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Identifying precursor of Sumatra squall line

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Abstract. Sumatra Squall Line (SSL) is a detectable mesoscale meteorological phenomenon at least prior to 3 hour using Doppler radar imagery interpretation. By identifying precursors, SSL can be detected 6-12 hours earlier before the occurences. Infrared data from MTSAT satellite were used to identify clusters of SSL clouds which then produce two types of SSL with different orientations, namely Northwest SSL (oriented northwest - southeast) and Northeast SSL (oriented northeast - southwest). Wind, helicity, and moisture transport were selected as precursor variables due to their importance information of squall line. The results of the precursor variable pattern comparison in the case of SSL with non-SSL showed clear differences. Bottom layer convergence and the westerlies wind patterns were proven to be formed in SSL cases. Helicity concentration was related to orientation of SSL cloud cluster. The convergence of moisture transport was detected 6 hours before the SSL occurences.

1 Introduction

Squall line is a linear interference system consisting of many complex thunderstorms organized on meso-scale convective system (MCS) or in the form of clusters of clouds lined up in rows [1]. Tropical squall line phenomenon was first discovered by Hamilton and Archbold in 1945 in West Africa [2]. In the region of the southern Malacca Strait, there was a tropical squall line that happened quite persistent, i.e. during the day on the East Coastals and evenings on the West Coastals [3]. British Meteorologists during the colonial era (before 1962) believed that the squall line was derived from the island of Sumatra in South East Asia, so-called Sumatra Squall Line (SSL) [4]. Diurnal circulation due to thermal differences between land and ocean on coastal area around Malacca Strait was considered as the cause of the SSL formation [3-5].

SSL is causing adverse weather conditions such as heavy rain, lightning and strong winds of up to 6-8 hours around Malacca Strait which covers three regions of the country, namely Indonesia, Malaysia, and Singapore [3], [6–8]. Heavy rains due to SSL intensity, which could reach 90.4 mm/hour, have caused flash floods in Malaysia and Singapore [9, 10]. While the high winds caused the collapse of the trees and damaging roofs of the buildings, with the highest speed ever recorded at 144 km/hour [11, 12].

Extreme weather due to SSL is classified as a dangerous weather conditions which need an early warning according to WMO technical regulation No. 49 Vol. I. This terminology has been also adopted by many meteorological agencies in South East Asia countries including Indonesia, Malaysia, and Singapore. However, construction of early warning is still depending on the detection of a new SSL that can only be done 3 hours before the occurrence of the real time data analysis of Doppler radar [13, 14].

Detection of SSL > 3 hours earlier is required to generate faster early warning, in order to minimize the damaging effects of the SSL. Peters and Schumacher (2014) succeeded in identifying MCS at 6 hours prior to the occurrence of a change of synoptic patterns as a precursor [15]. But the types of MCS are more specific, such as the squall line, no further assessment of the precursor. With the selection of some of the meteorological variables that becomes an important key squall line formation of literature, then the changes in the patterns of spatial and temporal as SSL precursors was studied.

The formation of convective cloud clusters in the squall line requires three important factors, namely: the availability of moisture, the process of appointing an air mass, mechanically and thermally, and vertical wind shear [16]. Variable of moisture transport vertically was integrated to show the source of moisture and its transport direction in a region [17]. While the quantity of vertical wind shear can be seen from the helicity values were calculated as Storm relative helicity (SRH) [18-20]. Positive helicity indicates a change in wind direction that follows the pattern clockwise to the altitude (veering), while the negative helicity indicates a change in wind direction that follows the pattern counterclockwise to altitude (backing) [21, 22].

According to the National Environment Agency [6], the convergence of winds in lower troposphere (<1 km) and wind patterns in layers of 2-4 km westerlies are blowing from Sumatra Island to Singapore. It plays an important role in the formation and movement of SSL. Large scale convergence is very important in the removal

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of wet air masses over a large area during the phenomenon of MCS [16]. This convergence will make the air mass becomes saturated before convection begins and continually create disturbances in the environment after the convection [16].

2 Methodology

In this study, several types of data were required for sample selection and determination of the case, with the SSL precursor study area covers the northern part of the island of Sumatra, Peninsular Malaysia, Singapore and Batam (Figure 2). Variables used as precursor variables are variables that were selected based on meteorological literature, namely: wind, helicity, and transport moisture. Furthermore, a simplified method (a composite analysis) was used to determine significant spatial and temporal patterns. Using the same method, the precursors were then tested on a sample of non-SSL convective events (cases non-SSL).

2.1 Data

There are four types of data used in the study: the report data, satellite Imagery data, rainfall data of meteorological stations, and reanalysis data. Report data consist of annual weather report of Singapore Meteorological Agency (NEA), typhoon tracks reports of the Regional Specialized Meteorological Center (RMSC) Tokyo by the Japan Meteorological Agency (JMA), and reports of MJO phase of the Australian Bureau of Meteorology (BoM). NEA's annual report (www.nea.gov.sg) in 2010-2013 was used to obtain dates of SSL events. While the typhoon track and report of MJO phase was used to separate the dates between the occurrence of SSL, typhoon in the South China Sea and the Philippine Sea, as well as strong MJO in the Indian Ocean. Both phenomenons are regarded as a trigger of SSL formation [4, 23, 24] therefore needs to be separated from the sample of SSL events to get the case sample that was not caused by typhoon and MJO.

From the samples of selected cases, hours of SSL incidence of MTSAT satellite Imagery canal IR1, IR2 and IR3 [25] were specified. Furthermore, the daily rainfall data in the Hang Nadim Meteorological Station in Batam and Changi Meteorological Station in Singapore were used in the analysis of heavy rain to get sample dates of convective non-SSL events which is also timely determined base on satellite imagery. Lastly, ERA Interim reanalysis of data from the European Centre for Medium-Range Weather Forecasts (ECMWF) with 0.125o spatial resolution and temporal resolution of 6 hours (http://apps.ecmwf.int) is used to calculate the value of the variable precursor of the study area.

2.2 Method

The research method consists of three main steps: identification of SSL, the determination of variable of precursors, and comparison with the case of non-SSL. Identification is done to obtain SSL case samples SSL in 2010-2013. NEA's annual report is used to obtain an SSL date of the occurences which further separated from the active typhoon and MJO events. Moreover, the incidence of SSL hours is determined by filtering three channels of satellite Imagery (IR1, IR2, and IR3) which meets the following criteria:

• Extending line clouds cluster which was detected in the coverage area of the radar image data in Singapore (0.5-2 °N, 103-104.6 °E) as shown in Figure 1.
• Meets MCS categories according to Chen et al. [26] that the precipitation area of cold cloud tops temperature <208 K.
• Values of Brightness Temperature Difference on IR1-IR2 by -2 to 2°K and in IR1-IR3 at ~ 0°K showed deep convection [27].
• The length of clouds row ≥ 100 km [2].

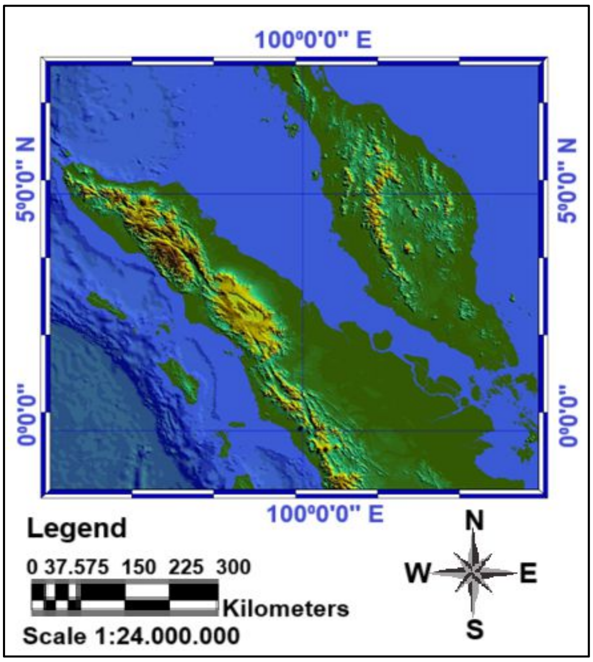

Fig. 1. Study area of SSL precursor.

Date and time of the occurences on the sample was used as a reference in data collection reanalysis so that the value of each variable precursor ranging from 6-24 hours before the occurences with the composite analysis. Further analysis of were focused on the most significant temporal patterns at that time range with zoning studies in A, B, and C area as can be seen in Figure 2.

The final step was the comparison with non-SSL cases. For non-SSL, sample cases are required to be at the same time frame, i.e 2010-2013. Non-SSL sample case was selected using heavy rain analysis of the daily rainfall data by Hang Nadim Meteorological Station of Batam, Indonesia and Changi Meteorological Station of Singapore. The heavy rain analysis is based on the Regulation KBMKG 009 of 2010 [28] on the criteria of the rain; the rain with an intensity of at least 50 mm/day was used as a threshold determination of the dates of occurrence of heavy rain and the intensity of at least 20 mm/day as the threshold of moderate rain. Next, dates when heavy rain happened in Batam and/or Changi with moderate rain in Batam or Changi were selected. Determination of hours of events in the case of non-SSL is similar to the case of non-SSL under the condition of the cloud cluster line was not elongated.

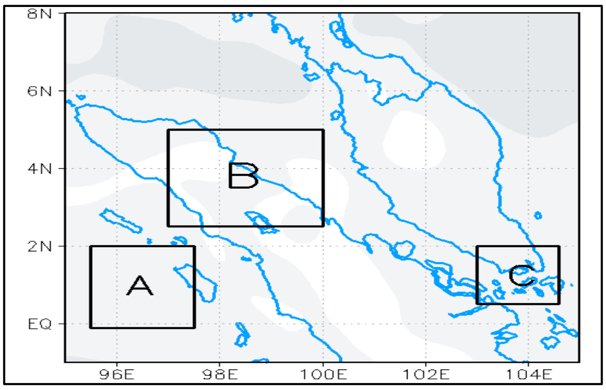

Fig. 2. Study Area of SSL is divided into A, B, and C area.

As in the case of SSL, the date and time of the occurences on a sample of non-SSL was used as a reference in data collection reanalysis in order to obtain the value of each variable of precursors in the period selected by the composite analysis. The next step was checking whether the spatial and temporal patterns of precursor in the case of SSL are different from the case of non-SSL or not.

3 Results and discussion

3.1 Sample case of SSL

From the identification of SSL case, SSL obtained two types of cases which have a different cloud clusters orientation, Northwest SSL (oriented northwest-southeast) and Northeast SSL (oriented northeastsouthwest). Total sample case of SSL in 2010-2013 were 18 events, with a Northwest SSL cases as many as 14 events and Northeast SSL as many as four events.

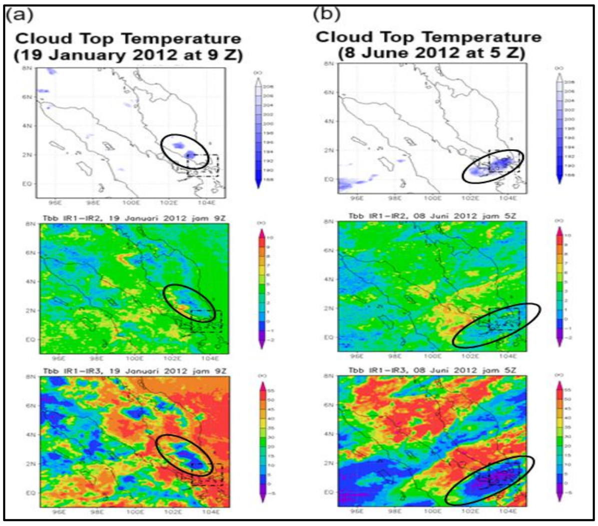

Fig. 3. (a) The Northwest SSL sample case and (b) Northeast SSL (indicated by a black ellipse) obtained from the identification using three filters satellite imagery MTSAT (TBB IR1, TBB (IR1-IR2), TBB (IR1-IR3)).

3.2 Variable precursor analisys of SSL

The temporal and spatial pattern of precursor variables of SSL case sample was analyzed to determine SSL precursor. From the analysis of temporal patterns in 6-24 hours before the SSL occurences, it is known that the wind variable consists of zonal wind and meridional wind don't have a significant change in that range, while helicity variable and moisture transport experienced significant change at 6 and 12 hours before the occurences. So the 6 and 12 hours prior to the event were selected as the time scale on the determination of SSL precursors.

3.2.1 Wind variable

Wind variable analysis was based on the statement of NEA (2007) on the convergence role in the lower troposphere (<1 km) and the westerlies wind patterns in the formation and movement of SSL. From Figure 4 it is known that wind convergence occurs in the lining of 0-1 km in area C in 6 hours and 12 hours before the occurences. But the wind patterns that formed convergence in the case of Northwest SSL is different from Northeast SSL.

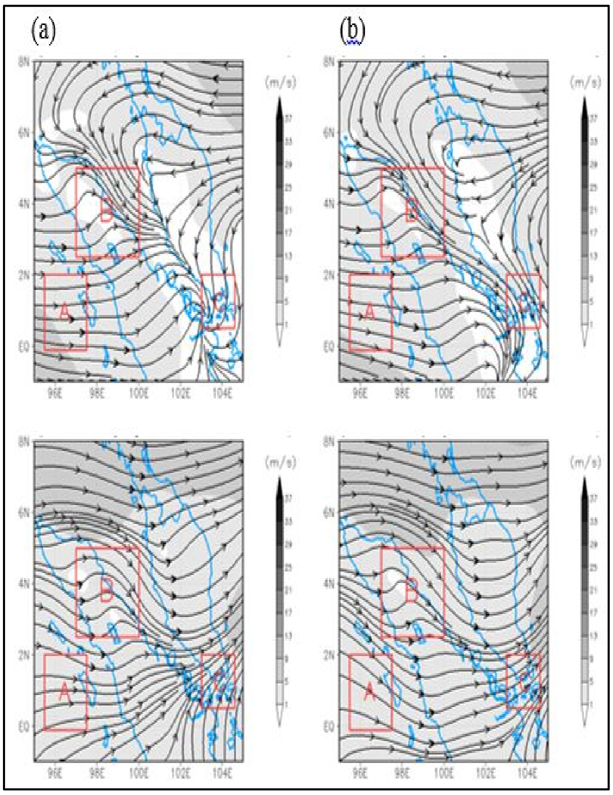

Fig. 4. (a) Pattern of composite wind of 0-1 km at 6 hours and (b) 12 hours before the occurences Northwest SSL (top) and Northeast SSL (below).

Westerlies wind patterns can be represented by positive vertical profile of zonal wind value (u) that has quite significant velocity changes in the area C (Figure 5a). The role of meridional wind (v) in the westerlies wind patterns are ignored because of the fluctuation is less significant vertically (Figure 5b).

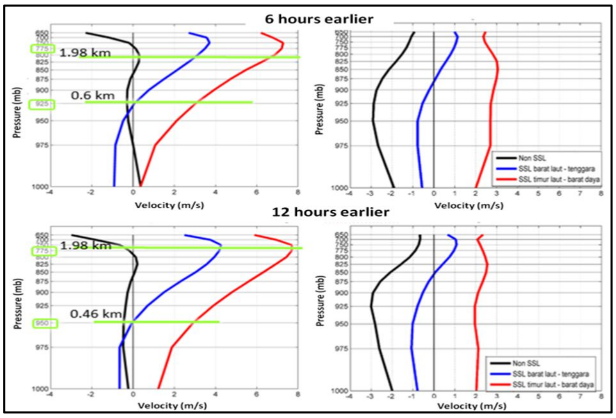

Fig. 5. (a) Profile of vertical zonal wind and (b) meridional wind in area C at 6 hours and 12 hours before the Northwest SSL occurences (blue line) and Northeast SSL (red line).

Vertical zonal wind patterns in the case of Northwest SSL and northeast is almost the same, but the zonal wind Northeast SSL stronger than Northwest SSL. Westerlies wind pattern is punctuated by wind spatial plot in Figure 6 and 7.

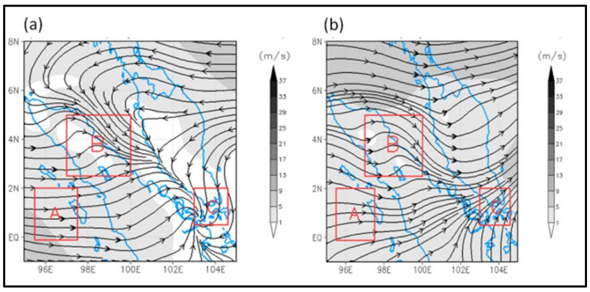

Fig. 6. (a) Wind streamline of layer 925-775 mb at 6 hours prior to the Northwest SSL event and (b) Northeast SSL.

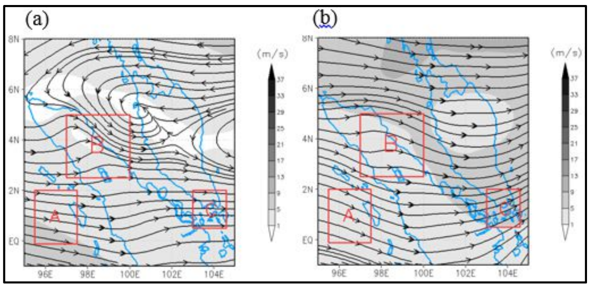

Fig. 7. (a) Wind streamline layer of 950-775 mb wind up to 12 hours before the Northwest SSL and (b) Northeast SSL occurences.

3.2.2 Helicity variable

From the results of helicity values plot in Figure 8 and 9, we know that there is a significant difference between the case of Northwest SSL and Northeast SSL. There was a wind backing mechanism in area C at 6 hours and 12 hours before Northwest SSL, indicated by the negative helicity (Figure 8a and 9a). However, negative helicity was really concentrated quite high in area C with a value around -10 to -30 m2/s2 at 12 hours before the occurences. This shows the wind backing mechanism that causes the lifting air mass on Northwest SSL occured at 12 hours prior to the event (Figure 10b).

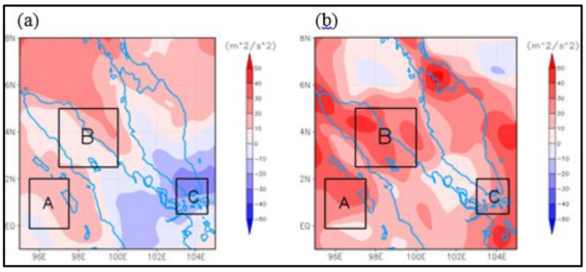

Fig. 8. (a.) Helicity values plot at 6 hours before the Northwest SSL occurences, and (b) Northeast SSL.

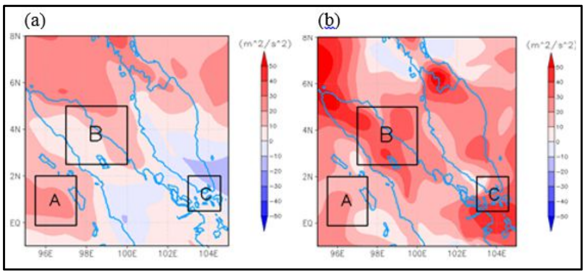

Fig. 9. (a.) Helicity values plot at 12 hours before the Northwest SSL occurences, and (b) Northeast SSL.

While on Northeast SSL, the value of helicity in area C is positive at 6 hours and 12 hours prior to the event (Figure 8b and 9b). However, 6 hours before the Northeast SSL occurences, positive helicity was highly more concentrated with a value of 10-50 m2/s2. It indicated lifting air masses by the wind veering occurs at 6 hours before the SSL occurences (Figure 10).

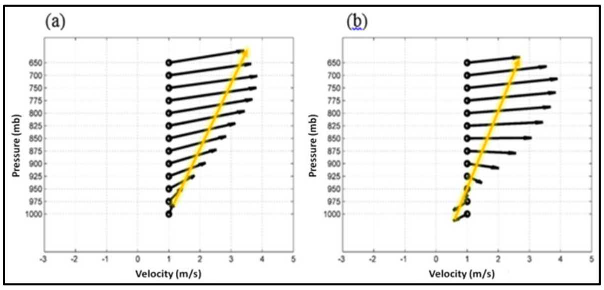

Fig. 10. (a) Profile of vertical wind 1000-650 mb at 6 hours before the Northeast SSL occurences and (b) 12 hours before the Northwest SSL occurences. The yellow line shows the wind shear vector.

From the two types of SSL, it is known that the formation of SSL cloud clusters occurs faster when the wind veering mechanism involves the air mass lifting. Meanwhile, the wind backing mechanism requires longer time for the air masses lifting that form clusters of clouds on SSL. It happens because of there is a gradual change of wind direction which made the process take longer time in vertical wind shear of the backing mechanism.

3.2.3 Moisture transport variable

Analysis of moisture transport variables was used to determine the source of the moisture on the formation of SSL in the surrounding area C. From Figure 11 and 12 it is known that the source of moisture during the establishment of Northwest SSL was different from Northeast SSL. At Northwest SSL, the main source of moisture came from local (area C). While on Northeast SSL, the source of the moisture came from local and got a sufficient supply from Malacca Strait.

Besides, it was known that the establishment of SSL required high moisture transport convergence, 6 hours prior to the event (Figure 13 and 14). This moisture transport convergence regions showed a mass of moist air that were accumulated in the area. At the establishment of Northeast SSL, there was a convergence of moisture transport in the area C which was slightly higher than Northeast SSL at around 0.002-0.006 kg/m2/s. While at Northwest SSL, there was a moisture transport convergence around 0.002-0.004 kg/m2/s in area C.

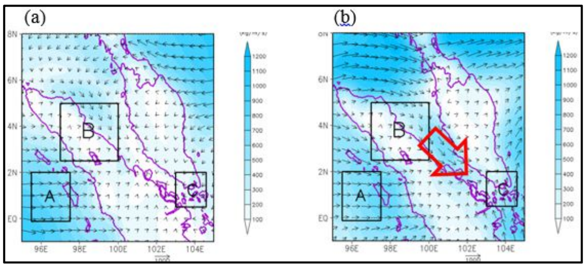

Fig. 11. (a) Moisture transport variables at 6 hours before the occurences Northwest SSL and (b) Northeast SSL.

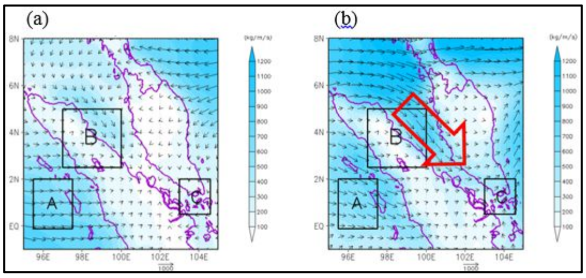

Fig. 12. (a) Moisture transport variables at 12 hours prior to the event Northwest SSL and (b) Northeast SSL.

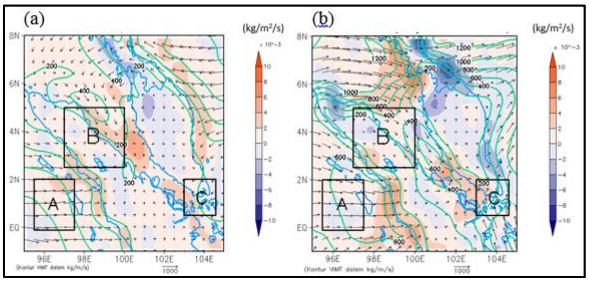

Fig. 13. (a) Moisture transport convergence, 6 hours before the Northwest SSL and (b) Northeast SSL occurences.

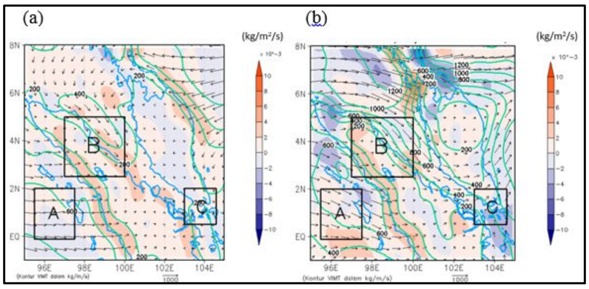

Fig. 14. (a) Humidity transport Convergence, 12 hours prior to the Northwest SSL and (b) Northeast SSL occurences.

3.3 Discussion

In this subsection, we will discuss the comparison of above variable pattern with a variable pattern of non-SSL case. It is conducted in order to check if the temporal and spatial patterns of SSL precursor were different from convective non-SSL occurencess. Case sample of non-SSL in 2010-2013 were obtained as many as 12 cases. By using the same procedure of SSL precursor variable pattern, we obtained precursors variables of spatial and temporal patterns in the case of non-SSL. Comparison of precursor variables patterns are shown in Table 1.

There were differences on the precursor variable spatial and temporal patterns on the case of SSL and non-SSL. It indicated that those three meteorological variables could be used as SLL precursor variable under certain conditions, such as:

a. There was a wind convergence in area C in troposphere layer 0-1 km at 6 hours and 12 hours before the occurences.
b. There was a westerlies wind pattern in area A, B and C at 6 hours and 12 hours before occurences with zonal wind that is stronger compared to meridional wind.
c. There was helicity concentration (positive or negative) in area C. Positive helicity concentration has role in the formation of Northeast SSL (the orientation of cloud cluster in Northeast – Northwest direction) 6 hours after. Meanwhile, negative helicity has role in the transformation of Northwest (cloud cluster orientation in the Northwest – Southeast direction) 12 hours after.
d. As normal convection (non SSL), the cloud formation process of SSL needed moisture source from local (area C). However, to form cloud cluster in SSL, moisture transport convergence area in area C was particularly needed since 6 hours prior to SSL occurences.

Table 1. Pattern of wind variable as precursor of SSLand non-SSL Case.

Wind Variable as Precursor		
Case	**Convergence at 0-1 km**	**Westerlies Wind**
SSL	strong in area C, 6 and 12 hours prior to event. (convergence patern of Northwest SSL and Northeast SSL are different)	At every area, layer 925-775 mb (6 hours prior to event) and 950-775 mb (12 hours prior to event) (positive zonal wind are dominant)
Non-SSL	None	At area A, layer 925-775 mb (6 hours prior to event). (meridional and zonal wind has even strong)

From the conditions shown in Table 1, it can be concluded that the wind variable, as in the statement of NEA (2009), has an important role in the formation of SSL, particularly the pattern of convergence in the lower troposphere and the westerlies wind patterns. While the vertical wind shear which is represented by the concentration of helicity determined the orientation of SSL cloud (Table 2). In general, significant changes in the pattern of precursor variables going on around the area C which is an area where the SSL case sample were detected.

Table 2. Pattern of helicity variable as precursor of SSL and non-SSL case.

Helicity Variable as Precursor (at 0-3 km)	
Case of SSL	**Case of Non-SSL**
• positive helicity concentration at area C in 6 hours prior to northeast SSL occurences. • negative helicity concentration at area C in 12 hours prior to northwest SSL occurences.	No positive nor negative helicity at area C.

Table 3. Pattern of moisture transport variabel as precursor of SSL and non-SSL case.

Moisture Transport Variable as Precursor (Vertically Integration at 1000-700 mb)		
Case	**Source of Moisture**	**Convergence of Moisture Transports**
SSL	Source of moistures at local (area C), during northwest SSL, Source of moistures at local (area C) and the Malaka Strait, during northeast SSL.	High convergence at area C, 6 hours prior to occurrences of SSL. Detail values : • Northeast SSL : 0.002-0.006 kg/m^2/s. • Northwest SSL : 0.002-0.004 kg/m^2/s)
Non-SSL	Source of moistures at local (area C) and the South China Sea.	None in area C. (however, it is extended a long coastal area)

4 Conclusion

This study aims to identify precursor of Sumatra Squall Line (SSL). After careful analysis and evaluation, there are two important points that can be concluded. First point, there are two types of SSL cloud cluster orientation, which are Northwest SSL (northwest–southeast orientation) and Northeast SSL (northeast–southwest orientation). It is related to the existence of positive and negative helicity concentration in the areas where SSL case sample was detected. The formation process of Northeast SSL was suspected to be faster than Northwest SSL. Second point, there was two potential times to detect SSL precursor which are 6 hours and 12 hours before the occurences.

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