Temporal and spatial variation of surface heat flux in Makassar Strait

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Abstract. Indonesian Seas have an important role on the sea-air interaction in Indo-Pacific region. Makassar Strait is located in the center of Indonesian Seas and part of Indonesian Throughflow (ITF), which has been influenced due to the coupled ocean-atmosphere phenomenon in Pacific and Indian Oceans, such as monsoon, El-Niño Southern Oscillation (ENSO), and Indian Ocean Dipole (IOD). The temporal and spatial variation of surface heat flux in Makassar Strait has been evaluated using the multi satellite dataset from 1984-2009. The remote sensing data with resolution of 1° × 1° obtained from Objectively Analyzed air-sea Fluxes (OAFlux) produced by Woods Hole Oceanographic Institution (WHOI). The results show that there is a seasonal fluctuation of surface heat flux related to the wind monsoon. The variation of the shortwave radiation and latent heat flux give a large contribution to the net surface heat flux that associated with ENSO and IOD events. In Makassar Strait, the variation of shortwave radiation and sea surface temperature (SST) is in a good agreement with the El-Niño/La-Niña events. There is a time lag between surface heat fluxes with the ENSO events.

Keywords: Interannual variability, Makassar Strait, monsoon, surface heat flux.

1. Introduction

Indonesian Seas, which is located between Indian and Pacific Oceans, have an important role on the sea-air interaction in Indo-Pacific region. Besides, Indonesian Seas are also influenced by the coupled ocean-atmosphere phenomenon in Pacific and Indian Oceans, such as monsoon, El-Niño Southern Oscillation (ENSO), and Indian Ocean Dipole (IOD). As the part of Indonesian Seas, Makassar Strait has unique oceanographic characteristics and takes part on that important role. Makassar Strait is located in the center of Indonesian Seas, between Kalimantan (Borneo) Island and Sulawesi Island, and also part of Indonesian Through-Flow (ITF). ITF plays a role in transporting the water mass from the Pacific Ocean to the Indian Ocean and also maintaining the heat balance.

The imbalance between the input and output of heat through the ocean surface causes changes in heat stored in the upper layers of the ocean [1,2,3]). The heat exchange through the ocean surface is called surface heat flux. The sum of heat flux into or out of a water column is the heat budget. There are four major terms of surface heat flux, i.e. insolation or shortwave radiation ($Q_{SW}$), the heat flux of sunlight...
into the ocean; net infrared radiation loss or long wave radiation \( (Q_{LW}) \), the flux of infrared radiation or long wave radiation from the ocean; latent heat flux \( (Q_L) \), the heat flux carried by evaporated water; and sensible heat flux \( (Q_S) \), the heat flux out the ocean due to conduction process [4].

Heat flux can changes the density of surface water mass and also has role in determining the global water mass distribution and thermohaline circulation [5]. The heat flux in the deeper layers is usually much smaller than the heat flux in the upper layers or surface heat flux. Besides, the total of global surface heat flux which entry and exit the ocean must equals to zero or balance, otherwise the ocean would warm or cool. Therefore, the aim of this research is to find out the process of heat exchange between ocean and atmosphere in Makassar Strait by analyzing the spatial and temporal variation of all terms of surface heat flux there.

2. Data and Methods

Data used in this research are secondary data retrieved from Objectively Analyzed air-sea Fluxes (OAFlux) [4], a research program by Woods Hole Oceanographic Institution (WHOI), including global data of total heat flux, long wave radiation, short wave radiation, latent heat flux, sensible heat flux, wind speed, sea surface temperature and, humidity. OAFlux Program is a sustainable research and development project for global ocean-atmosphere flux. The products of OAFlux are obtained from optimal assimilation of various multi-platform satellite and analysis of three numerical weather predictions (NWP). The OAFlux data are obtained from observation for 26 years, from 1984 to 2009. Moreover, the long wave and short wave radiation data are retrieved from International Satellite Cloud Climatology Project (ISCCP) [6].

Dipole Mode Index (DMI) [7] and Oceanic Niño Index (ONI) [8] are also used in this research to determine the influence of Indian Ocean Dipole (IOD) and El-Niño Southern Oscillation (ENSO) phenomena to the surface heat flux in Makassar Strait. The summary of used data are shown in table 1. The research area location is along the Makassar Strait that lays between Kalimantan Island and Sulawesi Islands. A cross section namely SMR to SMR” transect located along the strait was chosen to analyze the data (see figure 1).

\[
Q = Q_{SW} - Q_{LW} - Q_S - Q_L
\]

Where, \( Q \) is the resultant of heat gain or loss. \( Q \) and \( Q_{SW} \) are positive towards the bottom (sea), while \( Q_{LW}, Q_L, \) and \( Q_S \) are positive towards the top (atmosphere) and all the parameter unit is W/m\(^2\).

Figure 1. Research area location and a cross section namely SMR to SMR" transect located along the strait (red line)
Table 1. Data description used in this study

| Variable                        | Unit   | Resolution | Source                                                      |
|---------------------------------|--------|------------|-------------------------------------------------------------|
| Total heat flux ($Q$)           | W/m²   | 1° × 1°    | The Objectively Analysed Air-Sea Fluxes (OAFlux)            |
| Insolation or shortwave radiation ($Q_{SW}$) | W/m²   | 1° × 1°    | International Satellite Cloud Climatology Project (ISCCP)   |
| Net infrared radiation loss or long wave radiation ($Q_{LW}$) | W/m²   | 1° × 1°    | International Satellite Cloud Climatology Project (ISCCP)   |
| Latent heat flux ($Q_L$)        | W/m²   | 1° × 1°    | The Objectively Analysed Air-Sea Fluxes (OAFlux)            |
| Sensible heat flux ($Q_S$)      | W/m²   | 1° × 1°    | The Objectively Analysed Air-Sea Fluxes (OAFlux)            |
| Wind speed ($ws$)               | m/s    | 1° × 1°    | The Objectively Analysed Air-Sea Fluxes (OAFlux)            |
| Sea surface temperature (SST)   | °C     | 1° × 1°    | The National Oceanic and Atmospheric Administration (NOAA)   |
| Humidity (HUM)                  | g/kg   | 1° × 1°    | The Objectively Analysed Air-Sea Fluxes (OAFlux)            |
| Outgoing long wave radiation (OLR) | W/m²   | 2.5° × 2.5° | The National Oceanic and Atmospheric Administration (NOAA) |
| Dipole Mode Index (DMI)         | °C     | -          | Japan Agency for Marine-Earth Science and Technology (JAMSTEC) |
| Oceanic Niño Index (ONI)        | °C     | -          | The National Oceanic and Atmospheric Administration (NOAA)   |

3. Results and Discussions

The monthly mean distribution of total surface heat flux ($Q$) from OAFlux is shown in Figure 2. In January, April, July, and October, the value of total surface heat flux ($Q$) is positive for almost all Indonesian Seas, where the value in April and October are higher than the value in January and July. This appearance seems to be related to the pseudo-motion of the sun, where in April and October the sun moves to the equator, while in January and July the sun’s position is on the mid latitude region.

Figure 2. The monthly mean distribution of total surface heat flux ($Q$) on a) January, b) April, c) July, and d) October. Unit expressed in W/m².
However, in July, the total surface heat flux ($Q$) of southern Indonesian Seas is negative, which means the ocean releases more heat to the atmosphere. It is suggested as the influence of latent heat flux ($Q_L$) due to high wind speed and low humidity [6]. Based on figure 3, which shows the time series of monthly mean of all surface heat flux terms in Makassar Strait, it is shown that the highest total heat flux ($Q$) happens in April and the lowest happens in June to July. Moreover, there is also high total heat flux ($Q$) in November. The high total heat flux ($Q$) in April and November are caused by high solar insolation at the equator in the boreal spring and autumn seasons. High insolation is also seen from the time series of insolation or short wave radiation ($Q_{SW}$), which is high in April (spring) and September (autumn) and low in June (summer) and December (winter). The low total heat flux ($Q$) in June to August is caused by the high latent heat flux ($Q_L$) due to high wind speed (see figure 4) and low humidity in boreal summer season, especially in August as the peak [6]. The low humidity during boreal summer season is caused by southeastern monsoon wind, which tends to carry dry air masses from Australia.

![Figure 3. Time series of monthly mean of surface heat flux terms in Makassar Strait. Unit expressed in W/m$^2$.](image)

![Figure 4. The annual mean distribution of wind speed (m/s) on a) June, b) July, and c) August.](image)

The surface heat flux has a relationship with sea surface temperature (SST). Based on the correlation analysis between all surface heat flux terms and SST in table 2, the SST in the Makassar Strait is significantly related to the sensible heat flux ($Q_S$) and net infrared radiation loss or long wave radiation
It is shown that the variation of sensible heat flux \((Q_S)\) and net infrared radiation loss or long wave radiation \((Q_{LW})\) in the Makassar Strait are significantly related to the variation of SST. The higher SST means the higher heat transferred from the ocean to the atmosphere [9]. Previous studies show the phenomena that play roles on the interannual variation of SST in Indonesia, including Makassar Strait, are El-Niño Southern Oscillation (ENSO) [10] and Indian Ocean Dipole (IOD) [11].

Table 2. Correlation of surface heat flux terms to sea surface temperature (SST)

| \(Q\) : SST | \(Q_{SW}\) : SST | \(Q_{LW}\) : SST | \(Q_L\) : SST | \(Q_S\) : SST | \(Q_{C}\) : SST |
|------------|-----------------|-----------------|----------------|----------------|----------------|
| \(r\)      | -0.07*          | 0.05*           | 0.16           | -0.04*         | 0.26           |
| Lag (months)| 0               | 0               | 0              | 0              | 0              |

* No significant relationship between two variables.

Figures 5 and 6 show Hovmöller diagrams of all surface heat flux anomalies along the SMR to SMR" transects from 1987 to 2009 which are compared to ONI and DMI indices. Based on these two figures, it can be seen that there are positive anomalies of total heat flux \((Q)\), insolation or short wave radiation \((Q_{SW})\), and net infrared radiation loss or long wave radiation \((Q_{LW})\), and also negative anomalies of sensible heat flux \((Q_S)\) during El-Niño event (ONI > 0.5) and Positive IOD event (DMI > 0.5), as in 1994-1995, 1997-1998, and 2006-2007. Otherwise, during La-Niña event (ONI < –0.5) and Negative IOD event (DMI < –0.5), there are negative anomalies of total heat flux \((Q)\), insolation or short wave radiation \((Q_{SW})\), and net infrared radiation loss or long wave radiation \((Q_{LW})\), and also positive anomalies of sensible heat flux \((Q_S)\), as in 1998-1999 and 2008-2009. Besides, there is a lag time between the occurrence of ENSO or IOD with the surface heat flux anomalies, where the anomalies occur several months after.

Furthermore, for analysing the interannual variability clearly, the anomalies of all surface heat flux were filtered by using low pass filter method with cut off about 13 months and presented in figures 7 and 8. Based on those two figures, it became clear that during El-Niño and Positive IOD events (ONI and DMI > 0.5), such as in 1994-1995 and 1997-1998, there are positive anomalies of total heat flux
(Q), while during La-Niña and Negative IOD events (ONI and DMI < -0.5), such as in 1998-1999 and 2008-2009, there are negative anomalies of total heat flux (Q). During the El-Niño and Positive IOD events, the ocean tends to absorb more heat from the atmosphere, and vice versa.

**Figure 6.** The Hovmöller Diagram of surface heat flux terms anomalies in Makassar Strait compared to ONI and DMI during 1997-2009

**Figure 7.** The Hovmöller Diagram of surface heat flux terms anomalies after low pass filter (13 months cut off) in Makassar Strait compared to ONI and DMI during 1984-1996
Based on the correlation analysis in table 3, it can be seen that the correlation between the surface heat flux terms and ONI are higher than the correlation to the DMI. It is shown that greater influence is given by ENSO than IOD. It is also seen in figures 7 and 8, that when the DMI value is more than 0.5 and the ONI value is neutral, there is no significant positive anomaly of total heat flux ($Q$), but when the ONI value is more than 0.5 and the DMI value is neutral, there is a positive total heat flux ($Q$) anomaly.

Table 3. Correlation of surface heat flux terms to DMI and ONI in Makassar Strait

|        | $Q$  | $Q_{SW}$ | $Q_{LW}$ | $Q_{L}$ | $Q_{S}$ |
|--------|------|----------|----------|--------|--------|
| DMI    | 0.16 | 0.42     | 0.31     | 0.13   | -0.29  |
| ONI    | 0.36 | 0.86     | 0.62     | 0.16   | -0.55  |

The most related surface heat flux term to ENSO and IOD phenomena is insolation or short wave radiation ($Q_{SW}$). In addition, a fairly high and significant correlation was also seen in the net infrared radiation loss or long wave radiation ($Q_{LW}$) and sensible heat flux ($Q_{S}$) to the ENSO and IOD. In contrast to insolation or short wave radiation ($Q_{SW}$) and net infrared radiation loss or long wave radiation ($Q_{LW}$), the correlation of sensible heat flux ($Q_{S}$) to ONI and DMI are in opposite direction, which means that when the ONI and DMI values more than 0.5, negative sensible heat flux ($Q_{S}$) anomaly will occur, and vice versa. In addition, sensible heat flux ($Q_{S}$) is associated with lower SST during El-Niño and Positive IOD and higher SST during La-Niña and Negative IOD. Although significantly correlated with ENSO and IOD phenomena, the effect or contribution of sensible heat flux ($Q_{S}$) to the total heat flux ($Q$) tends to be low with values ranging from 2-42 W/m$^2$ [9]. Therefore, it is suggested that total heat flux ($Q$) anomalies that occur during ENSO and IOD events are caused by significant insolation or short wave radiation ($Q_{SW}$) anomalies.
4. Conclusion
The results show that there is a seasonal fluctuation of surface heat flux related to the wind monsoon. The variation of the insolation or shortwave radiation ($Q_{SW}$) and latent heat flux ($Q_L$) give a large contribution to the net surface heat flux that associated with El-Niño and Indian Ocean Dipole (IOD) events. In Makassar Strait, the variation of shortwave radiation and sea surface temperature (SST) is in a good agreement with the El-Niño/La-Niña events. There is a time lag between surface heat flux with the ENSO events.

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