Sensible heat transfer on atmospheric-oceanic boundary in the outer Ambon Bay of Indonesia

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ABSTRACT

Analysis of air-sea temperatures and sensible heat flux was conducted to investigate heat transfer process on the atmospheric-oceanic boundary for the outer Ambon Bay. The analysis used SST data derived from both satellite product and *in situ* measurement using linear regression method, as well as meteorological data such as air temperature and wind speed during daytime. The goals of the current work were to evaluate the relationship between SST and air temperature in the outer Ambon Bay, and to investigate the variation of sensible heat flux in association with seasonal variability of the bay. The major findings were: 1) SST was predominantly lower than air temperature, resulting in the dominance of negative feedback process on the atmospheric-oceanic boundary layer of the bay; 2) the seasonal SST variability was influenced by land heating and upwelling in the Banda Sea; 3) land heating resulted in large gradient of air-sea temperatures, whereas cooler upwelled waters exerted an opposite effect.

Keywords*:* atmospheric-oceanic boundary, SST, air temperature, heat flux, Ambon Bay.

INTRODUCTION

The outer Ambon bay is located along the coasts of Ambon city, the capital of Moluccas Province in Indonesia. It faces Banda Sea, the deepest sea in the Indonesian archipelago. Since the population has increased in Ambon city from 1961 to 2010 (the latest population census by BPS, 2010), there are many activities on land which give influence to seawater environment of the bay (Pelasula, 2008). Deforestation of the upper land in the city converts the forests to residential areas (Pelasula, 2008) and creates new business areas. These main developments in the city are required to meet demand for more space for the growing population and economy. However, it contributes to the increase in air temperature of the urban atmosphere which is commonly referred as the urban heat island (UHI) (Ichinose et al., 1999; Yap and Oke, 1974; Yoshikado, 1992; Hua et al., 2008). Recently, Basit et al. (2008) reported that the increasing of dense populated areas may give impacts on the environment of the bay, such as increasing sea surface temperature (SST) and salinity (SSS). Furthermore, air-sea interaction near the urban area is thought to be important for the local-climate where heat transfer between land and sea takes place. Previous studies have reported how land-sea heat transfer influences the weather on the urban area near Tokyo Bay (Yoshikado,1992; Fujibe, 2003; Kobayashi et al., 2007). As an implication of these studies, it is important to investigate air-sea interactions, over the outer Ambon Bay, which includes the influence of UHI effect. In addition, the outer Ambon Bay is also influenced by cooling due to upwelling of cool waters in Banda Sea (Wyrtki, 1961) associated with the Asian monsoon (June, July, August, and September) (Tarigan and Wenno, 1991). The upwelling waters may influence the thermodynamic of the atmospheric-oceanic boundary on the bay, giving rise to complex heat transfer process.

SST is a key parameter for understanding air-sea interactions (Kawai and Wada, 2007; Wu et al., 2006; Zhang and McPhaden, 1995) by directly and indirectly controlling heat, momentum, salt and gas fluxes within the atmospheric-oceanic boundary layer (Emery, 2002). SST change can affect atmospheric circulation by changing enthalpy fluxes across the surface (Kirtman and Vecchi, 2011; Kubota and Shikauchi, 1995). These boundary layer feedback processes are effective in transferring heat from the ocean to the atmosphere via sensible and latent fluxes (Zhang and Perrie, 2001; Knauss, 1998). Thus, in warm tropical regions, such as the Indonesian Seas, SST variability exerts substantial influence on the atmosphere (Wang et al., 2004; Kang et al., 2002). On global scale, the role of the SST on air-sea interaction over seasonal and interannual time scales is clear (Bjerknes, 1969; Horel and Wallace, 1981). For example, Inter Tropical Convergence Zone (ITCZ) is influenced by the location of warm SST which is also associated with the Asian monsoon onset (Chao, 2000). SST warming over the eastern equatorial Pacific weakens Walker circulation which triggers an El Nino episode (Lau and Yang, 2003; Meyers et al., 2007). In coastal environment, SST significantly influences atmospheric condition over urban areas (Oda and Kanda, 2009; Pullen et al., 2007; Kawai and Wada, 2007; Kawai et al., 2006) that potentially affects the local weather (Yoshikado, 1992; Fujibe, 2003; Kobayashi et al., 2007). In turn, atmospheric variability, which can manifest through anomalous atmospheric convection, influences SST through cloud-radiation, wind-evaporation effect, wind induced oceanic mixing and upwelling (Kirtman and Vecchi, 2011).

In terms of understanding the interaction between air and sea surface temperatures, the main heat flux to be analyzed is the sensible heat flux that is the heat flux due to air-sea temperature difference within the atmospheric-oceanic boundary (Stewart, 2008; Cayan, 1992; Large and Pond, 1995). The convention here is negative heat flux that indicates an input of heat from the atmosphere into the sea surface, whereas positive heat flux indicates a release of heat from the sea to the atmosphere.

The goals of this current work are: (1) to evaluate the relationship between SST and air temperature in the outer Ambon Bay, and (2) to investigate the seasonal variation of sensible heat flux using meteorological and oceanographic data in the bay. The benefit of this current work is to understand the heat transfer process on the atmospheric-oceanic boundary of the outer Ambon bay and its relationship with urban heating island (UHI) on Ambon Island.

MATERIAL AND METHODS

This research used data sets from various sources which included monthly air temperature during the day (1300 hours) and wind speed datasets gathered from Ambon Island from World Meteorological Organization Database (Ropelewski et al., 1985), and *in situ* daytime SST data (roughly 1100–1300 hours) measured by LIPI Marine Lab Ambon (the *in situ* station, labeled with "A", shown in Fig. 1). Air temperature data over land was used to represent that of over the sea due to the unavailability of air temperature data over the outer Ambon Bay. To a first order, this approximation was deem to be reasonable as the distance between the land and sea locations was short (990 meters). In Appendix I, reanalysis datasets, albeit the coarse resolution, were used to show that substituting air temperature over sea to that of over land was slightly different in sensible heat flux. Since the *in situ* data and daily satellite data of SST (daytime) were limited, satellite data of monthly daytime SST was also used (http://oceancolor.gsfc.nasa.gov/cgi/l3) as handled via SeaWiFS Data Analyzing System (SeaDAS). The complete *in situ* SST was obtained using linear regression between the *in situ* and the satellite data to estimate any missing *in situ* SST. This issue was expected to be minor since the correlation between the satellite and the *in situ* data was high (r = 0.82). The period for the SST was from July 2002 to September 2012 which was associated with Aqua MODIS sea surface temperature mission for daytime version. Meanwhile, the wind speed and the air temperature datasets are from January 2006 to September 2012 based on Meteorological, Climatological and Geophysics Agency station of Ambon City. SST and the air temperature were illustrated in Fig. 2a while the wind speed was described in Fig. 2b.

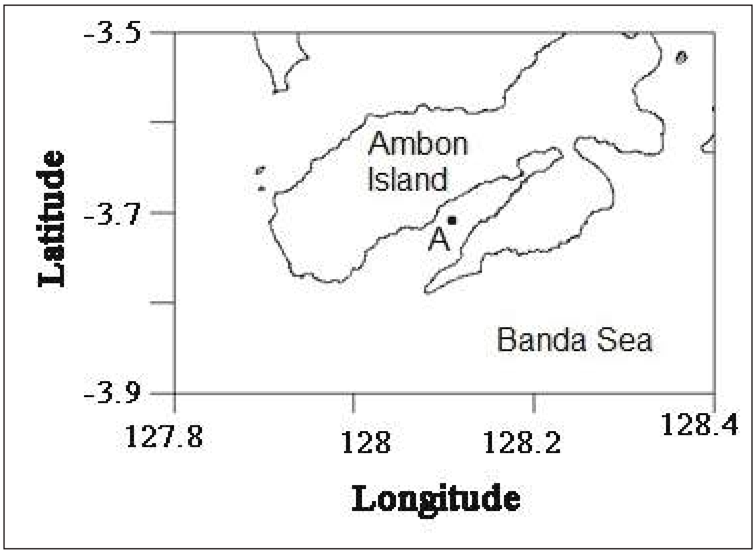

Figure 1. Map of the Ambon Bay showing the *in situ* station of SST "A".

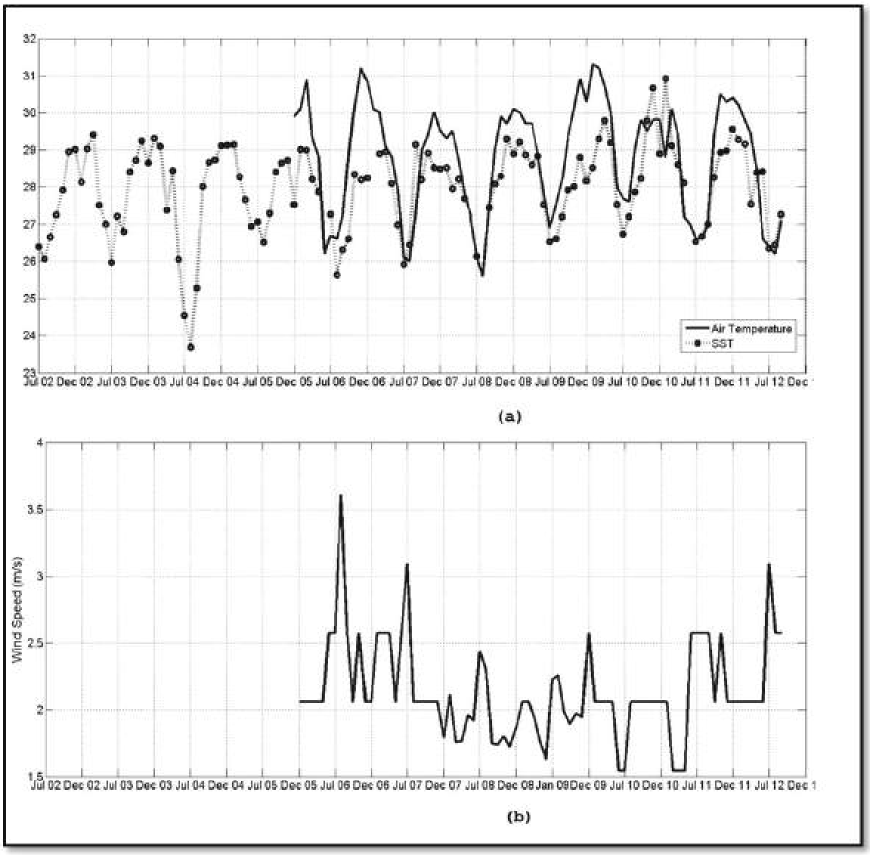

Figure 2. SST and the air temperature datasets (a), and wind speed dataset (b).

The sensible heat flux was derived using the bulk formula (Cayan, 1992):

$$Q_s = \rho C_p C_H w(T_o - T_a), \quad (1)$$

where ρ, C_p, C_H, w, T_o, and T_a are density of air, specific heat of air at constant pressure (1.0048×10^3 J kg^{-1} °C), the transfer coefficient for sensible heat (1.0×10^{-3}), wind speed, sea surface temperature, and air temperature, respectively (Cayan, 1992; Smith, 1988).

RESULTS

Fig. 3 showed the relationship between SST and air temperature in the outer Ambon Bay whereas Fig. 4 showed scatter plot of air temperature change versus sensible heat flux for monthly data. Fig. 4 was used to analyze how both the warming and cooling periods influence heat transfer process, represented by the sensible heat flux, which took place on the atmospheric-oceanic boundary on the outer Ambon Bay instead of taking a correlation between air temperature change and sensible heat flux. It may not be necessari to have high correlation between sensible heat flux and SST (or the air temperature) individually because the difference between SST and the air temperature is what determines the sensible heat flux. Thus, the aim of using the air temperature change for both negative and positive values (the x axis on Fig. 4) was to indicate warming and cooling periods on the outer Ambon Bay.

Both warming and cooling periods can be represented by either the air temperature changes or the SST changes since both periods affect the surface layer of the bay and its atmosphere (Tarigan, 1989), and the air-sea temperature relation shown by Fig. 3 was highly correlative (r = 0.75). Thus, either the air temperature change or the SST change can be chosen to represent monthly variations existing on the outer Ambon Bay. The monthly air temperature change, the x axis on Fig. 4, provided positive change, when the temperature was increasing and negative change exerts an opposite effect. The positive change, indicating the warming period, was sequentially represented by monthly data of September, October, November, December, January, and February (SONDJF) while the negative change, implying the cooling period, was sequentially represented by monthly data of March, April, May, June, July, and August (MAMJJA).

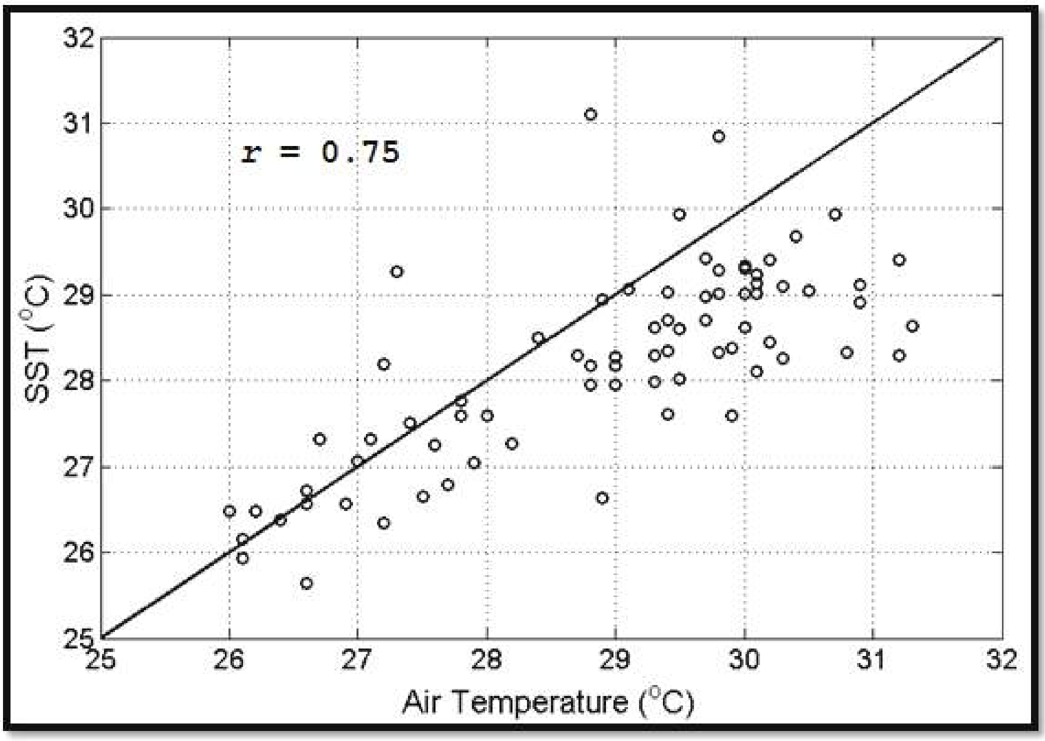

Figure 3. The relationship between SST and air temperature in the outer Ambon Bay (monthly dataset).

The SST was generally lower than the air temperature as shown in Fig. 2 and so the sensible heat flux was dominantly negative (Fig. 4), inferring an input of heat from the atmosphere into the ocean, thus it showed negative feedback on the SST within the bay. In Fig. 5, the average values of sensible heat flux for every month were calculated to illustrate the significance of the heat input from atmosphere into the ocean during cooling period when upwelling occured and warming period when land heating was intense. The average data were negative over all months, with weak values during cooling period (June-July-August) and strong values during warming period (November-December-January-February).

DISCUSSION

Ambon region showed seasonal climate variations, with dry season during December-January-February (DJF), the first transitional season occurred in March−April−May (MAM), wet season through June to August (JJA), and the second transitional season was in September-October-November (Huwae, 1970; Tarigan, 1989). Thus, the positive change in monthly air temperature shown in Figure 4 indicated that the increase of temperature (warming period) existed from the second transitional season (SON) to the dry season (DJF), while negative change (cooling period) illustrated that the decrease of temperature occurred from the first transitional season (MAM) to the wet season (JJA). Furthermore, the period of temperature decrease over March through August coincided with the surface upwelling event occurring in Banda Sea (Wyrtki, 1961).

In terms of heat budget flux existing on the atmospheric-oceanic boundary, the calculation of latent heat flux should be conducted beside the sensible heat flux for revealing heat transfer process on that boundary of the outer Ambon Bay. However, the latent heat flux cannot be calculated since *in situ* data of specific humidity at air of the sea surface was not available while coarse resolution becomes a problem in terms of using latent heat flux data from reanalysis product. Thus, this discussion was limited to the sensible heat flux.

Although the air temperature varies through warming and cooling periods, the sensible heat flux was predominantly negative (Fig. 4). Tarigan (1989) and Huwae (1970) reported that during cooling period, the atmospheric condition is characterized by cloudiness, strong winds, and high precipitation, with minimum insolation. When the

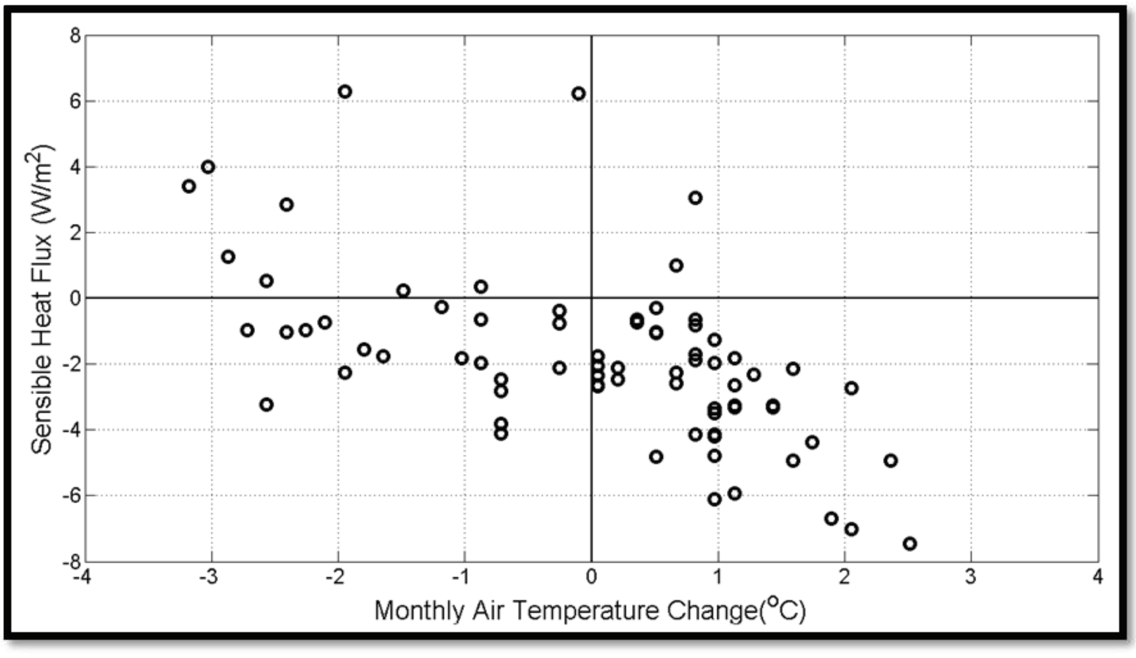

Figure 4. Scatter plot of monthly air temperature change vs the sensible heat flux over the outer Ambon Bay.

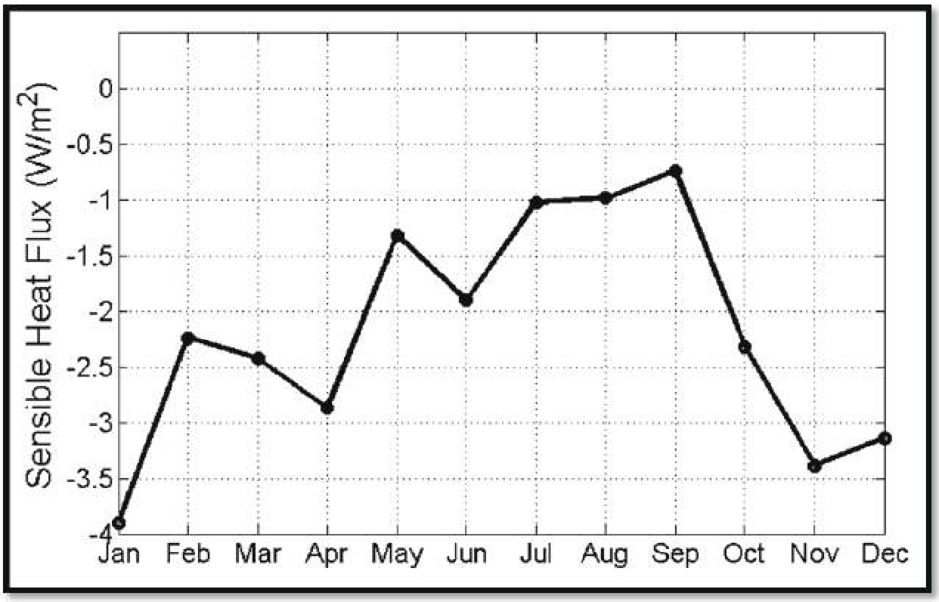

Figure 5. The mean monthly values of sensible heat flux in the outer Ambon Bay.

upwelling waters from Banda Sea enter the outer Ambon Bay, SST is reduced (Tarigan and Wenno, 1991), inducing negative sensible heat flux on the atmospheric-oceanic boundary of the bay. Thus, the upwelling waters could be considered as the cause of decreasing SSTs which then induced heat transfer from atmosphere into the ocean (negative sensible heat flux) as a negative feedback to the SST changes during cooling period.

During warming period, however, the dominance of negative sensible heat flux (Fig. 4) implied a heat transfer from the warming air temperature into the sea surface, that was, a positive feedback onto the SSTs. This situation contradicted the common view of warm SSTs inducing positive heat flux in response to insolation over the Indonesian Seas such as Java Sea, Flores Sea, South China Sea, Timor Sea, Arafura Sea, Sulu Sea, and Banda Sea (Wyrtki, 1961). Recently, Fan and Lin (2003) convinced the existence of positive latent and sensible heat fluxes in tropical oceans including Indonesia region. This negative heat flux that is predominant during warming period suggests the possibility of the Urban Heating Island (UHI) effect through a heat transfer process from Ambon Island which results in atmospheric warming over the bay. During warming period, wind speed and precipitation decrease on the outer Ambon Bay (Tarigan, 1989); both the land area of Ambon Island surrounding the outer Ambon Bay and the bay itself experience effective insolation. The air temperature over the land increases more rapidly than that over the waters due to intense latent and sensible heating during daytime, especially in a very hot day, because of the different properties of both media (Simpson et al., 2007). As a result, the air temperature over land was higher than that of over the ocean. Since the bay was narrow, the higher air temperature over land would be more effectively mixed with the lower air temperature over the waters, increasing the air temperature over the bay. The more rapid evaporation taking place over the land due to effective insolation, more rapid the influence of the higher temperature over land to that of over the bay. Because it was the air temperature over the bay that became warmer rather than SST through this process, negative sensible heat flux was expected (Fig. 4). Thus, the latent and sensible heating over land can be considered as the cause of higher air temperature over the bay to give rise to negative sensible heat flux during warming period.

The significance of sensible heat flux during warming period rather than that of during cooling period (Fig. 5) implied that the outer Ambon Bay received more significant sensible heat flux input from the atmosphere during warming period than during cooling period which, on the other hand, was the illustration of the role of upwelling on the negative air-sea feedback on the SSTs. This result highlighted the possible of UHI on the sea surface warming over the outer Ambon Bay, most notably during the dry season (DJF).

Monthly variation of air-sea temperatures in the outer Ambon Bay showed that the air temperature generally tended to be higher than the SST. Consequently, negative value of the sensible heat flux dominated the heat transfer process on the atmospheric-oceanic boundary, which implied that negative feedback mechanism is dominantly prevailing on the bay over all months. The upwelling waters entering the bay during cooling period that reduces SST, and heat transfer from the atmosphere over the land that increases air temperature over the sea during warming period appeared to be the main causes for negative sensible heat flux on the atmospheric-oceanic boundary of the outer Ambon Bay. During the wet season, the negative sensible heat flux, that was an input of heat from the atmosphere into the sea, highlighted the role of upwelling that cools SSTs. The negative sensible heat flux is however much stronger during dry season when atmospheric warming occurs. This suggested a possibility of an UHT effect on the warming of the outer Ambon Bay through an enhancement of air-sea temperature gradient. Note that this work should be viewed as a preliminary analysis since this has involved a number of approximations due to sparse observational data. More complete datasets from a high resolution model were required to be implemented in the future, and more importantly observational effort needs to be enhanced to gather a more complete record for the Ambon region.

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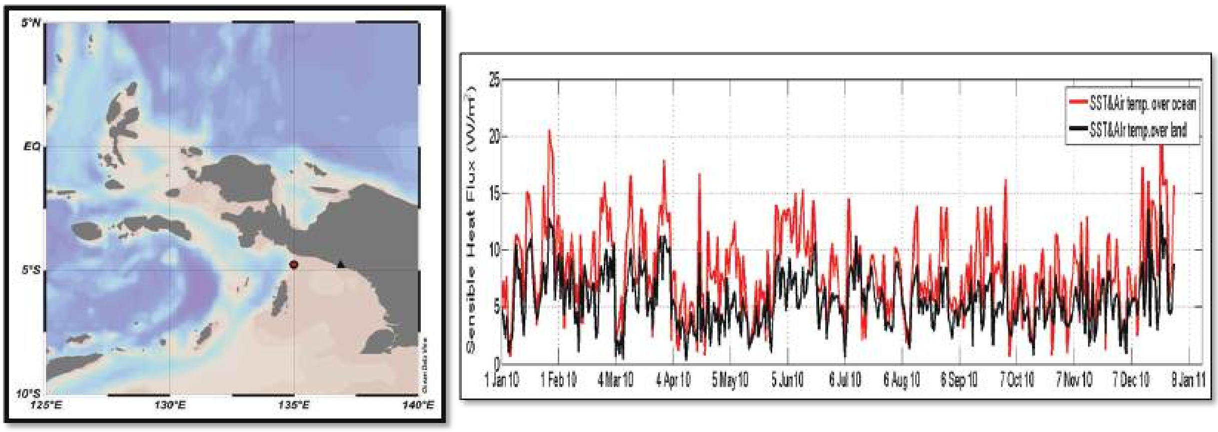
APPENDIX I

Since the air temperature data over the ocean ($T_{a=ocean}$) is not available on the outer Ambon Bay whereas the surface air temperature ($T_{a=land}$) exists on Ambon weather station (BMKG), the idea to replace $T_{a=ocean}$ by $T_{a=land}$ was proposed because the station is close to the bay (990 meters). However, every surface has different heat transmission property (emissivity, reflectivity, etc.). Thus, the air temperature will be different because the air temperature enhances more quickly over the land than the waters during the daytime in a particularly very hot day (Simpson et al., 2007) although the location over land is near the sea location. In order to do replacement, investigation of how much difference of heat transfer occurs over land instead of over ocean is important to be conducted. Some certain points representing land (coasts) and ocean locations in Indonesian archipelago can be determined since unavailability of $T_{a=ocean}$ in the bay by concerning on the characteristic of climate over Indonesian archipelago as shown clearly in Aldrian et al. (2003). In fact, it is difficult to find datasets covering somewhere near Ambon Island or some islands surrounding it, because of coarse resolution dataset of available satellite and reanalyzed data. Thus, the chosen points should represent land and ocean locations and have similarity of climate with Ambon Island as shown in Aldrian et al. (2003). The used data in this analysis are: air temperature (grid resolution: 2.5 deg, http://www.esrl.noaa.gov/psd), wind speed (grid resolution: 2.5 deg, http://www.esrl.noaa.gov/psd), and sea surface temperature (grid resolution: 0.25 deg, http://thredds.jpl.nasa.gov).

Figure A1a and A1b show location of both land and ocean, and comparison of the sensible heat flux over ocean and land. The flux over land (black line) seems to be comparable with the ocean flux (red line) and so the difference between both fluxes is generally quite low (RMSE = 3.2 W/m^2). This analysis confirms how reasonable $T_{a=land}$ can be substituted when $T_{a=ocean}$ is not available although it is to be noted that coarse resolution datasets mean that small scale variability is not captured.



(a) **(b)**

Figure A1. Sampling location of both land and sea (a); comparison on the sensible heat flux between land and sea (b).