Moisture Origin and Transport for Extreme Precipitation over Indonesia's New Capital City, Nusantara in August 2021

Purwaningsih Anis[1], Lubis Sandro W[2], Hermawan Eddy[1], Harjana Teguh[1], Nur Ratri Dian[3], Sujalu Akas Pinaringan[4], Ridho Ainur[5], Andarini Dita Fatria[1], and Risyanto Risyanto[6]

[1]Research Center for Climate and Atmosphere (PRIMA), National Research and Innovation Agency (BRIN)
[2]Rice University
[3]Meteorological Climatological and Geophysical Agency
[4]Universitas 17 Agustus 1945 Samarinda
[5]Cerdas Antisipasi Risiko Bencana Indonesia (CARI)
[6]Research Center for Climate and Atmosphere (PRIMA)

November 16, 2022

Abstract

Nusantara, the Indonesia's New Capital City, experienced a rare extreme rainfall event on 27 to 28 August 2021. This unusual heavy rainfall occurred during the dry season and caused severe flooding and landslides. To better understand the underlying mechanisms for such extreme precipitation events, we investigated the moisture sources and transport processes using the Lagrangian model HYSPLIT. Our findings revealed that moisture was mostly transported to Nusantara along three major routes, namely from Borneo Island (BRN, 53.73%), the Banda Sea, and its Surroundings (BSS, 32.03%), and Sulawesi Island (SUL, 9.05%). Overall, BRN and SUL acted as the main sources of terrestrial moisture, while the BSS was the main oceanic moisture origin having a lower contribution than that of its terrestrial counterpart. The terrestrial moisture transport from BRN was mainly driven by the large-scale high vortex flow, while the moisture transport from the SUL was driven by the circulations induced by boreal summer intraseasonal oscillation (BSISO) and low-frequency variability associated with La Niña. The near-surface oceanic moisture transport from BSS is mainly associated with prevailing winds due to the Australian Monsoon system. These insights into moisture sources and pathways can potentially improve skill in predictions of summer precipitation extremes in Indonesia's New Capital City, Nusantara, and benefit natural resource managers in the region.

Article

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Anis Purwaningsih*[1], Sandro W. Lubis[1,2], Eddy Hermawan[1], Teguh Harjana[1], Dian Nur Ratri[3,4], Akas Pinaringan Sujalu[5], Ainur Ridho[6], Dita Fatria Andarini[1], Risyanto [1]

1 Research Center for Climate and Atmosphere (PRIMA), National Research and Innovation Agency (BRIN), Jakarta, 10340 Indonesia; anis.purwaningsih@brin.go.id (A.P.); slubis.rice@gmail.com (S.W.L.); eddy001@brin.go.id; teghar120@gmail.com (T.H.); dita005@brin.go.id (D.F.A.); risyanto@brin.go.id (R.)
2 Department of Mechanical Engineering, Rice University, 5100 Main St, Houston, TX, 77005, USA
3 Meteorological, Climatological, and Geophysical Agency, Jakarta,10720 Indonesia; dianuratri@gmail.com
4 Wageningen University and Research, Droevendaalsesteeg, Wageningen, 6708, The Netherlands
5 Universitas 17 Agustus 1945 Samarinda, Indonesia; akaspinaringansujalu@gmail.com
6 Cerdas Antisipasi Risiko Bencana Indonesia (CARI), Bandung, 40293, Indonesia; ridhoain@gmail.com
* Correspondence: anis.purwaningsih@brin.go.id

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Keywords: Moisture sources; Moisture transport, Extreme precipitation; Nusantara, Indonesia

Citation: Title. *Journal Not Specified* **2022**, *1*, 0. https://doi.org/

Received:
Accepted:
Published:

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1. Introduction

Indonesia's parliament has designated to move the National Capital City from Jakarta to the province of East Kalimantan on the island of Borneo [1]. The name of this new Capital City is Nusantara which is publicly known as IKN (Ibu Kota Negara Baru) in Bahasa (Fig. 1). This city is a part of several sub-districts in Penajam Paser Utara (PPU) regency and Kutai Kartanegara regency in the province of East Kalimantan [2]. Several aspects informed as the underlying reasons why the government relocates the national capital city to Nusantara, such as population distribution, tackling the clean water source crisis on Java Island, and boosting economic growth outside of Java Island [3].

According to the Regional Disaster Management Agency (BPBD), Nusantara has experienced several flood disasters in the past few years. It has been documented that from January 2019 to January 2022 there have been 15 flooding events. One of the major floods occurred on 27-28 August 2021, which exerted strong impacts on human lives and society [4]. The heavy precipitation from 27-28 August 2021 was considered unusual because it lasted more than 11 hours and occurred during the dry season [5]. This extreme rainfall subsequently triggered floods and landslides in several places in East Kalimantan. During this period, the daily rainfall accumulation reached 82 mm/day, which was within the 99th percentile of the long-term daily precipitation distribution Section 2.1 for a detailed discussion). Investigating the underlying physical process of this extreme event can improve our understanding of the driving mechanisms of the unusual extreme rainfall event during the dry season in Indonesia's New Capital City, Nusantara, and potentially improve the summer rainfall prediction over the region.

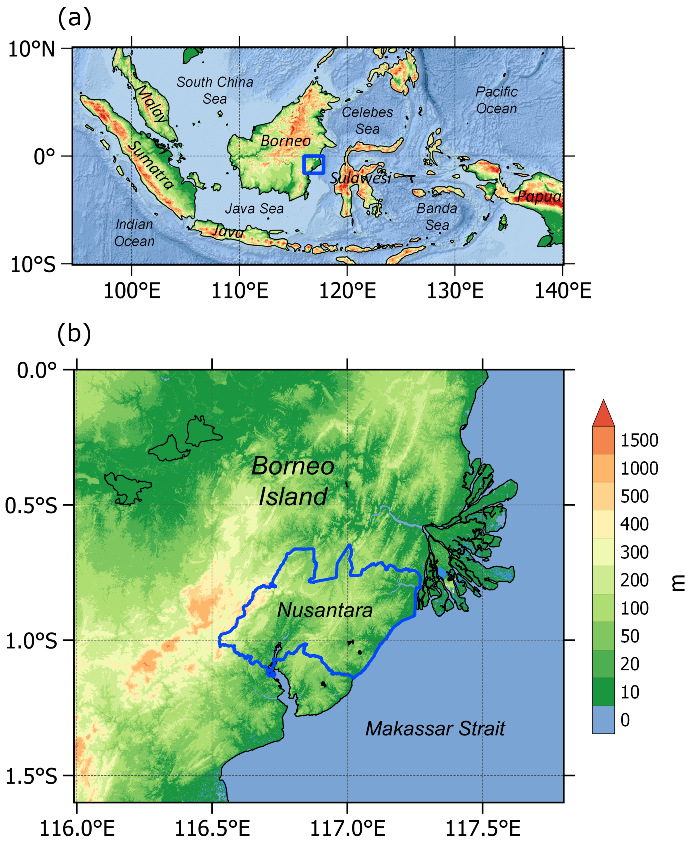

Figure 1. Topography map of (a) the area study (blue rectangle) located in the middle of the Maritime Continent in the eastern Borneo Island, (b) administrative borderline of the Nusantara City (blue looped-line).

There is still a lack of understanding of the mechanism for the formation of extreme rainfall over Nusantara in the province of East Kalimantan. This is likely due to the complexity of the dynamics of the atmosphere over the region, which is located over the equator. In general, the precipitation in East Kalimantan has a typical monsoonal-type pattern [6]. This monsoonal type is characterized by the driest months from June to August and the wettest months from December to February [6]. In addition, the heavy rainfall over the central Maritime Continent is also often associated with an organized convective system associated with Boreal Summer Intraseasonal Oscillation (BSISO) [7,8]. BSISO is a large-scale weather system that strongly influences intra-seasonal rainfall variability during boreal summer as a result of interaction between Madden Julian Oscillation (MJO) and monsoonal system [7–9]. Furthermore, the tropical synoptic activities associated with tropical high and low in a period range of about 2–8 days also often play a key role in modulating summertime convection that causes day-to-day weather variations and heavy rainfall over East Kalimantan during boreal summer [10]. In addition, the rainfall variation in East Kalimantan is also affected by the interannual variability of the tropical sea surface temperature (SST) in the Pacific and Indian Oceans associated with El Niño–Southern Oscillation (ENSO) [11,12]. In particular, El Niño causes prolong dry season, whereas La Niña is related to high rainfall above the average [13]. All these atmospheric drivers acting on different timescales can modulate and influence the formation and development of extreme summertime rainfall events in Nusantara.

The occurrence of extreme rainfall events is associated with the high moisture content in the atmosphere [14]. The more extreme the rainfall that occurs in a place depends on the longer the condition of high moisture content persists [15]. Previous studies have shown that moisture was one of the primary rainfall sources for the development of torrential rainfall events. For example, an investigation by Nie and Sun [16] using a Lagrangian approach concluded the extreme precipitation event over Henan in July 2021 was driven by moisture from Southern China and the western North Pacific. In addition, Zhou *et al.* [17] studied water vapor transports associated with torrential rainfall during the April–September period of 2008–2015 over Xinjiang, China. They found that water vapor related to heavy precipitation events is mostly transported by the westerly winds. Moreover, Tan *et al.* [18] analyzed a dominant contribution to the precipitation over western North America when the atmospheric river and extreme precipitation occurred simultaneously. And, they found that moisture flux convergence is the key. The aforementioned studies suggest that it is important to evaluate the source of the moisture transport responsible for the precipitation extremes to better understand the underlying mechanisms of such events.

In this study, we investigate the sources of moisture and transports for extreme precipitation events in Nusantara on 27-28 August 2022 that caused catastrophic flooding with significant socioeconomic effects in many places [19,20]. We employed a Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) method to track the origin of moisture and transports responsible for the extreme precipitation event. Furthermore, this study will also explore the underlying dynamics that drive such moisture transport during extreme rainfall events, similar to the previous studies [21,22]. This is the first comprehensive study that applies a Lagrangian moisture analysis to understand the cause of the extreme precipitation event in Indonesia. Therefore, we hope that this study can provide knowledge about the source monitoring and prediction system for water vapor transport in East Kalimantan, especially over the new Capital City of Indonesia, Nusantara. It is also expected that this system can be a decision support tool for decision-makers to help users in developing a hydrometeorological disaster risk reduction strategy. In addition, we hope that this research can be one of the integration and synchronization steps needed to understand the factors that cause flooding in the Nusantara area. Later, this is expected to be a consideration in environmental development planning to mitigate flood natural disasters. In Section 2 of this article, the data and methods are described. The results are presented in Section 3 before the article concludes with a discussion of the findings in Section4.

2. Data and Methods

2.1. Precipitation Data and Reanalysis Data

The half-hourly gridded rainfall dataset produced by the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) with 0.1° x 0.1° spatial resolution was employed in this study to investigate the characteristic of heavy rainfall [23]. We used the rainfall data for the period of 27 August 2021 14Z to 28 August 2021 08Z from the IMERG version 3 final (IMERG-F), a final product of IMERG that was adjusted by the analysis of the monthly Global Precipitation Climatology Centre (GPCC) gauge [24]. This data was accessed from Goddard Earth Sciences Data and Information Services Center (https://disc.gsfc.nasa.gov/datasets/, accessed on 25-March-2022). Moreover, the hourly rainfall data from the Indonesian Agency for Meteorological Climatological and

Geophysics (BMKG) weather station over Sepinggan, Balikpapan was used for the period of 27 August 2021 14Z to 28 August 2021 08Z.

This study also uses the top brightness temperature (TBB) of the Himawari-8 satellite retrieved from the Himawari receiver at the National Research and Innovation Agency (BRIN), which has a spatial resolution of 4 km and a temporal resolution of 1 hour. The infrared channel at 10.4 μm (Band 13) data was applied to identify the evolution of the mesoscale convective system (MCS) associated with heavy precipitation. Generally, the Himawari-8 with the interval of 10 minutes for the full disk scans creates the possibility for monitoring more detailed clouds [25,26]. The MCS in the study were tracked by using the GTG (Grab 'em, Tag 'em, Graph 'em) algorithm [27] which have been applied in the previous study for investigating the heavy rainfall events in some regions of Indonesia [21,26,28]

To analyze the moisture transport and contribution, this study utilized the European Center for Medium-Range Weather Forecast reanalysis 5 (ERA5) data, with a 0.25° x 0.25° horizontal resolution and hourly temporal interval [29]. The ERA5 data on the single surface level and pressure levels for the period of 24 to 27 August 2021 are used to track the moisture source of heavy rainfall using the HYSPLIT and calculate the vertically integrated water vapor transport (IVT). In addition, we also used horizontal wind data and specific humidity at pressure levels for the same period to analyze the meteorological drivers during extreme precipitation.

2.2. HYSPLIT Model and Backward Trajectories

The Lagrangian approach using HYSPLIT model version 5.1 is used to calculate the back trajectories of moisture properties that triggered the heavy precipitation over Nusantara during the flood event on 28 August 2021. HYSPLIT model developed by NOAA's Air Resources Laboratory is one of the most extensively used models for atmospheric transport and dispersion analysis [30,31]. In this study, we ran a total of 99 grid points surrounding the heavy rainfall area in Nusantara (116.2°–117.2°E, and 0.8°–1.6°S) with a horizontal interval of 0.1° (Figure 2). The start time of each trajectory is set at the peak of heavy rainfall events (27 August 2021 at 18Z). Then, we calculated the 72-hour backward trajectories from 500m to 5500 m above the ground level (with intervals of 500 m) to analyze moisture transport and sources.

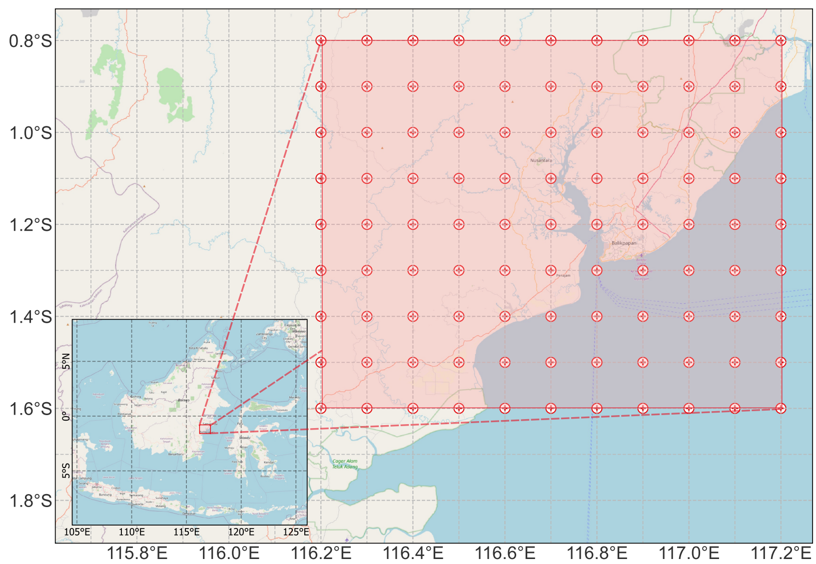

Figure 2. Release points of the moisture trajectories (every 0.1°, from 116.2°–117.2°E, and 0.8°–1.6°S). For every point, the vertical resolution is 500 m, from 500 to 5500 m above ground level (magl).

2.3. Moisture Source Attribution

The contribution of different moisture sources that led to heavy precipitation in Nusantara is identified by applying the algorithm from Sodemann *et al.* [32]. We calculated the moisture changes of an air parcel during a time interval of 1 hour using the following equation [33,34]:

$$\frac{Dq}{Dt} \approx \frac{\Delta q}{\Delta t} = E - P\left(gkg^{-1}h^{-1}\right) \tag{1}$$

$$\Delta q^{\circ}(t) = q(\vec{x}(t)) - q(\vec{x}(t-1h)) \tag{2}$$

Generally, the changes in specific humidity in a certain interval (Dq/Dt) show the net result of precipitation (P) and evaporation (E) processes along the trajectories [33]. A moisture source will be identified through the trajectory locations (moisture intake event) if the moisture of a particle increases ($\Delta q^{\circ} > 0$). Meanwhile, the precipitation is determined if the moisture decreases ($\Delta q^{\circ} < 0$) [16,32]. To estimate the moisture source attribution of specific areas, we divided the region of the study area (11°S–9°N and 93°–133°E) into ten sub-regions by considering the land and ocean (see later in Fig. 7a). The 72-hour evolution of moisture intake is then calculated for each sub-region.

2.4. Clustering for the Trajectories

The backward trajectories simulated by the HYSPLIT model have two-dimensional locations (longitudes and latitudes) that can be categorized into several clusters. In this study, *k*-means clustering was performed to identify the main groups of trajectories. The *k*-means algorithm is an unsupervised clustering method that classifies a given data into a set of *k* groups according to their characteristics [35,36]. This method also has the ability to produce more stable cluster boundaries [37]. In addition, to determine the best number of clusters, we applied the within-cluster sum of square errors (WCSS) metric based on the elbow method [37,38]. The optimum number is selected when the WCSS reaches the minimum value, which is 3 cluster centres in our study.

3. Results

3.1. Overview of the Extreme Precipitation Event

Figure 3a shows the precipitation accumulation distribution from 14Z 27 August 2021 to 08Z 28 August 2021. It is indicated that intense precipitation occurred in eastern Borneo, central Borneo, southern Sulawesi, and the Banda Sea. It also shows that the coastal area of Nusantara experienced heavy rainfall (precipitation of more than 100 mm), however, inland the intensity decreased. The bar chart in Fig. 3 reveals that the rainfall in Nusantara started at 14Z and reached its peak at 18Z with a maximum intensity of 15 mm/hour, and decreased thereafter. The total precipitation from 14Z 27 August 2021 to 08Z 28 August was 80 mm 2021, which reached the 99th percentile climatology value of daily precipitation amount in this area, and hence it was categorized as an extreme rainfall event.

IVT between 1000-300 hPa (color shading) superimposed with streamlines of the vertically integrated moisture flux (contour lines) during the peak of precipitation at 18Z 27 August 2021 is shown in Fig. 3b. There was a flow of moisture transported westward along the surrounding sea area of the Banda Sea, and the Flores Sea, before its break into Makassar strait and the Java Sea. The moisture flux streamline shows a converged path pattern from the peripheral region into the middle of Borneo Island. In addition, it is also evident that a vortex-like pattern was established on the sea of west Borneo Island, which is also a prominent feature associated with the flux during the extreme precipitation period. These results give us hints about possible sources of moisture transport responsible for the extreme rainfall event in Nusantara during this period, which will be further discussed in Sections 3.1 to 3.2.

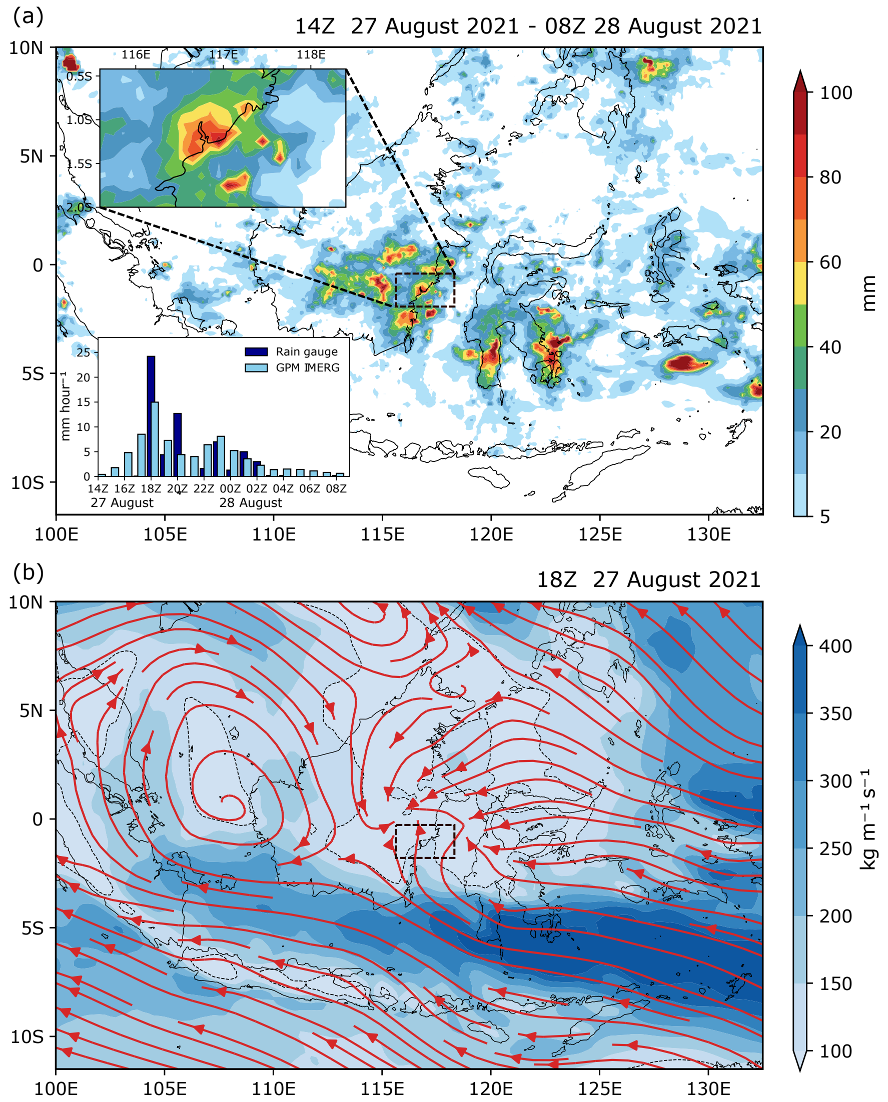

Figure 3. a) Precipitation accumulation distribution between 14Z 27 August 2021 to 08Z 28 August 2021 shown by contour color in eastern Indonesia, inset map shows the precipitation accumulation zoomed-in over Nusantara region. Timeseries box shows the hourly precipitation observed by Rain gauge of Sepinggan (dark blue) and area-averaged hourly precipitation of the Nusantara City and surrounding area based on GPM IMERG (sky blue) and . b) Shade color represents 1000-300 hPa vertically integrated moisture condition and red streamline shows vertically integrated moisture flux at 18Z 27 August 2021.

It is important to note that the occurrence of a rare extreme rainfall event on 27 to 28 August 2021 during the dry season in Nusantara was associated with the formation and development of the MCS. Figure 4 shows the three-hourly evolution of the MCS from the Himawari-8 satellite superimposed with the rainfall rate from GPM IMERG for the period of 27 August at 12Z to 28 August 2021 at 9Z. These complex convective clouds were developed and lasted for about 22 hours, which mostly concentrated on the central area of Borneo. The MCS initiated from several small cloud clusters emerged locally in the northern part of Nusantara City (Fig. 4a). It constantly grew and became larger covering mostly the central area of the Island and a minor part of eastern Borneo including Nusantara (Figs. 4b-c), generating the peak rainfall rate at 18Z 27 August 2021 in the region. On the other side, another cloud cluster developed along the coast of East Borneo starting at 18Z 27 August 2021 and eventually merged to form the second MCS surrounding Nusantara City three hours later (Fig. 4d). Afterward, the first MCS which was previously developed in central Borneo merged with the second MCS which was developed along the coast of East Borneo (Fig. 4e). Then, they gradually dissipated followed by the decreasing intensity of rainfall(Figs. 4f-h).

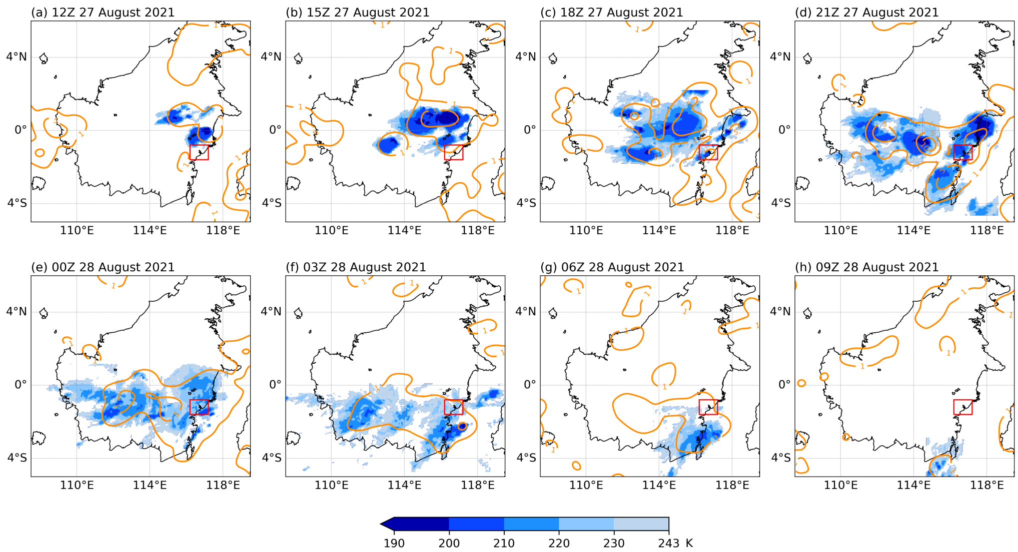

Figure 4. Three-hourly evolution of the MCS (K, shaded) from Himawari-8 satellite superimposed with rainfall rate from GPM IMERG (mm.h1, contour) for the period of 27 August at 12Z to 28 August 2021 at 9Z. The location of Nusantara City is denoted by a red box.

3.2. Moisture Sources and Transport for Summer Extreme Precipitation in Nusantara

One of the key factors that favor the occurrence of deep convection such as MCSs and extreme rainfall is the substantial moisture content in the lower atmosphere. Our results so far suggest that moisture responsible for the formation of MCS and extreme rainfall events in Nusantara was transported from different regions (Fig. 3 and Fig. 4). Therefore, it is important to investigate where the atmospheric moisture came from that favored the MCS and consequently the extreme total amounts of precipitation in Nusantara (Fig. 3). In the following, we will discuss in detail the origin, pathways, and contributions of moisture from different sources as well as the role of atmospheric modes in driving the moisture transport during extreme precipitation events in Nusantara on 27 to 28 August 2021.

3.2.1. Dominant Moisture Origin, Pathways, and Contributions

Our results indicate that the higher moisture content (higher IVT) is detected over the BSS, the South China Sea and vicinity, and the Pacific Ocean near the equator (Fig. 3b). To accurately investigate the source and pathways of these moisture transports, the moisture over the flooding region is tracked back in time for 72 hours before the peak of rainfall on 27 August 2021 at 18Z (Fig. 5). To categorize these trajectories objectively, the pathways are grouped by *k*-mean clustering [35,36], resulting in three main clusters based on the elbow method [37,38]. The results show that moisture responsible for the extreme rainfall event was transported from 3 directions: from the southeast as cluster 1, from the northwest as cluster 2, and from the east as cluster 3 (Fig. 5b-d). Each cluster has distinct characteristics based on the moisture content. Specific humidity was higher over trajectories from south-east/over cluster 1 (more than 12.5 g/kg) (Fig. 5b). The high specific humidity over this cluster was consistent with the more abundant moisture showed by IVT magnitude over the Banda Sea and its vicinity (Fig. 3b). Moreover, the high specific humidity along the tracking was also detected from the northwest (cluster 2), ranging from 7.5 g/kg to nearly 17.5 g/kg. IVT vector explains that moisture is transported clockwise over the South China Sea and Borneo (Fig. 3b). Trajectories are consistent with IVT which follows the anticyclonic flow over the South China Sea, then intrudes on Borneo Island to the flooding area (Fig. 5c). Some pathways in cluster 2 also originated from the island of Borneo 72 hours before heavy precipitation. All these pathways (from the South China Sea and the Island of Borneo) area converged into the flooding area within cluster 2 (Fig. 5c). Moreover, cluster 3 has different moisture characteristics among all clusters, with the fast westward movement of a drier air parcel (approximately less than 12.5 g/kg) (Fig. 5d). The velocity of the air parcel is shown by shorter pathways over 72 hours. Overall, these moisture propagation regimes are consistent with the IVT vector which illustrates the moisture transported toward the flooding location from various locations, including moisture movement from the southeast, east, and northwest (IVT vector in Fig. 3b). However, the trajectories result indicates more accurate pathways of moisture propagation toward Nusantara.

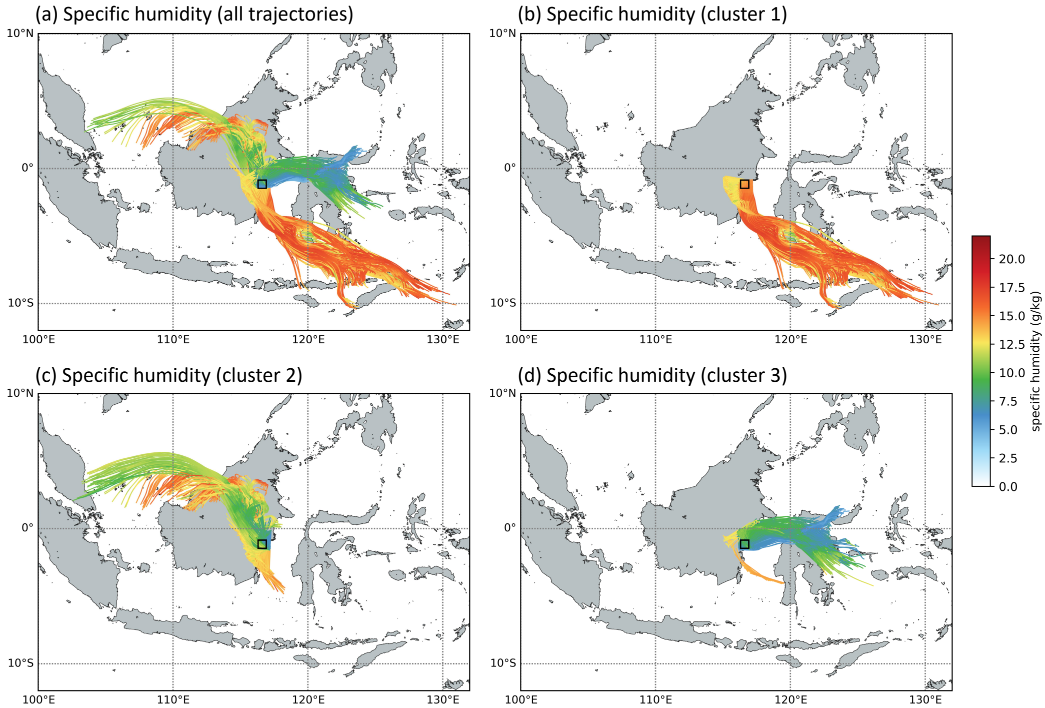

Figure 5. 72-hours backward trajectory of moisture responsible for the extreme rainfall event over the Nusantara region (at 18Z, 27 Aug 2021). Trajectories (lines) and moisture along the pathways (colors) for a) all trajectories and b-d) for each cluster.

The characteristics of moisture transport from each cluster are further explained by taking into account the vertical structure of trajectories. Figure 6 shows the altitude of tracked air parcels within 72 hours. The mean altitude of each cluster is calculated (solid line in Fig. 6) and presented with its maximum and minimum value (shading in Fig. 6). It is shown that within clusters 1-3, moisture arriving toward various release altitudes was dominated from the altitudes lower than 4.5 km. This is expected as the moist or humid air is found much below 5 km under a layer of warmer air in the lower troposphere [39].

Each cluster has a distinct characteristic based on its altitude profile. More specifically, cluster 1 is mainly advected horizontally toward the study area over low altitudes (ranging from 0 km-1km) (Fig. 6). The low-level transport over this cluster denotes moisture exchange (moisture uptake and moisture outtake) over the earth's surface. Moreover, the additional moisture/moisture uptake over the lower altitude (planetary boundary layers) is closely related to the surface evaporation process [32]. Therefore, the indication of oceanic evaporation as the main mechanism of moisture uptake is strong as this cluster spreads along the BSS. Section 3.2.2 will discuss more the moisture transport drivers at the lower level toward Nusantara. Furthermore, cluster 2 propagates horizontally with an altitude between 0-2.1 km from 72-35 hours prior to the extreme event. Within this cluster, the moisture ascended to an altitude between 1.8-2.8 km during t=35-25 hours prior to the peak of the extreme rainfall events. Moreover, moisture that arrived from Sulawesi and its

Surroundings (cluster 3) was mainly transported over higher altitudes (2.7 km on average) and converged over flooding locations at an altitude of 4.7 km. The fast propagation of air particles within cluster 3 (shorter pathways in Figure 5d) can be explained by a higher wind speed in the free troposphere as there is no friction influenced by the roughness of the earth's surface. Furthermore, the additional moisture over the higher altitude was more likely through some mechanisms such as convection and evaporation of precipitating hydrometeors, or because of errors related to numerical calculation of trajectories [32]. In more detail, the factors that drive the moisture transport from clusters 2 and 3 toward Nusantara City will be further discussed in Section 3.2.2.

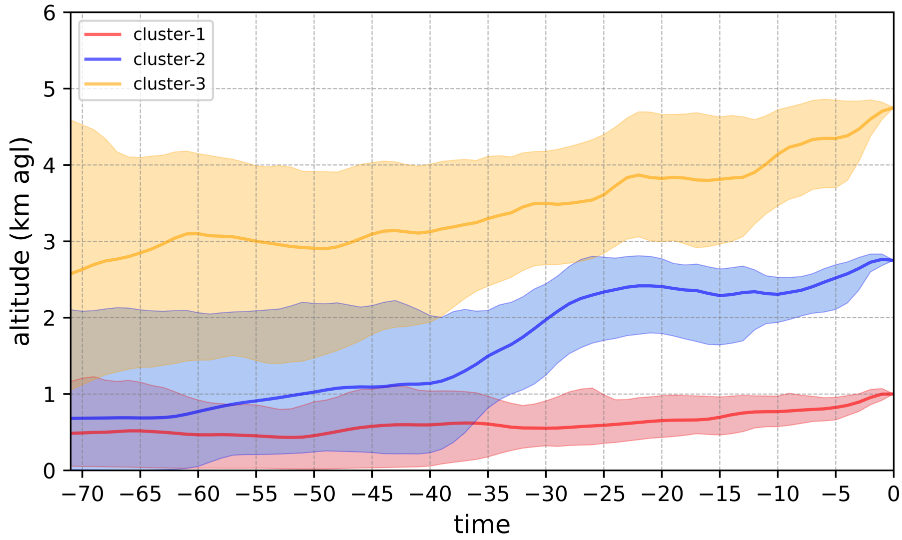

Figure 6. Evolution of moisture transports as a function of altitudes and time prior to the extreme rainfall event (18Z, 27 August 2021). Solid lines represent the mean altitude for each cluster, shadings denote altitude ranges.

Our results so far indicate that there are three main sources of moisture transport toward Nusantara that produced the extreme rainfall event. To quantify the contribution of this moisture source, we further calculated the integrated moisture intake precisely over ten different regions and quantified its percentages (Fig. 7). Similar to the previous studies (e.g., [32] [33]), changes in moisture along the pathways can define the precipitation (moisture outtake) and evaporation (moisture intake) process along the pathways. We defined moisture intake as increasing moisture in time along its pathway (positive dq), wherein the lower troposphere is highly correlated with evaporation (evaporative moisture uptake) [32]. Our results indicate that moisture intakes increase gradually over time, indicating the moistening of air parcels during their pathways upon arrival (Fig. 7b). The terrestrial moisture source is the dominant contributor to heavy rainfall, which accounts for 62.78% of the total moisture intake (53.73% of the moisture is evaporated over Borneo (BRN) and 9.05% from Sulawesi (SUL)) (Fig. 7c). Moreover, the most significant oceanic moisture source, about 32.03%, is evaporated over BSS. About 3.77% of moisture intake is from the South China Sea (SCS), and 0.43% is from the Pacific Ocean and Surroundings (POS), as the rest oceanic source of moisture for this heavy rainfall case (Fig. 7c).

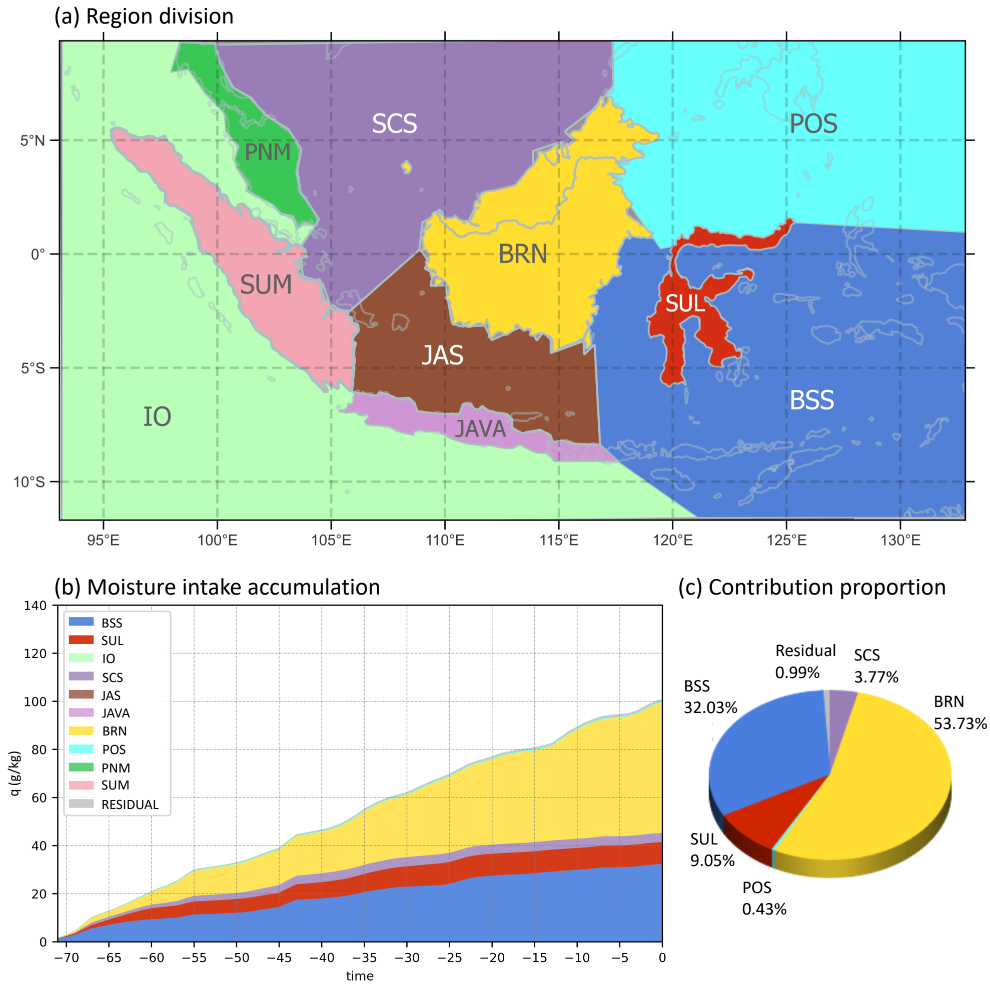

Figure 7. The moisture source contributions by different regions. (a) The division into 10 regions including Peninsular Malaysia (PNM), Sumatera (SUM), Indian Ocean (IO), South China Sea (SCS), Java Sea (JAS), Java Island (JAVA), Borneo Island (BRN), Pacific Ocean and Surroundings (POS), Sulawesi Island (SUL), Banda Sea and Surrounding (BSS). b) The averaged of integrated moisture intake of the 10 sources along the trajectories in the target region. (c) The relative moisture contributions of different regions at the release time (0 days).

Further quantification of moisture contributions in each cluster from the different source regions is explained in Figures 8b,d,f, where the moisture intake accumulation in a particular area helps to calculate this contribution as shown in Figures 8a,c,e. It can be seen that cluster 1 is dominated by oceanic moisture sources from the BSS which accounts for 92.3% of the total moisture intake over cluster 1. The rest moisture sources are from terrestrial (BRN and SUL), where moisture is entrained to its pathways at a more stable pace. Moisture intake over BSS location is detected since -72h and increases gradually until the release time. Sudden entrainment is detected over the BSS at 23-20 hours before the heavy rainfall, indicating intensive evaporation over the ocean since this cluster is characterized by moist air parcel with low-altitude moisture propagation (Figs 5b and 6). As mentioned in the previous section, higher IVT is detected over BSS (Fig. 3b), and the specific humidity along this cluster's trajectories is higher than in the other clusters (Fig. 5b). Therefore, this cluster is essential as the moisture contributor to heavy precipitation. The Australian monsoon is suspected of atmospheric conditions corresponding to the pattern over this cluster, which is further explained in the following sub-section.

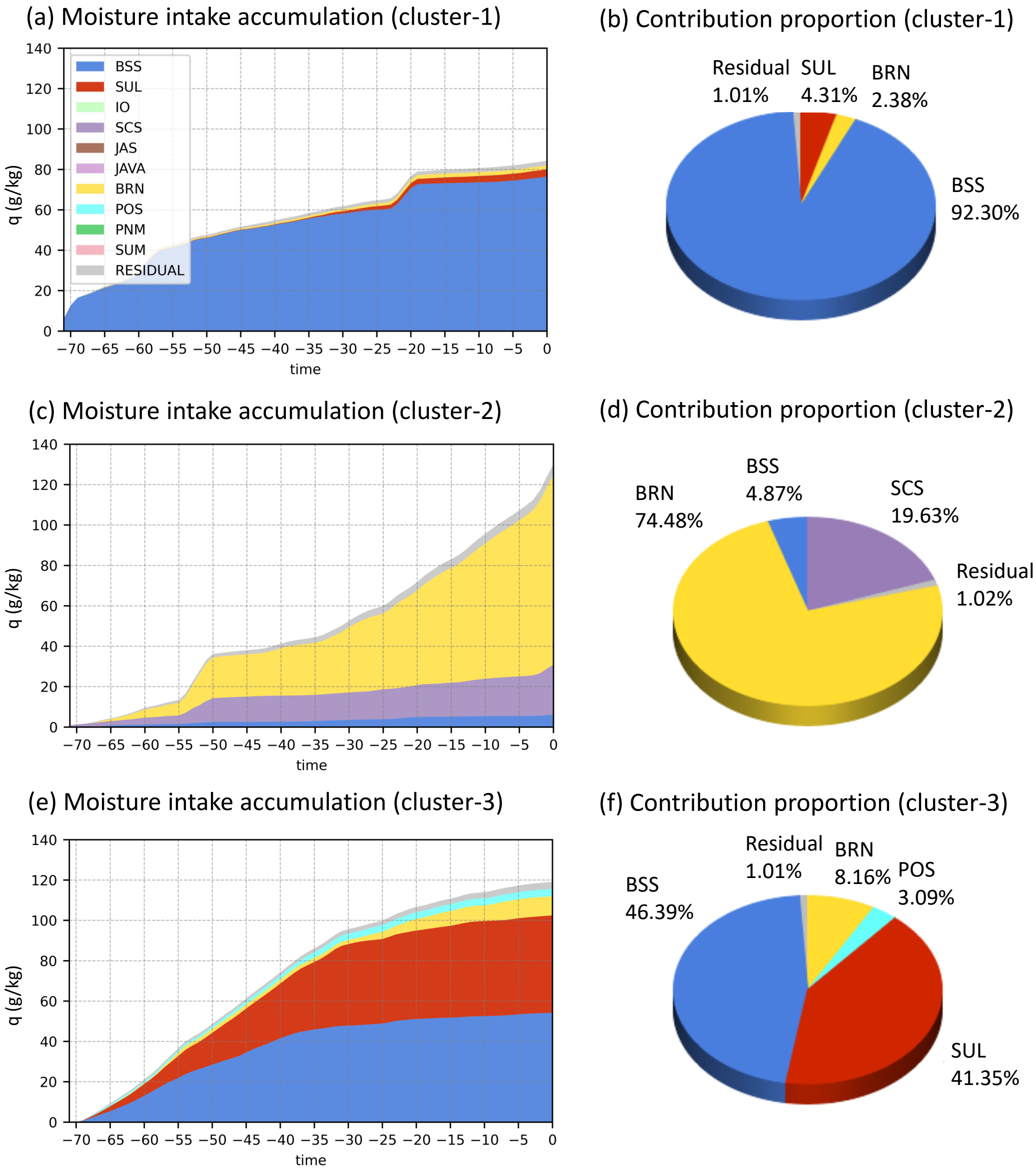

Figure 8. As Figures 7b and 7c in the manuscript but for the moisture intake in the three clusters.

In cluster 2, about 74.48% moisture was transported from BRN with a relatively steep pattern indicating faster moistening of air parcel along the pathways over this area. It is worth noting that since the release point of trajectory is also located over Borneo as well, this cluster indicates moisture recycling. Moisture is recycled when the evaporation over an area contributes to the precipitation over the same area, in which the evaporation is closely related to vegetation and catchment area over a land [40,41]. This cluster is crucial for the moisture source of the extreme rainfall event in Nusantara since BRN accounts for half of the total moisture sources (Fig. 7), and the specific humidity along the trajectory is relatively high (Fig. 5c). This high relative humidity also can be explained by the MCS analysis indicating the intensive cloud formation thus representing moisture intake over BRN (Fig. 4). Over this cluster, the SCS, as the oceanic moisture source, contributes to 19.63% of the total moisture intake of this cluster. Furthermore, in Cluster 3, the contribution of terrestrial (SUL and BRN) and oceanic (BSS) moisture sources is comparable (Fig. 8f). Terrestrial moisture sources contribute 49.51 % and oceanic moisture source contributes 46.39 % of moisture sources. The pattern shows that moisture intake is increasing at a nearly linear pace in time over this cluster (Fig. 8e).

In summary, our results indicate that the moisture responsible for the extreme rainfall in Nusantara on 27-28 August 2021 was mainly transported along three major routes, namely from Borneo Island (BRN, with the contribution of 53.73%), the Banda Sea, and the Surroundings (BSS, with the contribution of 32.03%), and Sulawesi Island (SUL, with the contribution of 9.05%).

3.2.2. The role of atmospheric modes in the variability of moisture transport

To understand the mechanisms responsible for driving the three main pathways of the moisture transport responsible for the extreme precipitation event during 27-28 August 2021 in Nusantara, we decompose the IVT stream function during the event into different contributions of the atmospheric variability components. Figure 9 shows the decomposition of the total IVT stream function into the contribution of 10–20 days, 30–60 days, >120 days, and residual. The 10-20 day periodicity represents the contributions of high-frequency oscillation that are often associated with synoptic weather systems (such as cyclones and anti-cyclones) as well as the BSISO second mode (BSISO2) in summer [42]. The 30-60 day periodicity is mainly associated with BSISO first mode (BSISO1) in summer [42]. The low-frequency variability (>120 days) is often associated with monsoonal flow, Indian Ocean Dipole (IOD) and ENSO [12,22,39,43]. Finally the residual includes other contributions of another variability. In addition, we also calculate the time series of climate indices associated with the Australian Summer monsoon index (AUSMI), BSISO, Nino 3.4, and IOD to elucidate the drivers of such variability (Fig. 10).

Our results indicate that the near-surface moisture transport from the South East (cluster 1) toward the Nusantara is mainly dominated by the low-frequency variability (>120 days) (indicated by the dense stream function, Figs. 9a,d). We attribute this to the active phase of the Australian monsoon system (Fig. 10a). As can be seen in the time series of the AUSMI index, a strong and persistent Australian monsoon was observed with the amplitude ranging between –8 and –6 a week before the flood event (Fig. 10a). More importantly, this value increased from –7.2 m/s to –8.3m/s on 27 and 28 August 2021. This indicates a strengthening of near-surface south-easterly wind toward Nusantara. This is consistent with the warm SST over the Northern Hemisphere (Asia) and colder SST over the Southern Hemisphere (Australia) during boreal summer (not shown), which causes the wind blows from high pressure in Australia to low pressure in Asia during the Australian Monsoon [44]. An extensively warm SST in BSS enhanced the ocean evaporation that triggered intense moisture uptake throughout this circulation (not shown). Therefore, the prevailing wind pattern associated with the Australian Monsoon system induced the near-surface south-easterly moisture transport from BSS to the Nusantara (cluster 1) as the most significant oceanic moisture origin.

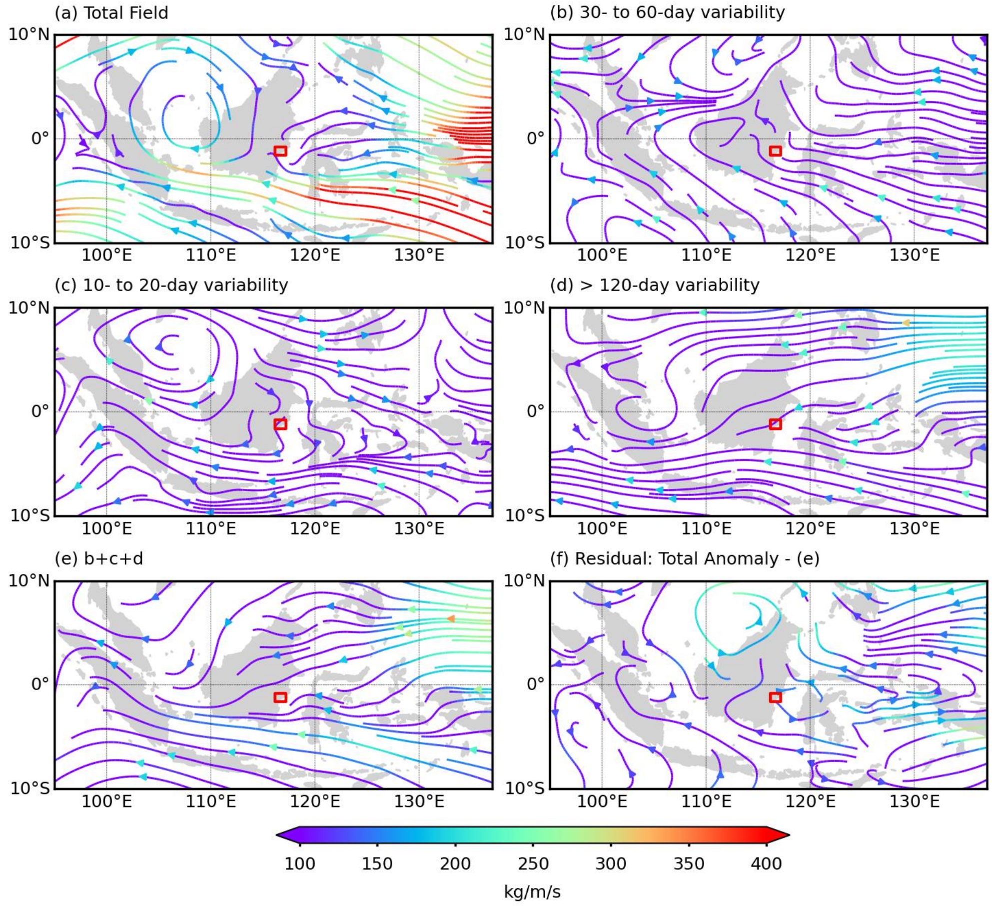

Figure 9. (a) Streamlines of the IVT during the period extreme rainfall (27-28 August 2021) and its decomposition into contributions of (b) 30 - 60 day variability, (c) 10 - 20 day variability, (d) >120 day variability, (e) b+c+d, and (f) residual (total - (b+c+d). The streamlined colors denote the amplitude of IVT, and a red box denotes the location of Nusantara.

Furthermore, the activity of high-frequency mode (10 to 20 days) associated with large-scale high vortex flow located next to the west of Borneo (Fig. 9c) was mainly explained by the transport from the SCS and BRN toward Nusantara. This circulation modulated the water vapor propagation from the South China Sea (SCS) to Borneo Island as the source of the oceanic moisture source in cluster 2. Then, it initiated a favorable environment for the development of MCS that represents the moisture intake over Borneo Island (BRN), contributing to the highest terrestrial moisture source for extreme precipitation events in Nusantara. On the other hand, Boreal Summer Intraseasonal Oscillation 2 (BSISO2) which is also identified as 10 to 20-day variability did not contribute to the enhanced moisture over Nusantara as it was in the weak amplitude of phase 2 (Fig. 10b).

The eastward transport of moisture toward Nusantara (cluster 3) was mainly driven by the combined influence of 30 to 60-day and > 120-day variability (Figs. 9b,d). The 30-60-day variability during summer is consistent with the active phase 3 of BSISO1, where its amplitude exceeded the threshold value (more than 1, in Fig. 10b). It then reached a peak at around 1.8 during 27–28 August 2021. This BSISO1-induced easterly circulation contributes to the moisture propagation from the eastern region of Indonesia towards Nusantara and its surrounding area (Fig. 10b). On the other hand, the low-frequency variability during this period is associated with La Nina which also played an important role in this zonal transport (Fig. 10c). Those phenomena induced a relatively equal contribution of terrestrial (SUL and BRN) and oceanic (BSS) moisture sources over cluster 3. The active

La Nina strengthened the zonal circulation that modulates the propagation of moisture to Nusantara resulting in extreme precipitation. Our finding further showed that the low-frequency variability has a greater contribution than that of BSISO1 in modulating the easterly transport of moisture toward Nusantara (Figs. 9b,d).

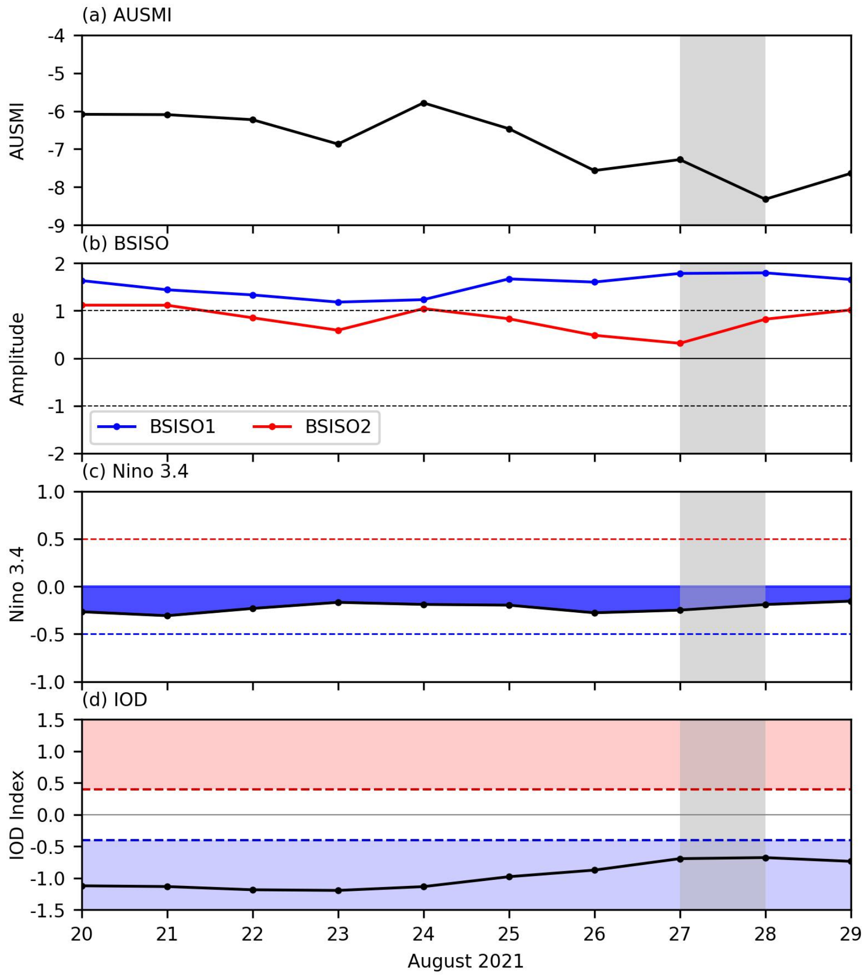

Figure 10. Daily time series of climate mode indices during 20-29 August 2021 for (a) AUSMI, (b) BSISO, (c) Nino 3.4, and (d) IOD. The Grey color shows the flood event over Nusantara on 27 - 28 August 2021

In addition, we have also examined a possible role of the other variability such as IOD (Fig. 10d). It is shown that there was an active negative phase of IOD during 20–29 August 2021, with the threshold value of –1.0. A higher negative IOD index started on 20 August at about –1.2, then decreased gradually during the extreme precipitation event on 27–28 August 2021 to around –0.6. Even though IOD was in its active negative phase (that was possible to drive the westerly zonal transport toward Nusantara), our results show that the streamline of low-frequency IVT is mainly dominated by the south-easterly and easterly transport associated with Monsoon and Niña, suggesting that IOD did not play an important role during this extreme event.

In summary, we show that the transport of moisture from the south-eastward direction toward Nusantara (cluster 1) is mainly driven by the low-frequency variability (>120 days) associated with the Australian summer monsoon system, while the north-westward transport of moisture (cluster 2) is mainly driven by the anti-cyclonic activity having a synoptic periodicity of about 10-20 days. The combined influence of the 30 to 60-day oscillation associated with BSISO1 and the low-frequency variability associated with Niña is responsible for driving the westward transport (cluster 3) toward Nusantara during the extreme precipitation event.

4. Conclusion and Discussion

This study investigates the moisture transport and sources responsible for the extreme precipitation event over Indonesia's New Capital City, Nusantara on 27–28 August 2021 based on the HYSPLIT model, using the ERA-5 reanalysis, satellite, and in-situ data. Our major findings in this study are summarized as follows:

- The moisture responsible for the extreme precipitation event in Nusantara on 27–28 August 2021 was transported along three dominant routes, namely BRN with the contribution of 53.73%, the BSS with the contribution of 32.03%, and SUL with the contribution of 9.05%.
- The BRN and SUL acted as the main sources of terrestrial moisture, while the BSS acted as the main oceanic moisture origin because most of the trajectories travel across the ocean where the evaporation takes apart.
- The Australian Monsoon system contributed significantly to the oceanic moisture transport from BSS. A strong and persistent prevailing wind strengthened the near-surface flow passed a warm sea surface temperature in the BSS which supported the large moisture intake from BSS.
- Large-scale high vortex flow located to the west of Borneo Island contributed to the highest terrestrial moisture transport from BRN, while BSISO1 and low-frequency variability associated with La Nina modulated the moisture propagation from the eastern region of Indonesia.
- The results indicate the importance of terrestrial and oceanic moisture sources from the Borneo and Sulawesi Islands as well as the Banda Sea for the formation of extreme precipitation events in Nusantara, Indonesia.

The mechanisms driving the moisture transport during the extreme rainfall event in Nusantara are summarized in a schematic diagram in Figure 11. This diagram illustrates that the influence of the strong prevailing wind due to the Australian Monsoon system is dominant at the near-surface layer to modulate the highest oceanic moisture source from the southeast region. On the other hand, a large-scale high vortex circulation in the west of Borneo Island transported the moist air from the South China Sea that favored the development of MCS in Borneo Island, hence contributing to the highest proportion of terrestrial moisture transport from BRN. Finally, the effects of BSISO1 and low-frequency variability associated with La Nina play an important role in zonal circulation to supply the moisture from the eastern part of Indonesia and the Pacific Ocean to Nusantara.

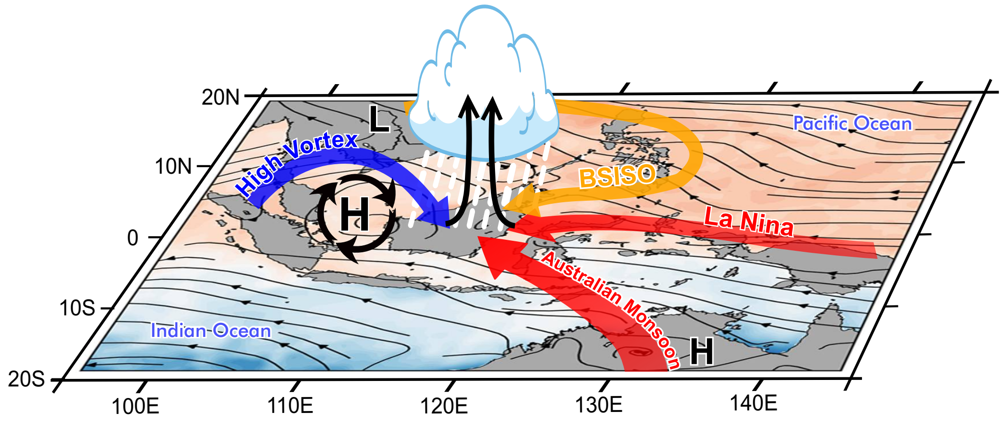

Figure 11. A conceptual diagram depicting the role of atmospheric modes in the variability of the moisture source regions during the flood event over Nusantara on 27-28 August 2021. Color shading denotes SST.

Previous studies have revealed that the summertime rainfall variability in East Kalimantan is influenced by several atmospheric modes such as the Australian Monsoon, ENSO, IOD, MJO, BSISO, and equatorial waves [8,45–51]. However, how the interaction among those atmospheric modes drives the extreme precipitation from the perspective of the moisture transport and sources, hence, devastating flood events in east Kalimantan is still unknown. Our study is the first to show the mechanisms driving the extreme rainfall event in Indonesia through the lens of the moisture transport and sources based on the Lagrangian approach while taking into account the underlying atmospheric drivers. While our current study mostly focused on the large-scale transport of moisture responsible for the extreme rainfall event, other local forces such as topography and land-sea breeze circulation can create unique interactions that in turn drive moisture transport resulting in extreme precipitation [49,52]. Therefore, understanding multi-scale interaction among atmospheric phenomena resulting from extreme precipitation remains to be further studied.

The present study advances our understanding of the moisture sources and pathways for the extreme precipitation over Nusantara as well as the role of atmospheric modes in triggering moisture intake and propagation. These results can provide an important source of predictability for improving a skillful summer precipitation extreme prediction over Nusantara in the future, which in turn, can be potentially used by multi-stakeholders in developing disaster management in Indonesia's New Capital City, Nusantara.

Author Contributions: A.P., S.W.L., E.H., T.H., D.N.R., A.R., D.F.A., R., and A.P.S are the main contributors. Conceptualization, S.W.L. and E.H.; methodology, S.W.L., A.P., R., A.R. and D.F.A.; software, A.R., A.P. and R.; validation, A.R.; formal analysis, S.W.L., A.P., R., A.R. and D.F.A.; Data, A.P., R., A.R. and D.F.A. writing—original draft preparation, D.N.R., A.P., R., A.R. and D.F.A.; writing—review and editing, S.W.L. and D.N.R.; visualization, A.P., R., A.R. and D.F.A.; funding acquisition, E.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Budget Execution (Allotment) Document, National Research and Innovation Agency (BRIN) 2022 (grant No. SP DIPA-124.01.1.690504/2022).

Institutional Review Board Statement: No applicable

Informed Consent Statement: No applicable

Data Availability Statement: The ERA-5 meteorological reanalysis dataset used in this study is available from the European Centre for Medium-Range Weather Forecasts (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, accessed on 30 March 2022). The hourly rainfall data from Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) can be accessed freely through https://disc.gsfc.nasa.gov/datasets/ (accessed on 25 March

2022). The Himawari-8 satellite top brightness temperature (TBB) data and in-situ hourly rainfall data presented in this study are available upon request from the corresponding authors.

Acknowledgments: The authors would like to thank the Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG) in Balikpapan for providing the observational data for this study

Conflicts of Interest: The authors declare no conflict of interest.

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