Role of cold surge and MJO on rainfall enhancement over Indonesia during East Asian winter monsoon

R R Fauzi and R Hidayat*
Department of Geophysics and Meteorology, Faculty of Mathematics and Natural Science, Bogor Agricultural University, Bogor, Indonesia

E-mail: rahmath@apps.ipb.ac.id

Abstract. Intensity of precipitation in Indonesia is influenced by convection and propagation of southwest wind. Objective of this study is to analyze the relationship between cold surge and the phenomenon of intra-seasonal climate variability Madden-Julian Oscillation (MJO) for affecting precipitation in Indonesia. The data used for identifying the occurrence of cold surge are meridional wind speed data from the ERA-Interim. In addition, this study also used RMM1 and RMM2 index data from Bureau of Meteorology (BOM) for identifying MJO events. The results showed that during East Asian Winter Monsoon (EAWM) in 15 years (2000-2015), there are 362 cold surge events, 186 MJO events, and 113 cold surge events were associated with MJO events. The spread of cold surge can penetrate to equator and brought mass of water vapor that causes dominant precipitation in the Indonesian Sea up to 50-75% from climatological precipitation during EAWM. The MJO convection activity that moves from west to east also increases precipitation, but the distribution of rainfall is wider than cold surge, especially in Eastern Indonesia. MJO and cold surge simultaneously can increase rainfall over 100-150% in any Indonesian region that affected by MJO and cold surge events. The mechanism of heavy rainfall is illustrated by high activity of moisture transport in areas such as Java Sea and coastal areas of Indonesia.

1. Introduction

Indonesia is a country that located in area where crossed by global wind variations. One of the wind patterns that affect climate conditions in this country is the monsoon. Monsoon is a large-scale wind that occurs because the difference between temperature and pressure in the ocean and land. Asian monsoon affect the maximum rainfall in South Asia, especially in Southeast Asia [1]. Meanwhile, one of the extreme weather and climate events in Java and Sumatra were occurred during the influence of monsoon winds [2].

Various occurrences of climate variability often affect the extreme rainfall in some parts of Indonesia. Besides affecting rainfall in annual and inter-annual periods, some climate variability also affects the rainfall in intra-seasonal periods [3]. Extreme rainfall anomaly can be predicted from water vapor that carried away through Intertropical Convergence Zone (ITCZ). Moisture transport defined as an important components to see the potential areas where extreme rain occurs [4]. The amount of water vapor that concentrated in some region causing extreme rain which can be categorized based on threshold and percentile 95% calculation [2]. Some of the intra-seasonal climate variability during boreal winter that can bring water vapor is cold surge and Madden-Julian Oscillation (MJO).

During boreal winter, the flow of surface wind from north that commonly referred as East Asian winter monsoon much observed in East and Southeast Asia [5]. The active winds coincide with the onset
of weather extreme where occurred in East Asia that results from interaction between vapor transport and the monsoon. In that condition, often found in the form of a mass flow of cold air which carries more air masses from Siberia. That phenomenon can be called as cold surge [6].

The impact of cold surge not only causes extreme weather where occurred in East Asia, but causes great intensity of rainfall in Southeast Asia, especially in Indonesia [7]. In 2007, there is a strong cold surge occurred five times whose propagation passes through the equator, even the island of Java. The incident became a major factor where Jakarta have a heavy rainfall that causing massive flooding [8]. In addition, some recent study shows that the effect of cold surge takes one day or less to influence the weather of southeast asia region [9].

Further analysis of cold surge with MJO needs to be done to see the influence of intra-seasonal climate variability events against climatological condition in Indonesia. This study was conducted because the previous research is more research about the characteristics of cold surge, while the research emphasizes on influence of cold surge in changing conditions of rainfall patterns in Java Island and the others area are not done yet [2,6,10].

2. Methodology

2.1. Data collection and literature studies

The downloaded data is then selected based on 15ºS-25ºN and 95º-140ºE in this study area. Area studies include Southeast Asia including Indonesia's maritime continent, a small part of the Indian Ocean and Pacific Ocean (see figure 1).

Wind speed is indicated by shading in map, while the wind direction is indicated by arrows. The fastest meridional wind speed on the East Asia winter monsoon period especially in 2000-2015 located in the South China Sea area, as shown in figure 1. Usually, that area is affected by cold waves formed in October - april with average wind direction coming from NE, NNE, N, NNW and NW [11]. Identifying of cold surge performed using an indication that averaging the value of meridional wind component in the 110º-117.5ºE and 15ºN region at 925 hPa marked by thick line in figure 1 [12]. Cold surge events can be indicated by the activity of northerly wind speed exceeds 8 m / s and heading south. The analysis period is limited to when the occurrence of EAWM among November-February in 2000-2015 [13]. The thick lines that make up the square plane in figure 1 indicates the area of Cross-Equatorial Northerly
Surge (CENS) events that used as an area of propagation analysis in cold surge event, while the dashed lines that form a square plane signifies the conventional central area of MJO events [10].

2.2. Preparation of meridional wind data, RMM1, and RMM2 index
Six-hour data from ECMWF modified into daily averaged with Climate Data Operator (CDO). Daily MJO events affect Indonesia's cloud conditions in phases 4 and 5 with the power of amplitude is more than 1, so the selection of phases 4 and 5 is required before composite analysis [2].

2.3. Plotting the day of cold surge and MJO events in 2000-2015 of the EAWM period
The result of plotting is a table that contains the date and number of occurrences in each year.

2.4. Composite analysis of wind and rainfall condition when no cold surge and cold surge events
This method is done by averaging meridional winds when no cold surge, cold surge, and daily averaged of EAWM periods when has been separated in the previous method. The composite technique is none other than ensemble average, is an arithmetic mean from a data under the same conditions.

2.5. Calculate moisture transport
The definition of water vapor transport is a movement of the wind that carries water vapor mass and can be expected from the following equation [4].

\[
Q = \frac{1}{g} \int_{p_t}^{p_s} qV dp
\]

Q is moisture transport (kg/m/s), g is earth gravitation (m/s²), q is specific humidity (gr/kg), V is horizontal wind vector (m/s), p is pressure levels with pt and ps is pressure level at 300 hPa and 1000 hPa. The use of data parameters is limited at 300 hPa due to the amount of data lost at 300 hPa upwards that potentially affecting the calculation results of water vapor vertically integration.

2.6. Composite analysis of rainfall condition when cold surge and MJO events
This method is the same thing like 5th procedure, but the result is a condition map of rainfall when cold surge and MJO events occurs in millimeters and anomalies units.

2.7. Wind propagation and its influence analysis when cold surge and MJO events occurs using hovmoller diagram
Observation of wind movement and rainfall conditions in 105º-115ºE With time variations can be seen using hovmoller diagram. The hovmoller diagram is a diagram that can show fluctuations in data values with time and region variations. Latitude variations are limited from 20ºN-20ºS and its time on 1 November-29 February.

3. Result and discussion

3.1. Climatological conditions on Indonesian rainfall and wind on East Asian Winter Monsoon (EAWM) periods
The Asian and Australian monsoons are two global monsoons that mainly affects rainfall in Indonesia. The monsoon is the largest surface wind cycle that has a seasonal pattern in certain areas. One of the important things that should be noted that the beginning of monsoon usually occurs together with high intensity of rainfall in the area that crossed with the monsoon wind pattern [14].
Figure 2 shows that the meridional wind on climatological condition across the equator region up to 6°S in mid-January to February with 2-4 m/s. The cold surge event was visible in climatological in December and January that potentially can affect rainfall in Indonesia, especially in Jakarta [8]. Cold surge spread to equator and turn eastward because wind moves from high pressure to low pressure [2]. Deflection is caused by pressure difference that stronger between the eastern and western regions in the equatorial area, compared with the pressure difference between the Continent of Australia and East Asia.

This study uses TRMM and GSMaP satellite data to observe the effect of cold surge and MJO against rainfall in Indonesia. The application of TRMM and GSMaP satellite data often used for analyzing the diversity of precipitation in the region that is difficult to observed [10,15]. In figure 3, the difference seen on measurement results of the intensity of rainfall in the oceans and coastal as well as distribution of rainfall in the land. Validation results with station data shows that TRMM rainfall data has correlation value about 0.28 and GSMaP about 0.57. TRMM data visualization tend to display the rainfall value that is too high which compared with observation data, while the GSMaP data capable to displaying the rainfall value that is more precise due to algorithm data organized to further evaluate from performance of several satellites of observation.
3.2. Cold surge propagation in Indonesia Region

Cold Surge (CS) is the spread of cold air mass that moved from East Asia to the Western Pacific Ocean during the Asian winter monsoon [16]. The number of occurrences of cold surge and MJO can be seen on table 1.

| Year     | CS  | MJO | CS-MJO |
|----------|-----|-----|--------|
| 2000/01  | 26  | 14  | 7      |
| 2001/02  | 25  | 14  | 11     |
| 2002/03  | 14  | 6   | 11     |
| 2003/04  | 22  | 14  | 10     |
| 2004/05  | 26  | 8   | 2      |
| 2005/06  | 28  | 15  | 2      |
| 2006/07  | 27  | 15  | 4      |
| 2007/08  | 32  | 10  | 17     |
| 2008/09  | 26  | 25  | 6      |
| 2009/10  | 16  | 7   | 6      |
| 2010/11  | 31  | 9   | 6      |
| 2011/12  | 20  | 19  | 13     |
| 2012/13  | 13  | 12  | 4      |
| 2013/14  | 28  | 3   | 9      |
| 2014/15  | 28  | 15  | 5      |
| Sum      | 362 | 186 | 113    |

The results show that there are 362 cold surge events, 186 MJO events, and 113 cold surge-MJO events simultaneously, with a total EAWM period in 2000-2015 is 1803 days. The most cold surge events has occur in 2007-2008, MJO in 2008-2009 and the most cold surge-MJO events simultaneously occur in 2007 - 2008.

Cold surge propagation can be seen in figure 4. The negative value in figure 4 defines the north wind, and the positive value defines the south wind. Wind velocity is illustrated with different colors for each interval. Furthermore, meridional wind velocity is represented by color gradation and wind direction represented by arrows with maximum speed is 15 m/s (figure 4). The Domination of north wind caused by different position of the sun in Australia so the pressure gradient in the north-south area became stronger [6].

In figure 4a, the north wind conditions in 2012-2013 from the South China Sea turn eastward at Java Sea with 1-3 m/s. It also happened in 2010-2011 and its climatological condition in 2000-2015. Cold surge is sourced from the South China Sea and can be seen in figure 5c. In climatological condition, cold surge wind pressing the speed of south wind and dominate Java Island especially in Jakarta with 1-6 m/s. Compressive power of cold surge strongly influenced by frequency of its occurrence. Cold surge was low in 2012-2013 and less reducing the strength of the north wind (figure 4iii), so the Java Island still crossed by Australian monsoon patterns. The wind pattern will shift up to 15ºS when the cold surge is commonly occurs, like in 2010-2011, with the north wind propagation reach 3 m/s in Java Island. In figure 5c, meridional winds generally reach the island of Sumatra with velocity 1-3 m/s. Cold surge events may increase north wind propagation in the equatorial area as a result of wind propagation towards the south from Siberian-Mongolia High (SMH) [10].
3.3. Influence of MJO on cold surge events in Indonesia

Defining the MJO phase is performed based on convective region of OLR that greatly affects the water vapor mass and rainfall distribution in the East Indian Ocean, Maritime Continent and West Pacific Ocean [2]. Furthermore, there are 113 total days of MJO and cold surge events simultaneously (table 1).

![Figure 4](image)

**Figure 4.** Composite map of average meridional wind on EAWM periods from 2010-2011 (Panel i), 2012-2013 (Panel ii), dan 2000-2015 (Panel iii) when (a) no cold surge, (b) cold surge, and (c) daily averaged of EAWM periods.

![Figure 5](image)

**Figure 5.** Time-latitude cross-sections of the fastest meridional wind when (a) cold surge, (b) MJO, and (c) cold surge-MJO occurs simultaneously from day -5 to day 5.

Figure 5 shows the effect of MJO oscillation from the west on cold surge propagation to the south at the largest meridional wind speed for each events. The color on hovmoller diagram and the y-axis on the graph below shows wind velocity, with a contour line defines the north wind. The x-axis from figure 5 is the lag day after and the occurrence of intra-seasonal climate variability with the highest meridional
wind speed. The rising speed of north wind is seen on five days before the strongest cold surge occurs, while the wind propagation in 10°S requires five days later. Such as Compo et al. [17] results, about a strong relationship between cold surge in 15°N, 115°E and convection activities in the southern part of Indonesia.

MJO events with the largest meridional wind causing cold surge pressure stuck by the western wind following the power of convection from MJO in 6°N, so the cold surge reduce the spread of meridional wind. It’s influenced by frequency of cold surge itself. When the frequency of cold surge events continually happens, the lag time when wind is going to equator requires 4-6 days after cold surge was detected in Hong Kong [3].

3.4. Characteristics of Indonesian Rainfall when influenced by cold surge and MJO Events

Indonesia has unique patterns of annual and inter-annual climate variability, because there are differences in rainfall patterns in every part of the region [18]. Daily rainfall distribution on a zonal average at 105-115°BT in 2000-2015 shown in figure 6.

In figure 6, Region of Java Island marked by line breaks at 5-10°S, while at 0-15°N representing the South China Sea region. Java Island has daily rainfall intensity about 10-15 mm. Distribution of 10-25 mm rainfall in the South China Sea varies and have a great intensity from 16 November-16 February then weakened until 1 March. The movement of water vapor horizontally when intra-seasonal phenomena occurs can be seen on figure 7.

Figure 7 showing average mass of water vapor is in 5-20°N. According to Zhou and You [4], the main source of that mass comes from the East China Sea and the Pacific Ocean side. While no cold surge, a low wind speed makes water vapor mass from the East China Sea cannot carried over to Indonesian territory. While cold surge, water vapor mass has been transported from East China Sea and increasing the intensity of water vapor in the area of South China Sea, then the mass spreading to the Java Sea (figure 7b). Futhermore, MJO events can also increasing the speed of water vapor transport in the Philippine Sea and the Java Sea region that come from Indian Ocean (figure 7c). The moisture transport happens because of propagation to the east that will causes rainfall anomaly in some areas of Banda Sea and Java Sea [15]. When both intra-seasonal climate variability occurs simultaneously, rising a mass of large water vapor that concentrate in the South China Sea and Java Sea and also potentially for produce rain clouds.
Figure 7. Moisture transport during the occurrence of (a) no cold surge, (b) cold surge, (c) MJO, and (d) cold surge-MJO simultaneously.

The velocity of vertical water vapor mass tend to move fast horizontally in the oceans caused by topographic fluctuations in the Indonesian area that have different geopotential heights [4]. Its raises sharp deflection of water vapor transport in Sunda Strait. Mass movement of moisture in the air have negarife correlation with OLR [2]. The larger water vapor transport then the smaller value of OLR impact on the amount of potential convective cloud formation.

Figure 8. Composite map of daily rainfall (GSMaP) in 2007-2008 (Panel i), 2012-2013 (Panel ii), and 2000-2015 (Panel iii) during (a) no cold surge, (b) cold surge, (c) MJO, and (d) cold surge-MJO simultaneously.

Hattori et al. [9] tells that there are 11 cold surge events that greatly affect rainfall enhancement in Indonesia, especially in Java Island. Some of that may spread to Java Island, but its propagation can also be reducting or following the MJO convective power of phases 4 and 5. Cold surge stuck can also be caused by Easterly Wave, Borneo Vortex, and cyclone in the middle of South China Sea [3].

In 2007-2008, the most cold surge and MJO events occur simultaneously. Rainfall intensity in Java Island especially in Jakarta has the intensity 30-50 mm/day when MJO and cold surge occur
simultaneously (figure 8). Flood incident in Jakarta caused by the presence of north winds and convective clouds that causing rainfall evenly on the Java Island. Climatologically, rainfall occurs when cold surge has an intensity 10-15 mm/day in Java Sea, South China Sea, Java Island, Sumatra and Kalimantan (figure 9). When MJO occurs, increased rainfall moving up to Eastern Indonesia, but in South China Sea its rainfall intensity not as strong as cold surge events. When both intra-seasonal variability active the intensity of rainfall is up to 15-25 mm/day in Java Sea and South China Sea.

The anomaly map that shows on figure 9 has a percent unit (%) which indicates increasing and decreasing rainfall climatology on EAWM (figure 3). Decreasing rainfall is represented by negative value and increasing rainfall is represented by positive value. Increased rainfall in 2007-2008 in the South China Sea during cold surge is 150%. But, decreased rainfall is also seen in Indonesian region at 20-75%. While MJO occurs, increased rainfall seen in Eastern Indonesia at 50-150%, East Kalimantan is 10-100% and slightly in Java Island at 5-50%. When MJO and cold surge occur simultaneously can increse rainfall more than 200% in the East Indian Ocean. Futhermore, Increased daily rainfall also seen in the South China Sea, Java Sea, Banda Sea, Central Java, NTT, NTB, and Jakarta at 25-150%.

In 2012-2013, cold surge events can cause positive rainfall anomaly at 10-100% in the Indonesia (figure 9i). The largest increase in rainfall intensity located around Banda Sea and Sunda Strait up to 150%. Decreased rainfall also occurs in Central and West Kalimantan 5-50%. The occurrence of MJO also improves rainfall in area that the conditions is almost same as the effect of cold surge. The greatest increased rainfall is located in the East Indian Ocean region up to 200%. While MJO and cold surge occur simultaneously, rainfall is seen rising in region that affected with MJO and cold surge respectively. However, its large increase is about 25-200%.

Climatologically, cold surge is generally affect on Indonesian Oceans. Cold surge that blows from the South China Sea through Java Sea to Flores Sea in Indonesia. The incidence of rainfall on the track depend on water vapor conditions in the South China Sea. The averaged rainfall increase in the trajectory ranges at 10-50%, including Jakarta. Increased rainfall 100% also seen in the South China Sea and Philippine Sea. The influence of MJO climatologically on West Indian Ocean and Indonesia Ocean with a large increase at 25-150%. While MJO and cold surge occur simultaneously, increased climatological rainfall at 25-150% seen in Indonesian Ocean. However, decreased rainfall usually occurs in mainland area at 5-50%.
4. Conclusion
In the cold phase, cold surge and MJO events have a relation that can be analyzed with meteorological parameters such as meridional wind, rainfall, and moisture transport. The results show that both phenomena effect on increasing Indonesian rainfall, especially Java Sea. The results showed that during East Asian Winter Monsoon (EAWM) in 15 years (2000-2015), there are 362 cold surge events, 186 MJO events, and 113 cold surge events were associated with MJO events. Moisture transport value shows that East China Sea is the source of extreme rainfall on cold surge events, while MJO has two sources of water vapor transport i.e. Indian Ocean and East China Sea. While cold surge and MJO occurs simultaneously causes the source of water vapor move to Indonesia and increase rainfall up to 100-150% from its climatological conditions.

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