiles have been used. Temperature profile from Research Moored Array for African – Asian-Australian Monsoon Analysis and Prediction (RAMA), Argofloat and World Ocean Data (WOD) were sampled with an area 2°×2° where RAMA buoy position as a center. The monthly 1°×1° gridded Optimum Interpolation Sea Surface Temperature (OISST) data are obtained from National Oceanic and Atmospheric Administration (NOAA). Monthly longwave flux Up is obtained from Clouds and Earth’s Radiant Energy System Project (CERES) with resolution 1°×1° gridded. All data 2000 through 2015 were used in this research.

3. Methodology

3.1. Mixed Layer Depth

Daily average vertical temperature profiles was used to calculate MLD. MLD was calculated using Threshold Method base on temperature [6]. Temperature criterion used in this research is \( \Delta T = 0.31^\circ C \). Threshold method give more stable MLD value than gradient method [7].
In threshold method, MLD calculate based on temperature difference ($\Delta T_{\text{cal}}$) between temperature in certain depth ($T_{\text{depth}}$) and reference temperature ($T_{\text{ref}}$). $\Delta T_{\text{cal}}$ is calculated by following equation:

$$\Delta T_{\text{cal}} = \left| T_{\text{depth}} - T_{\text{ref}} \right|$$

(1)

then, $\Delta T_{\text{cal}}$ compared to temperature difference reference ($\Delta T_{\text{ref}}$). In this research, $\Delta T_{\text{ref}} = 0.31^\circ$C is used. If $\Delta T_{\text{cal}} \geq \Delta T_{\text{ref}}$ then depth in $T_{\text{depth}}$ was a mixed layer depth. Reference temperature ($T_{\text{ref}}$) used in this research is temperature at 10 meter from surface. Utilization temperature at 10 meter depth was intended to avoid daily cycle of surface water temperature [6].

3.2. Correlation

Cross correlation was used to calculate relationship between MLD, LW Up and SST with some lag time. Cross correlation coefficient calculated by [8]:

$$r_{xy} = \frac{C_{xy}(\tau)}{\sigma_x \sigma_y}$$

(2)

where $r_{xy}$ is cross correlation function, $C_{xy}(\tau)$ is cross covariance, $\sigma_x$ and $\sigma_y$ are standard deviation of parameter $x$ and $y$. The next step is calculated Z score to figure out if results from a test are valid or not. Z score is calculated by:

$$Z_{\text{score}} = r \sqrt{N - 1}$$

(3)

where $r$ is correlation coefficient and $N$ is number of data. Last step is Z score compared with Z analytic ($\pm 1.96$ for 5% two tailed). If Z score greater than Z analytic, it means the cross correlation coefficient is valid and the relationship can be accounted.

4. Results

Monthly climatology of mixed layer depth, sea surface temperature and LW Up radiation are shown in figure 2 below. LW Up in east equator zone (St 5 to St 7) has minimum (maximum) value about 469 W/m$^2$ (477 W/m$^2$) while SST value is 28.7°C (30°C) and MLD value is 70 meter (41 meter). Minimum condition happened in southwest monsoon (June – September) and maximum in northeast monsoon (December – March). For north zone, minimum (maximum) value of LW Up about 456 W/m$^2$ (478 W/m$^2$) which happen while SST value is 26.3°C (30°C) and MLD value is 80 m (28 m). Minimum condition happened in northeast monsoon while maximum in transition 1 (April – May). For south zone, minimum (maximum) value of LW Up about 460 W/m$^2$ (475 W/m$^2$) which happen while SST value are 27°C (29.2°C) and MLD value are 60 m (28 m). Minimum condition happened in southwest monsoon while maximum in transition 1.

From description above, it appears that LW Up maximum occurs while MLD become shallow and LW up minimum occurs in deep MLD condition. Shallow MLD exhibits a decrease thermal capacity so that SST increase more rapidly as a result of solar energy absorption. High SST means that ocean has excess energy and must release it, one of them as LW Up to achieve the equilibrium state. Deep MLD exhibits an increase thermal capacity. It makes ocean need to absorbs more energy to increase SST by 1°C. At this time, SST has decrease and followed by the decreasing of LW up too.
Figure 2. LW Up (above), SST (middle) and MLD (below) monthly climate from 2000 – 2015 in north zone, east equator zone and southeast zone.
Variation of SST and MLD in Indian Ocean depend on monsoon system, water column stability and ocean circulation. MLD and SST in east equator zone mainly affected by equatorial circulation and Wyrtki Jet. Equatorial current that moving eastward throughout the year, will accumulate water in the eastern equatorial Indian ocean and causing mean MLD in equator zone is deeper compared to north and southeast zone. In transitional season, the Wyrtki jet accumulate more warm water the east so that make MLD become deeper and SST higher during 2 to 3 month. For southeast zone, southwest monsoon lead upwelling along south coast off java and moving westward to Indian Ocean and west coast of Sumatra. Strong wind and cold water weaken the water column stability and cause MLD to become deeper. This condition cause ocean emit less LW Up radiation. Meanwhile in northeast monsoon, weak wind and warm water which carried by equator current and Wyrtki Jet from equator increasing SST and make MLD become shallow. At this time, sun position in the southern hemisphere contribute to increase the SST. This condition lead to increasing of LW up radiation. For north zone, southwest wind that stronger than northeast wind are lead to a deeper MLD while cold water from coastal upwelling in the north of St 1 that move southward in northeast monsoon make water column unstable so that MLD is deeper. Deeper MLD with cold SST weaken LW up radiation. Meanwhile in transitional season, weak wind and warm water input from equator carried by Wyrtki Jet to Bengal Bay lead to shallow MLD and increasing of SST. It makes ocean emit more LW up radiation to the atmosphere.

Table 1. Correlation coefficient between MLD, LW up and SST in 10 stations in Indian Ocean. $r = \text{correlation coefficient}$

| Zone   | Station | MLD and LW Up | SST and LW up |
|--------|---------|---------------|---------------|
|        |         | $r$    | $Z$ (month) | $r$ | $Z$ (month) |
| North  | St 1    | -0.81  | -8.06  | 0  | 0.97 | 9.65  | 0  |
|        | St 2    | -0.77  | -6.11  | 1  | 0.97 | 7.70  | 0  |
|        | St 3    | -0.55  | -3.30  | 0  | 0.92 | 5.52  | 0  |
|        | St 4    | -0.57  | -5.44  | -1 | 0.96 | 9.16  | 0  |
|        | St 5    | -0.48  | -5.10  | 1  | 0.97 | 10.31 | 0  |
| Equator| St 6    | -0.38  | -3.89  | -1 | 0.97 | 9.94  | 0  |
|        | St 7    | -0.45  | -5.11  | 1  | 0.96 | 10.90 | 0  |
|        | St 8    | -0.48  | -5.58  | -1 | 0.94 | 10.92 | 0  |
| Southeast| St 9  | -0.77  | -6.30  | -1 | 0.91 | 7.45  | 0  |
|        | St 10   | -0.64  | -4.87  | 0  | 0.91 | 6.93  | 0  |

Cross correlation coefficient between SST and LW up shown in Table 1. All station shown strong relationship with coefficient greater than 0.9 and 0 month lag time. Positive coefficient mean that LW up emitted from ocean surface depend on its temperature. High SST make ocean emit LW up and vice versa. Zero month lag time mean that response of temperature change to LW up variation take a short time.

Cross correlation coefficient between MLD and LW up shown in Table 1. The coefficient varies from -0.38 to -0.81 with Z calculation greater than Z analytic. Negative coefficient mean that deeper MLD followed by decrease of LW flux up and shallow MLD followed by increase of LW up flux. Deep MLD has larger thermal capacity than shallow MLD. It makes ocean must absorb more energy to increase the temperature by 1°C. The result is ocean will emit lesser LW up flux in deep MLD than in shallow MLD condition. Based on Table 1, stations further from equator have higher correlation coefficient than station near equator. It explains that variability of LW Up in equator is not strongly affected by MLD. Equatorial circulation and Wyrtki jet are possibly the causes of this small value. Lag time calculation give negative and positive results with range 1 month. Positive value indicate
that change of LW Up happen first before change of MLD while lag time negative mean change of MLD happen first before LW up change. Lag time zero mean that MLD or LW up change followed by other parameter change in short time.

5. Conclusion
From this preliminary research, it can be conclude that LW Up in Indian Ocean has strong relationship with SST in all study area. It mean that warm water emit more longwave to the atmosphere than cold water. LW Up and MLD has strong relationship in area far from east equatorial Indian Ocean while weak correlation seen in east equator zone. SST and MLD which influence LW Up variability are driven by wind induce current that transport warm or cold water into or out of the study area.

Acknowledgement
This result is part of research activity “The Ocean Current System of Indonesian Waters and its effects on Marine Fisheries Production” funded by Research and Innovation, Bandung Institute of Technology 2017.

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