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The Atmospheric Dynamics Related to Extreme Rainfall and Flood Events during September-October-November in South Sulawesi

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Abstract
This study was conducted to analyse the occurrence of extreme rainfall and the dynamics of the atmosphere prior to the occurrence of extreme rainfall and flood events in South Sulawesi during September-October-November (South Sulawesi's dry season). The data used is daily data for the period 2001-2020. Using 50 mm/day and the 90th percentile rainfall threshold of 119 rain stations distributed over 24 regencies, extreme rainfall events in each region were identified. Furthermore, after screening for extreme rainfall events followed by flood events, a composite analysis was carried out to obtain patterns of atmospheric conditions before the extreme rainfall events. The results of the study confirm that spatially, the highest extreme rainfall indices values dominate in the western and northern regions of South Sulawesi, both frequency and intensity indicators. Flood events in South Sulawesi during September-October-November 2001-2020 were recorded as 23 days, of which 19 days were the flood events after extreme rainfall events. The dynamics of the atmosphere before the extreme rainfall event followed by the flood event showed anomalies in precipitable water, 850 mb winds, and 200 mb winds. An increase in the amount of precipitable water and a wind speed of 850 mb, as well as a decrease in wind speed of 250 mb compared to normal in the South Sulawesi region and its surroundings, has resulted in an increase in the formation of rain clouds that have the potential to increase the chance of extreme rainfall.

Keywords: extreme rainfall, flood, atmospheric dynamics, South Sulawesi.

1. Introduction

South Sulawesi is a province in Indonesia that is prone to floods which regularly cause heavy losses in this area. In 2009-2019, a total of 340 flood events were recorded with various intensities (BNPB, 2021). Typically, floods are preceded by either intense rainfall in the preceding day or continuous rainfall over an extended period. Furthermore, the capacity of river catchments also plays a significant role in determining the characteristics and severity of flood occurrences (Merz *et al.,* 2021). Extreme rainfall is essentially a form of natural variability, but currently the frequency and intensity of extreme rainfall and flood events are increasing, affecting all climate regions and seasons (Dey *et al.,* 2019; Myhre *et al.,* 2019; Tabari, 2020).

Extreme rainfall events can be caused by various factors, for instance global, regional and local factors. Global factors for example El Niño/La Niña activity (Al-Fugara *et al.,* 2023; Amalia, 2023) play a substantial role. This involves significant changes in sea surface temperature, Dipole Mode and the active Madden Julian Oscillation (MJO) (Hendrawan, *et al.,* 2019; Lestari *et al.,* 2019; Fauzi *et al.,* 2018). Regional factors such as monsoon activity that experience anomalies in the form of direction and speed, the emergence of tropical disturbances (tropical cyclones, low-pressure areas, eddies, or the presence of Inter Tropical Convergence Zone-ITCZ), also contribute. Simultaneously, several local factors for instance local topography, elevation, atmospheric lability and local convective also have an impact (Basso *et al.,* 2023). In 2007, a study analysing data spanning 22 years from 1982 to 2003 identified the primary factor behind floods in Indonesia as the occurrence of extreme wet weather systems (Chan *et al.,* 2023). These systems are typically triggered by a combination of convective rains, converging weather patterns and the influence of tropical cyclones, which have the potential to result in both localised and widespread flooding. In addition, the La Niña event has also increased the intensity of flooding in Indonesia (Chaqdid *et al.,* 2023).

Climatologically, South Sulawesi is influenced by the monsoon system. Two influential monsoon systems are the northwest monsoon which typically occurs from November to March and the southeast monsoon which occurs from May to September. In addition to the monsoon effect, the difference in topography causes the weather and climate in South Sulawesi to be influenced by local wind systems, such as land-sea winds and mountain-valley winds (Chaubey *et al.,* 2023). Daily wind systems commonly trigger local weather variations. Furthermore, orographic conditions can increase the rainfall on the windward slope (Hao *et al.,* 2023).

Located between 0°12' – 8' S and 116°48' – 122°36' E, South Sulawesi covers an area of 46,717.48 km^2 and is divided into 24 regencies namely; Bantaeng, Barru, Bone, Bulukumba, Enrekang, Gowa, Jeneponto, Kepulauan Selayar, Luwu, Luwu Timur, Luwu Utara, Makassar, Maros, Palopo, Pangkep, Parepare, Pinrang, Sidrap, Sinjai, Soppeng, Takalar, Tana Toraja, Toraja Utara and Wajo. The mountainous area of this province extends from the middle to the south, resulting in distinct seasons in the west and east. The beginning of the rainy and dry seasons varies from region to region. For example, the rainy season in the western regions typically begins in October/November while the dry season starts around April/May (Hong *et al.,* 2023). Conversely, the rainy seasons in eastern regions generally begin around March/April and the dry season begins about July/August. However, the beginning of the rainy and dry seasons in the southern and northern regions is more varied (Jian *et al.,* 2023). In South Sulawesi, the peak of the rainy season may differ, but the peak of the dry season is typically in August/September (BMKG, 2021). In addition to the duration of the season, the rainfall during the season is also different in each region (Chen *et al.,* 2017).

Although there is a national-scale analysis of the meteorological factors that lead to flooding in Indonesia, there is a dearth of information available at the regional scale, particularly in relation to South Sulawesi Province, and the majority of the publish work focuses on the flood events that occurred at a specific location within a limited time. Thus, the purpose of this study was to identify atmospheric dynamics patterns or characteristics that cause extreme rainfall and flooding in South Sulawesi during September-October-November using 20-year long-term data. Obtaining average atmospheric conditions that can cause extreme rainfall and flooding is crucial in terms of forecasting and mitigating flood events. In the following section, data and analysis techniques are described, followed by specific results, a discussion and finally a conclusion (Cheong *et al.,* 2023).

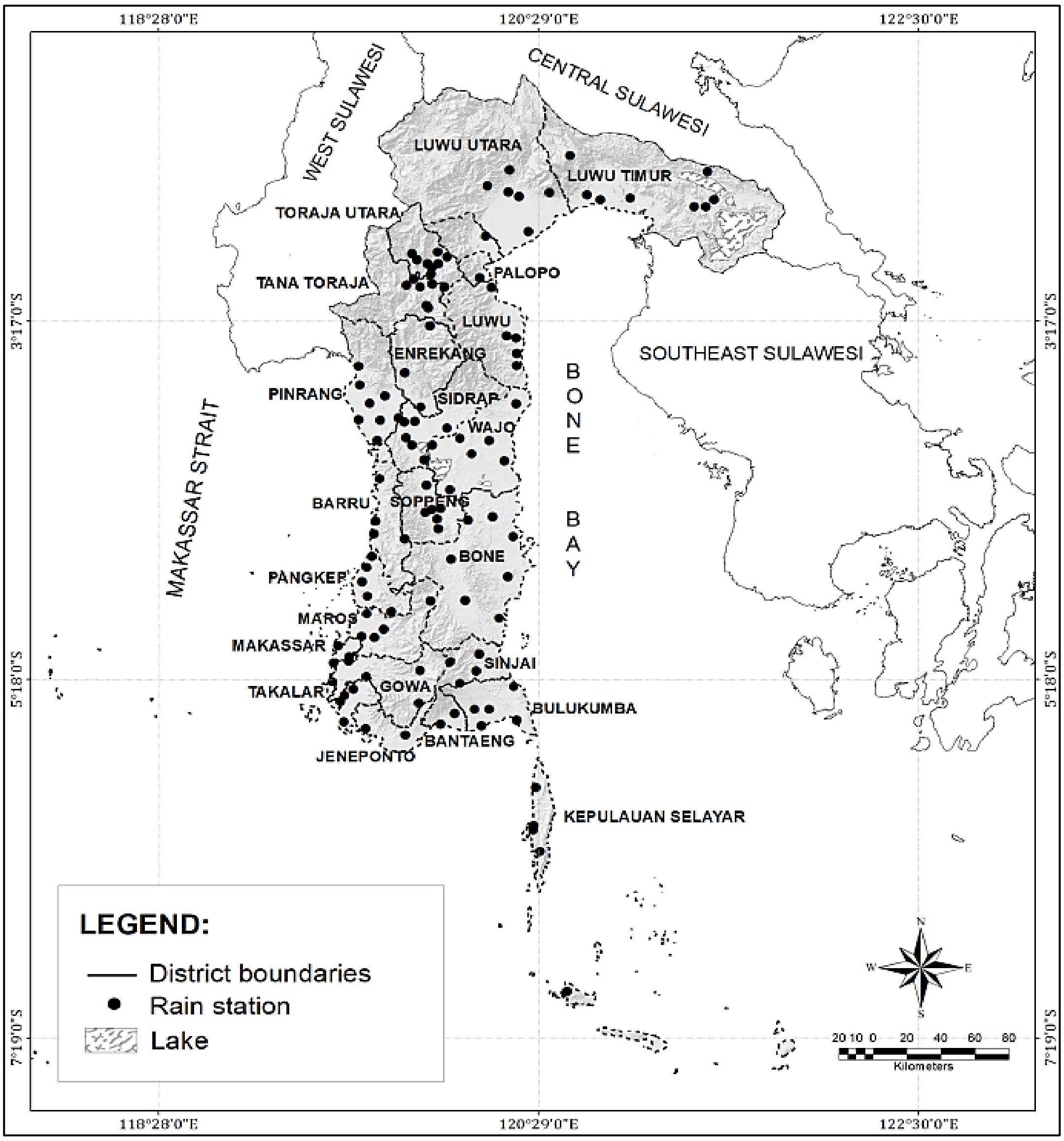

Figure 1. Study Area.

2. Research Methods

The data applied in this study are daily rainfall from Badan Meteorologi, Klimatologi dan Geofisika (BMKG) Region IV in Makassar, flood events from Badan Nasional Penanggulangan Bencana (BNPB) and atmospheric dynamics reanalysis data from NCEP-NCAR for the period of 2001 to 2020. Figure 1 reveals the locations of 119 rain stations that were used. For the analysis of atmospheric dynamics during the September-October-November floods, we used variables: precipitable water, 850 mb wind and 200 mb wind between 20° N - 20° S and 80° - 160° E with 2.5° x 2.5° horizontal resolution.

2.1. Identification of Extreme Rainfall Events

The threshold values for extreme rainfall consisted of the fixed threshold and site specific threshold. The fix threshold employed was 50 mm of rainfall in one day (R50mm), which is used by BMKG as a category for heavy rain (BMKG, 2010). Concurrently, the site specific threshold was determined for each regency by calculating the 90th percentile (R90p) from the maximum daily rainfall data series per regency during the period 2001 - 2020. Likewise, in line with research conducted by Supari *et al*. (2012), threshold values were calculated using the highest daily rainfall for all rain stations for each regency.

Several extreme indices recommended by the World Meteorological Organisation were also calculated, including frequency indicators, R50mm and R90p, as well as intensity indicators, RX1d, RX5d and RTOT (Chkeir *et al*., 2023). The extreme indices used are presented in Table 1. This calculation was performed using R-Climdex (Dey *et al.,* 2019). To begin with, the daily rainfall data from all stations are grouped by regency to obtain the maximum rainfall value per regency (Fauzi and Hidayat, 2018). Using RClimdex, the rainfall data of each regency is processed by calculating the frequency and intensity of extreme rainfall events by year (Giarno *et al.,* 2018). The extreme rainfall indices were calculated on an annual basis, indicating that there was only one index value per year (Gosset *et al.,* 2023; Gupta *et al.,* 2023). The value of each index for 20 years was averaged so that the average value for each index for one location is obtained. These values are then categorised and mapped (Hendrawan *et al.,* 2019).

2.2. Identification of Extreme Rainfall before Floods

The identification of extreme rainfall was first conducted using South Sulawesi's historical flood data from BNPB. The flood data was subsequently compared with daily rainfall data on the day of the flood events and one day before the flood events in each regency. Days that have extreme rainfall and were followed by flooding events were recorded. Flood events that were recorded but not associated with extreme rainfall were also recorded, as shown in Table 1.

Table 1. Extreme Rainfall Indices.

Indices	Description
Frequency indicators	
R50mm	Number of rainy days with rainfall greater than or equal to 50 mm
R90p	Number of rainy days with rainfall greater than or equal to the 90th percentile
Intensity indicators	
RX1d	Daily maximum rainfall
RX5d	Maximum cumulative rainfall of five consecutive rainy days
RTOT	Amount of annual rainfall

2.3. Analysis of Atmospheric Dynamics before Extreme Rainfall and Floods

In this section, atmospheric reanalysis data was used to ascertain more about atmospheric conditions before extreme rainfall and flood events (Hidayat *et al.,* 2018). In this study, an analysis of the events was not carried out separately but climatologically analysed using composite analysis. Composite analysis was performed by calculating the average value of each atmospheric dynamic variable during September-October-November 2000 – 2020 together with the average value of the variables when there were extreme rainfall and flood events with the aim of obtaining the anomaly values. These values are then mapped and analysed for each variable (Hounvou *et al.,* 2023).

3. Results and Discussion

3.1. Results

Prior to calculating the extreme indices, we first established the threshold values for each region (Huang *et al.,* 2023; Iliadis *et al.,* 2023). The calculation revealed that the 90th percentile-based extreme rainfall threshold varies from 19 mm to 68 mm for different regencies in South Sulawesi. The lowest threshold value was observed in Parepare, while the highest was in Luwu Timur. Figure 2 illustrates the spatial distribution of these thresholds based on the 90th percentile.

Thresholds ranging from 51 to 100 mm were identified in the western region of South Sulawesi, incorporating areas from Pinrang to Maros (excluding Parepare, which had a threshold value of 6 to 20 mm), as well as in the northern (Luwu Utara and Luwu Timur) and eastern regions (Bone and Wajo; Wu *et al.,* 2023). Conversely, most other locations exhibited a threshold value between 21 and 50 mm. These locations include Makassar, Gowa, Takalar, Jeneponto, Bantaeng, Bulukumba, Kepulauan Selayar, Sinjai, Soppeng, Sidrap, Enrekang, Tana Toraja, Toraja Utara and Luwu.

The results of the frequency indicators calculation determined that the frequency of rainy days with rainfall of more than or equal to 50 mm (R50mm) varies in the range of 1 to more than 60 days per year (Wilby *et al.,* 2023). The highest average R50mm (more than 60 days per year), was found in Luwu Timur, Luwu Utara and Jeneponto, while the lowest frequency (1 to 10 days per year), was identified in Parepare (Figure 3a). In contrast, the different spatial distribution of the frequency of rainy days with rainfall greater than or equal to the 90th percentile exhibited a frequency of occurrence by 31 to 40 days per year in practically every region, excluding Bantaeng, Sinjai and Toraja Utara that had 21 to 30 events per year (Figure 3b).

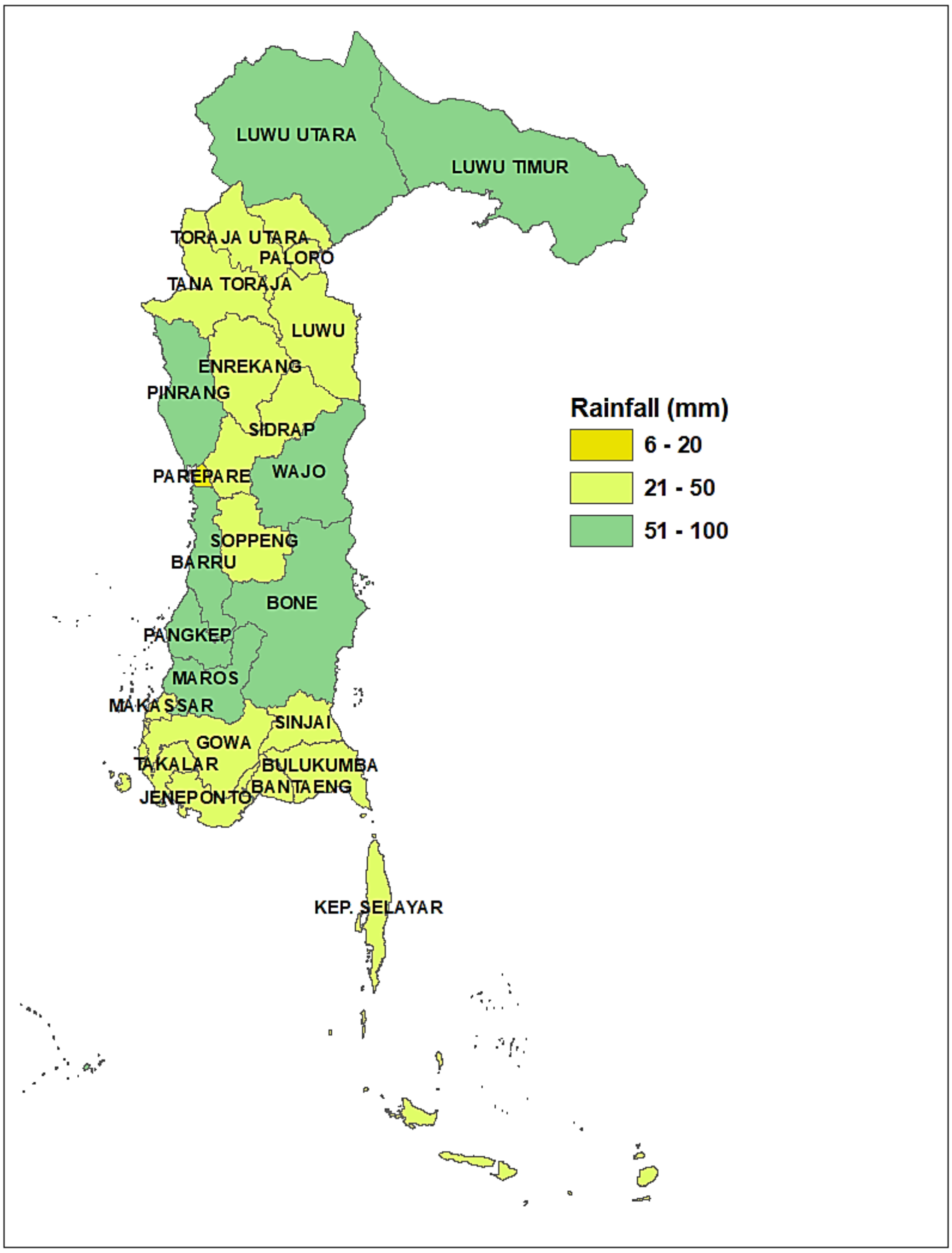

Figure 2. Spatial Map of Rainfall Threshold Based on 90th Percentile in South Sulawesi.

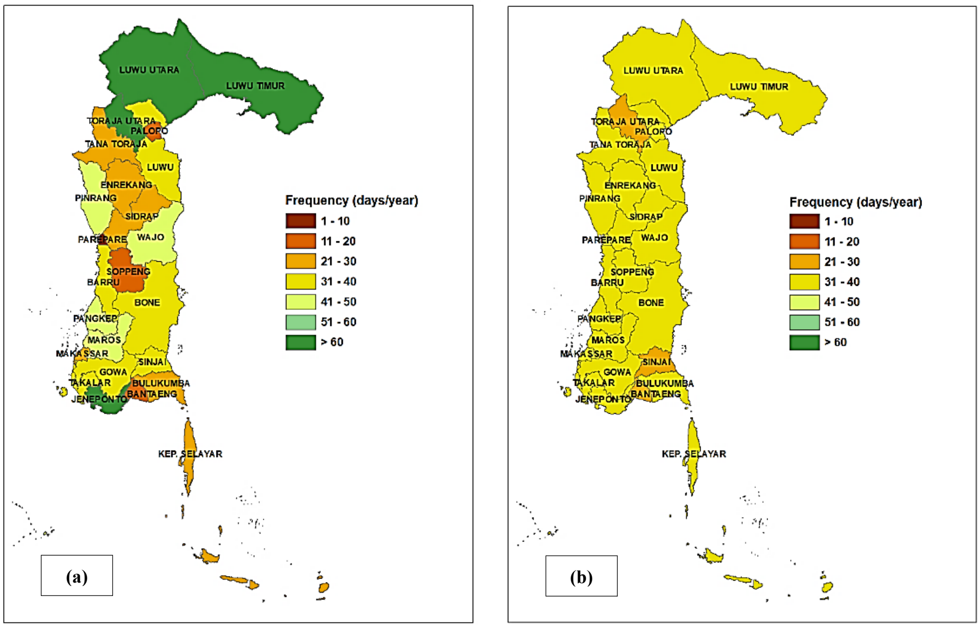

Figure 3. Spatial Map of Climatological Extreme Indices of (a) R50mm and (b) R90p in South Sulawesi.

In relation to intensity indicators, the climatological average of maximum rainfall in one day (RX1d) showed the values between 121 and 220 mm (Figure 4a). The lowest values with an average of 121 to 140 mm were located in Palopo, Tana Toraja and Bantaeng. Nonetheless, the highest values with an average value of 201 to 220 mm were identified along the western region of South Sulawesi, comprising areas from Pinrang to Gowa (excluding Parepare and Makassar) (Tamoffo *et al.,* 2023). Furthermore, the spatial distribution of average RX5d revealed a pattern that is predominantly similar to RX1d, where the highest values were ascertained in the western region, including areas from Barru to Takalar (excluding Makassar). Nevertheless, the lowest values were determined in Palopo, Enrekang and Parepare (Tradowsky *et al.,* 2023) on Figure 4b.

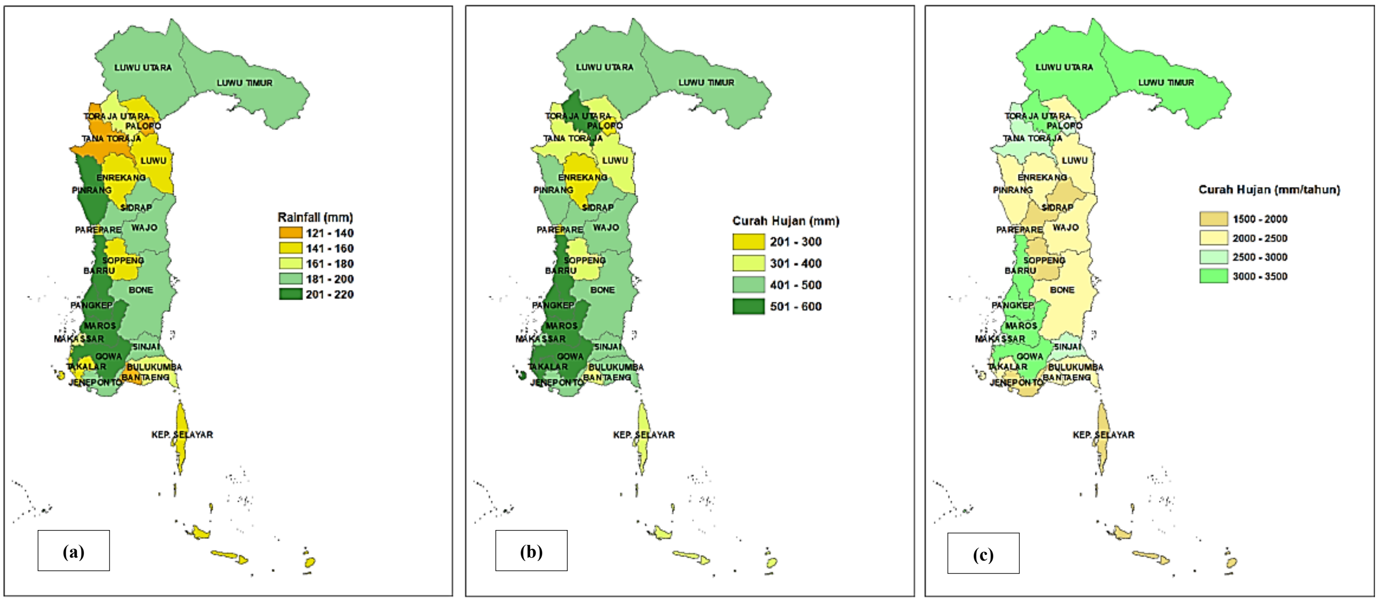

Figure 4. Spatial Map of Climatological Extreme Indices Of (a) RX1d, (b) RX5d, and (c) RTOT in South Sulawesi.

The average annual rainfall (RTOT) confirmed a range of values between 1500 mm to 3500 mm per year (Umer *et al.,* 2023) on Figure 4c. The wettest areas with an average rainfall of 3000 – 3500 mm per year were observed along the western region of South Sulawesi, incorporating areas from Barru to Gowa (excluding Makassar) and the northern regions (Luwu Timur, Luwu Utara and Toraja Utara). Areas with the lowest amount of rainfall ranging from 1500 to 2000 mm per year were observed in Sidrap, Soppeng, Jeneponto and Kepulauan Selayar (Wasko *et al.,* 2023).

At the same time, other regions had an amount of rainfall ranging between 2000 to 3000 mm per year.

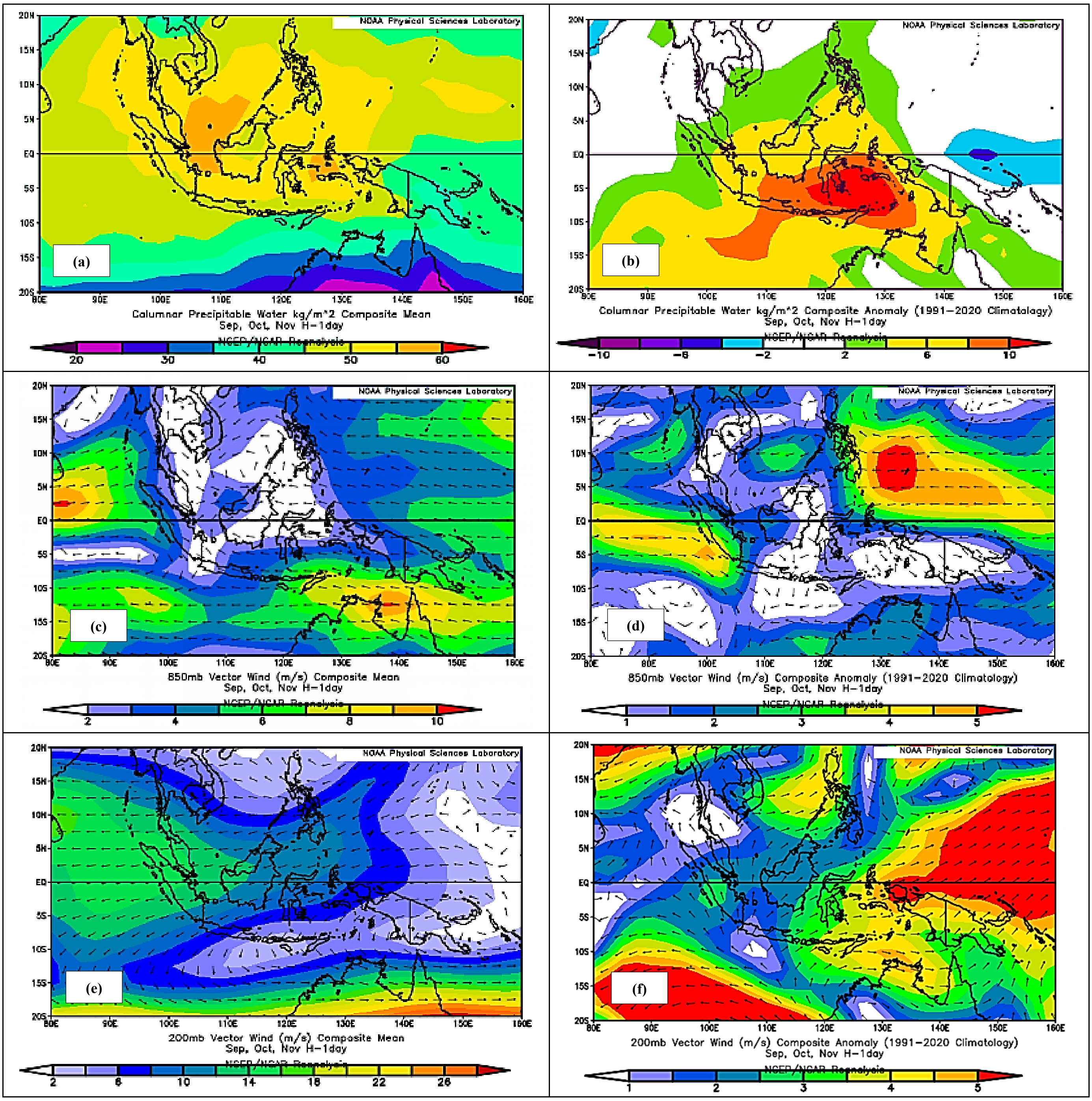

Figure 5. Composite of (a) Precipitable Water, (c) 850 Mb Wind, (e) 200 Mb Wind and Anomaly of (b) Precipitable Water, (d) 850 Mb Wind, (f) 200 Mb Wind.

Floods during September-October-November 2001 – 2020 predominantly occurred in the northern and eastern regions of South Sulawesi, such as Luwu Timur, Luwu Utara, Luwu, Palopo, Bone, Sidrap and Wajo, as well as in one area in the west, specifically Pinrang. Flood events during September-October-November 2001 – 2020 and the extreme rainfall before are presented in Table 2.

Conversely, the composite analysis of the 200 mb wind revealed a reduction in wind speed throughout Indonesia, both in the northern and southern hemispheres, with a maximum decrease in speed of > 5 m/s (Figure 5f). This was denoted by the change in wind direction in the area, suggesting that there was a slowdown in wind speed (Lestari *et al.,* 2019; Bosch *et al.,* 2023; Li *et al.,* 2023). The highest decrease in wind speed was in the eastern part of Indonesia, covering the northern Pacific Ocean of Papua, Papua, North Maluku, Maluku, Banda Sea to Nusa Tenggara and the south sea of Nusa Tenggara, ranging from 3 to more than 5 m/s.

Table 2. Extreme Rainfall Events Followed by Flood Events During September-October-November 2001 – 2020.

Flood Events (dd/mm/yyyy)	Location	Rainfall (mm)	Extreme Rainfall Events (dd/mm/yyyy)
05/09/2007	Luwu Utara	71	04/09/2007
04/09/2008	Luwu	107	03/09/2008
17/09/2010	Luwu	57	16/09/2010
18/09/2010	Palopo	43	17/09/2010
01/11/2010	Luwu Timur	70	31/10/2010
01/11/2010	Pinrang	60	01/11/2010
01/11/2010	Wajo	56	01/11/2010
14/09/2011	Luwu Utara	139	14/09/2011

3.2. Discussion

Comparing the results of calculations for the two types of thresholds, 50 mm and 90th percentile, the 50 mm per day rainfall threshold is close to the threshold value for the 90th percentile in South Sulawesi, as realised from the average rainfall threshold for the 90th percentile. Using a threshold of 50 mm, the values of R50mm varies in each region, from 1 – 10 days/year to > 60 days/year. Conversely, when using the 90th percentile, the frequency of extreme rainfall events in each region which ranges from 21 – 30 days/year to 31 – 40 days/year, tends to be the same or does not vary (Liu *et al.,* 2023). Furthermore, the average extreme indices for 2001 – 2020 in South Sulawesi explains that the areas in the west and north of South Sulawesi tend to be higher than other regions, both in terms of frequency and intensity indicators, such as Barru, Pangkep, Maros, Makassar, Gowa, Takalar and Jeneponto, as well as Luwu Utara, Luwu Timur and Toraja Utara. This situation shows that the wet northwest monsoon along with the topographical factor in South Sulawesi has a significant influence on the high extreme indices value in western South Sulawesi (Luo *et al.,* 2023). This occurs because the wet northwest monsoon which occurs from November to April, which carries a substantial amount of water vapour, generates a substantial amount of rain in South Sulawesi (Marengo *et al.,* 2023). The moist wind blows from west to east of the Java Sea's wide waters and creates persistent rain events in South Sulawesi. However, the mountains in the middle of South Sulawesi act as a barrier to the monsoon wind, indicating that the influence of the northwest monsoon in the east of South Sulawesi is not as significant as that seen in the west (Mashao *et al.,* 2023; Merz *et al.,* 2021).

Extreme rainfall events followed by floods in South Sulawesi during September-October-November 2001 - 2020 occurred as many as 19 days (Monjo *et al.,* 2023). Flood events generally occur in the eastern and northern parts of South Sulawesi. Several of the flood events did not record the previous extreme rainfall. This could be due to the fact that the flood area was not covered by the rain stations in this study and/or because the analysis was limited to rainfall on the day and one day before the flood event, notwithstanding that the flooding could have been caused by the accumulation of rainfall for several days (Moses *et al.,* 2023; Myhre *et al.,* 2019). Therefore, it is advisable to analyse the accumulation of rainfall for several days to identify flood events that may occur due to several days of rain, albeit the rainfall intensity is low to moderate (Palmer et al. 2023; Sa'adi., 2023).

Composite analysis of atmospheric dynamics variables showed anomalies in precipitable water, 850 mb wind and 200 mb wind (Sauter *et al.,* 2023). There was an increase in the value of precipitable water by 8 - > 10 kg/m^2 in South Sulawesi and its surroundings (Sougué *et al.,* 2023). It is recognised that an increase in precipitable water also triggers an increase in rainfall and extreme precipitation events (Sun *et al.,* 2023; Sundriyal *et al.,* 2023). Furthermore, the 850 mb wind experienced a slight increase in speed, while the 200 mb wind experienced a greater reduction in speed. The presence of an anomaly in the upper troposphere at 200 mb exhibits a reverse pattern in contrast to the anomalous circulation at 850 mb, indicating a baroclinic vertical structure of circulation anomalies in tropical regions (Chen, 2017). The wind anomaly at the upper level (Mathew *et al.,* 2023), which tends to be attracted to the east may have been associated with the initial stages of the strengthening of the Walker Circulation as La Niña developed towards the end of spring. This is known to create wet conditions in South Sulawesi (Tamm *et al.,* 2023), including during September-October-November.

4. Conclusion

Based on the results of the analysis and discussion, the conclusions obtained are as follows: (1) the average value of the extreme rainfall indices in 2001 – 2020, both the frequency indicator and the intensity indicator, generally demonstrated a spatial pattern that described the characteristics of rain in South Sulawesi. The highest values dominate in the western and northern regions of South Sulawesi. (2) Flood events during September-October-November 2001 – 2020 in South Sulawesi were recorded as 19 days. Several extreme rainfall events were not followed by flood events and vice versa. (3) The dynamics of the atmosphere prior to the extreme rainfall followed by flood events exhibited anomalies in precipitable water, 850 mb winds and 200 mb winds. An increase in the amount of precipitable water and wind speed at 850 mb, as well as the decrease in wind speed at 250 mb in South Sulawesi and its surroundings, has led to an increase in the formation of rain clouds that have the potential to increase the chance of extreme rainfall.

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Author Contributions

Conceptualization: Amhar Ulfiana, Muhammad Arsyad, Pariabti Palloan; **methodology**: Amhar Ulfiana, Muhammad Arsyad, Pariabti Palloan; **investigation**: Amhar Ulfiana, Muhammad Arsyad, Pariabti Palloa; **writing—original draft preparation**: Amhar Ulfiana; **writing—review and editing**: Amhar Ulfiana, Muhammad Arsyad, Pariabti Palloan; **visualization**: Amhar Ulfiana. All authors have read and agreed to the published version of the manuscript.

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