

# DETERMINING MONSOON ONSET DATES IN MAKASSAR USING RAINFALL ANOMALIES AND MOISTURE SOURCE TRAJECTORY ANALYSIS (1991–2020)

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## ABSTRACT

Makassar exhibits a typical monsoonal rainfall regime, characterized by a strong annual cycle with peak rainfall occurring in January–February. Understanding the onset of the rainy season in this region is crucial for water resource management and disaster preparedness, yet previous studies have generally relied only on rainfall-based criteria with coarse temporal resolution. This study aims to determine the onset date of the rainy season in Makassar by combining local rainfall anomalies with regional-scale moisture-source trajectories. Daily rainfall data for 1991–2020 were analyzed using harmonic reconstruction to identify the climatological peak of the monsoon season, which then guided the moisture trajectory analysis. The results show that most rainy-season onsets occur in November–December, with high interannual variability influenced by large-scale climate drivers such as ENSO. Moisture transport during the peak rainy months is predominantly derived from the Northern Maritime (58.8%) and Tropical Maritime (40.5%) sources, highlighting the essential role of cross-equatorial water-vapor advection. In addition, changes in zonal wind direction at 850 hPa consistently coincide with the onset, providing an independent dynamical indicator of the transition from dry to wet phase. By explicitly linking rainfall anomalies with the timing of dynamical shifts and dominant moisture pathways, this approach reduces ambiguities commonly found in rainfall-only methods and produces onset estimates that align more closely with regional atmospheric dynamics. Compared to previous rainfall-only approaches, this combined local–regional method provides a more representative onset estimate at daily resolution, offering new insight into the mechanisms of monsoon rainfall in coastal areas of eastern Indonesia.

**Keywords:** Rainfall anomalies, Moisture transport, Climate variability, Backward trajectory analysis

## 1. Introduction

The monsoon system plays a crucial role in shaping seasonal climate patterns in Indonesia [1]. As an archipelagic country situated between the Indian and Pacific Oceans, Indonesia is influenced by complex atmospheric circulation, particularly the Asian–Australian monsoon system [2]. This system regulates the onset and cessation of wet and dry seasons, thereby affecting water availability, agricultural practices, and broader socio-economic activities [3,4]. Among various aspects of monsoon dynamics, accurately determining the onset of the rainy season is especially important because it marks the transition into a climatologically sensitive period for agriculture, hydrometeorological disaster preparedness, and water-resource management [5].

Makassar, a coastal city in southern Sulawesi, represents a strategic location for examining monsoon transitions due to its position along the pathway of cross-equatorial flow and its strong seasonal contrast between wet and dry periods [6,7]. Its exposure to both regional circulation changes and local rainfall variability makes Makassar an appropriate case study for evaluating methods of monsoon onset determination. Despite the importance of monsoon rainfall for local livelihoods, detailed assessments of onset timing in this region remain limited, creating challenges for climate-sensitive sectors.

A key challenge in defining monsoon onset lies in the limitations of relying solely on local rainfall indicators. Rainfall-based definitions often fail to represent the broader atmospheric processes that trigger the seasonal transition, and they may

introduce ambiguity during years with suppressed or intermittent early-season rainfall [8]. Previous studies in Indonesia and surrounding regions have predominantly used rainfall-only criteria [9,10], with limited consideration of large-scale circulation features such as moisture transport or zonal wind reversal. This narrow focus restricts the ability to capture the dynamical mechanisms underlying onset formation. These limitations highlight the need for an approach that integrates both local rainfall anomalies and regional atmospheric indicators, particularly the identification of moisture sources contributing to early-season precipitation.

Therefore, this study aims to determine the onset date of the monsoon in Makassar using a combination of local rainfall-based and regional moisture-source criteria, analyze the interannual variability of the onset dates and examine the role of large-scale climate drivers, such as the El Niño–Southern Oscillation (ENSO) and zonal wind dynamics, in modulating monsoon onset timing. By addressing these objectives, this research contributes to improving the accuracy of monsoon onset determination and provides relevant information for climate adaptation strategies in eastern Indonesia.

## 2. Methods

This study utilized precipitation data from the Multi-Source Weighted-Ensemble Precipitation version 2 (MSWEP-v2), obtained from <https://www.gloh2o.org/mswep/>, with a spatial resolution of  $0.1^\circ \times 0.1^\circ$  and a temporal resolution three hourly. In addition, zonal wind (u) data at the 850 mb level were sourced from the ERA5 reanalysis, which offers a spatial resolution of  $0.25^\circ \times 0.25^\circ$  and a temporal resolution one hourly, accessible via <https://cds.climate.copernicus.eu/>. The study also employed the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to conduct backward trajectory analysis, using wind and specific humidity inputs from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). All datasets used in this study cover the period from 1991 to 2020.

The determination of monsoon onset in the Sulawesi region was carried out by identifying the peak rainy month through the first harmonic analysis of climatological precipitation data, as described by Eq. (1) [11]. Here,  $A_n$  and  $B_n$  represent the sine and cosine functions,  $R_n$  denotes the amplitude of the  $n$ th harmonic wave, and  $\phi_n$  represents the phase angle, which corresponds to the peak timing of the  $n$ th harmonic function [12]. After identifying the peak month, a backward trajectory analysis using the HYSPLIT model was conducted to trace the primary

sources of moisture during the peak monsoon period (active Monsoon), particularly focusing on the Makassar region.

$$A_n = \frac{2}{N} \sum_{t=1}^N x(t) \cos\left(\frac{2n\pi t}{T}\right); B_n = \frac{2}{N} \sum_{t=1}^N x(t) \sin\left(\frac{2n\pi t}{T}\right)$$

$$R_n = \sqrt{A_n^2 + B_n^2}; \phi_n = \arctan\left(\frac{B_n}{A_n}\right) \quad (1)$$

The next step is the determination of the monsoon onset date by integrating both local and regional criteria. The local criterion is calculated using the Cumulative Anomaly (CA) method, which utilizes the total accumulation of daily rainfall anomalies ( $A_t$ ) from January 1 to December 31 [13]. In this context,  $P_n$  represents the daily rainfall, and  $\bar{P}$  denotes the climatological average of daily rain, as shown in Eq. (2). The date on which the  $A_t$  value reaches its minimum is considered the reference point and is used as the center of the scanning window for onset detection, with a range of  $\pm 30$  days.

$$A_t = \sum_{1 \text{ Jan}}^{31 \text{ Des}} (P_n - \bar{P}) \quad (2)$$

The regional criterion is determined through backward trajectory analysis using the HYSPLIT model to identify the percentage contribution of each moisture source [14], as illustrated in Figure 1. All air parcels were traced backward for 240 hours (10 days) from 1991–2020. In this study, a 10-day trajectory window was selected to represent the typical transport timescale of moisture parcels traveling from the dominant upwind source regions affecting Makassar. The average low-level wind speed in the tropical Western North Pacific and Maritime Continent at 850 hPa ranges between 8-10  $\text{m s}^{-1}$  [15,16], which corresponds to physically realistic advection rates during the monsoon transition. Based on this range, the estimated travel time for air parcels along the representative paths shown in the Figure 1 approximately 2212 km from point A to B and 3.140 km from point C to D falls within 6-12 days and 9-16 days, respectively. These estimates align well with the expected moisture-transport timescales into the Maritime Continent, indicating that a 10-day window is sufficiently long to capture the full evolution of monsoonal moisture inflow while remaining short enough to avoid unrealistic long-range contributions or excessive trajectory uncertainty. Based on Eq. (3), the change in specific humidity over a given time interval ( $Dq/Dt$ ) generally reflects the difference between the amount of precipitation (P) and evaporation (E) occurring along a trajectory path [17]. Moisture source regions are identified when there is an increase in specific humidity ( $\Delta q > 0$ ),

whereas sink regions are characterized by a decrease in specific humidity ( $\Delta q < 0$ ). Each trajectory is analyzed to calculate hourly changes in specific humidity, with only positive values of  $\Delta q > 0$  considered and expressed as a percentage contribution.



Figure 1. Transport distances from the NM moisture source region to Celebes Island. Estimated travel distances of  $\approx 2,212$  km and  $\approx 3,140$  km.

$$\frac{Dq}{Dt} \approx \frac{\Delta q}{\Delta t} = E - P \text{ (kg.kg}^{-1}\text{h}^{-1}\text{)}$$

$$\Delta q^0(t) = q(\vec{x}(t)) - q(\vec{x}(t - 1h)) \quad (3)$$

The trajectories' starting point (sink) was set at the longitude and latitude coordinates of the South Sulawesi Climatology Station, representing the observation site in Makassar. Moisture source regions were classified into seven major zones: the North Indian Ocean (NIO), South Indian Ocean (SIO), Northern Maritime Continent (NM), Tropical Maritime Continent (TM), Southern Maritime Continent (SM), Northwest Pacific (NP), and Southwest Pacific (SP). The percentage of air parcels originating from each of these regions was used to assess the dominant sources of moisture during the active monsoon period in the study area (Figure 2).

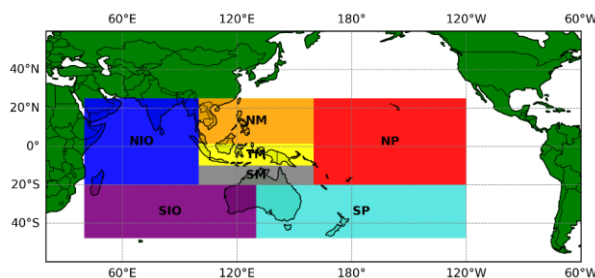


Figure 2. Moisture source region.

Monsoon onset dates were determined by calculating the percentage contribution of each moisture source based on the regional criterion for each date within the scanning period. This calculation was performed

using daily backward trajectories, excluding the first five days of each trajectory to minimize the influence of local circulation. Contribution percentages were computed on a pentad (five-day average) basis to smooth out short-term local fluctuations. A given date was considered to meet the regional criterion if the moisture source distribution matched that observed during the active monsoon phase in the peak month. Furthermore, the date had to fall within the scanning period and must not be interrupted by more than five consecutive days during which the moisture source distribution failed to meet the regional criterion. It should be noted, however, that this framework has limitations. The accuracy of backward trajectories decreases with integration time, so the 10-day tracing period may introduce uncertainties in detecting remote moisture sources. In addition, the spatial resolution of the reanalysis and precipitation datasets may not fully capture local-scale processes in Makassar, while the assumption that onset is achieved when the moisture source distribution resembles that of the peak monsoon month simplifies the complex dynamics of seasonal transition. These considerations suggest that the onset dates should be interpreted as approximations, although the combined local-regional approach still provides a more representative estimate than rainfall-only criteria.

### 3. Result and Discussion

Makassar exhibits a monsoonal rainfall pattern, as illustrated in Figure 3. The rainfall pattern shows an increase toward the end and beginning of the year and a decrease in the middle of the year. This pattern is also reflected in the first harmonic reconstruction, indicating a strong annual cycle. In other words, Makassar experiences one rainy season and one dry season each year. The application of the first harmonic to daily rainfall data for the period 1991–2020 is shown in Figure 3. The peak phase of the first harmonic wave effectively represents the peak of annual rainfall. Figures 3 and 4 confirm the monsoonal rainfall regime in Makassar, with a single wet and dry season each year and peak rainfall in January–February. This aligns with the seasonal reversal of monsoon winds, when cross-equatorial flow transports moisture from the Asian continent into the Maritime Continent. Such a strong annual cycle underlines the critical importance of accurately defining the onset of the rainy season. [18]. Winter in Asia occurs from November to February, triggering wind flows that carry moisture from the Asian continent toward Australia through the Indonesian region [19]. Therefore, further analysis focuses on January–February to identify the primary sources of moisture affecting rainfall in Makassar, which serves as the basis for determining regional criteria during the active phase of the Asian Monsoon.

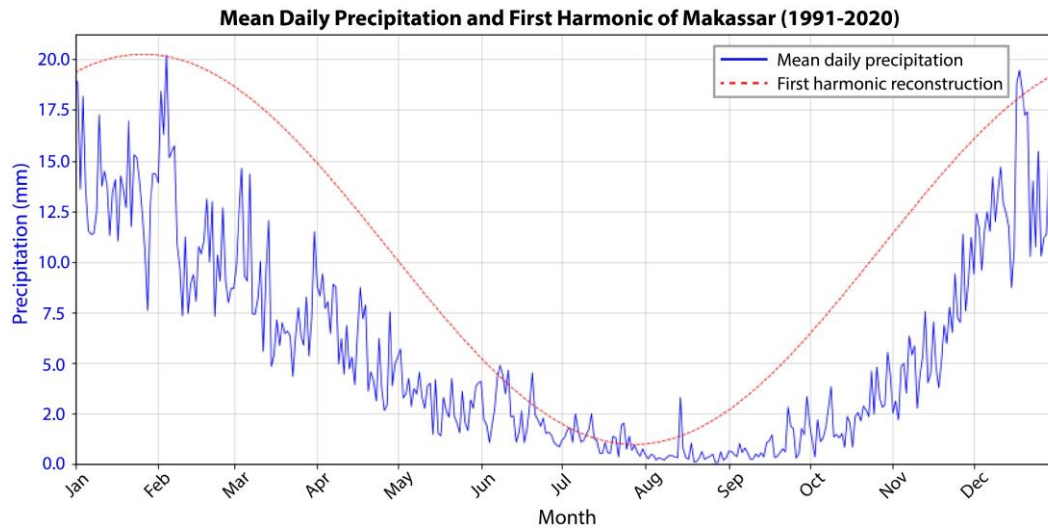


Figure 3. Makassar Climatological daily average precipitation (blue line) and its first harmonic reconstruction (red dashed line) in Makassar.

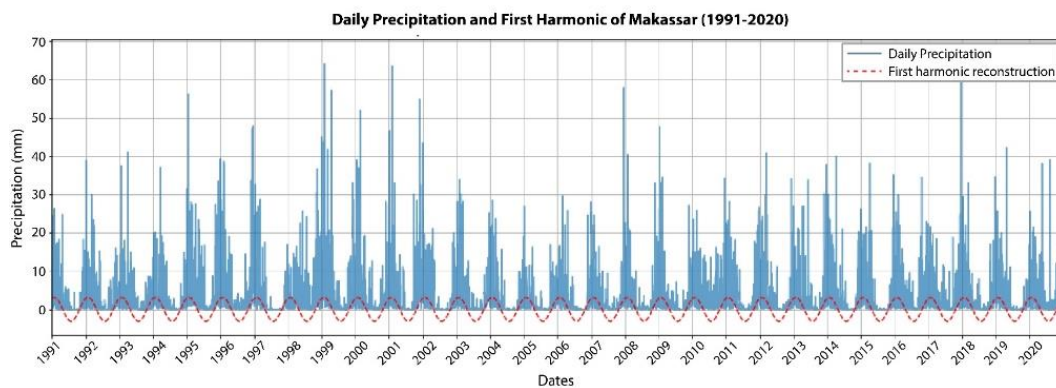


Figure 4. Daily precipitation time series in Makassar from 1991 to 2020 and its first harmonic reconstruction (red dashed line).

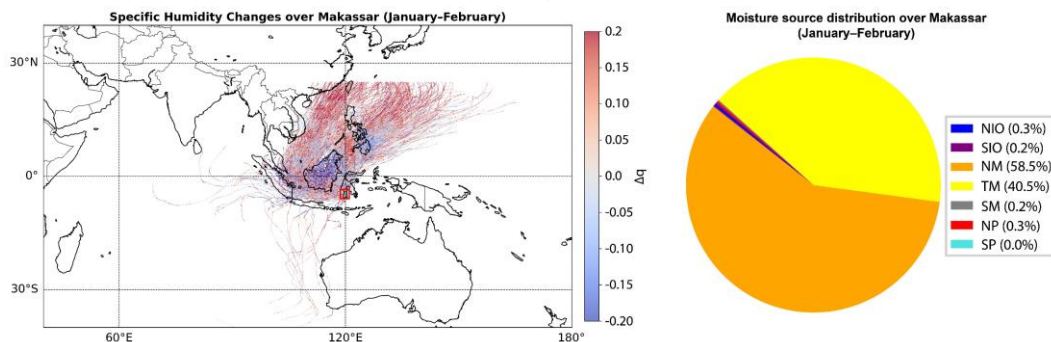


Figure 5. Hourly changes in specific humidity during January–February from 1991 to 2020 (left) and the contribution of moisture sources from various source regions during the active monsoon (right). The red box indicates the Makassar region as the Sink point.

The average hourly change in specific humidity along particle trajectories is shown in Figure 5. Referring to the study by Stohl and James [20], changes in specific humidity reflect the net result of precipitation (P) and evaporation (E) processes along the trajectory. Areas with positive changes in humidity ( $\Delta q > 0$ ) are identified as moisture sources, while those with negative changes ( $\Delta q < 0$ ) are considered sink regions or areas of precipitation. Based on Figure 5 (left), during January–February, the primary sources of moisture for Makassar originate from the northern

Maritime Continent. Two major pathways bring moisture into the region: first, from the South China Sea, turning eastward over the island of Borneo, and second, from the western Pacific Ocean, moving southward through the Makassar Strait.

Figure 5 (right) shows that rainfall in Makassar is predominantly sustained by cross-equatorial transport from the Northern Maritime Continent (58.8%) and reinforced by Tropical Maritime sources (40.5%). This result highlights the essential role of long-range

advection of water vapor, a mechanism widely recognized in monsoon regions (Stohl & James, 2004; Purwaningsih et al., 2022). Minor contributions from the Indian and Pacific Oceans suggest that localized evaporation plays only a secondary role.

The onset dates of the rainy season based on local and regional criteria are presented in Table 1. Most of these onset dates are dominated by moisture contributions from the Northern Maritime (NM) region, which in many years exceeds 50%. In certain years, such as 5 December 1994, 13 December 2005, and 21 December 2015, the NM contribution even reached 80%, underscoring its pivotal role as the main moisture supplier. However, Table 1 also illustrates substantial interannual variability both in onset timing and in source-region dominance. The onset dates range from early November to late December, indicating that the transition into the rainy season is not fixed but responds dynamically to large-scale circulation anomalies [21]. Likewise, the moisture contribution from NM fluctuates considerably across years, while in some cases other regions (e.g., Tropical Maritime or Southern Maritime Continent) become relatively more prominent. Such variability is consistent with the influence of large-scale climate drivers including ENSO, which modulates SST gradients and convection over the Maritime Continent and monsoon activity [22]. For example, El Niño years tend to delay the onset and reduce the NM contribution, whereas La Niña years favor earlier onset and stronger NM dominance. These findings emphasize that while NM is generally the primary source of moisture, interannual variations in atmospheric–oceanic dynamics can significantly shift both the onset date and the relative contributions of different source regions.

Interannual variation in the onset dates of the rainy season in Makassar is shown in Figure 6. In general, the onset occurs between November and December. However, no clear linear trend indicates whether the onset is progressively earlier or later over the years. The pattern appears to fluctuate, suggesting a strong influence of interannual climate variability, particularly the ENSO phenomenon [23]. For instance, the 1998–2000 period shows significant dynamics [24], with a strong El Niño event in 1998 followed by a strong La Niña, likely affecting shifts and uncertainties in the rainy season onset. Moreover, in the 2000s, fluctuations in onset dates appear more pronounced compared to the relatively stable 1990s, potentially indicating changes in regional atmospheric dynamics over the past two decades. Importantly, when these interannual shifts are viewed through the combined lens of rainfall anomalies, moisture-source dominance, and zonal wind behavior, several refinements to onset interpretation emerge. During El Niño years, for example, small early-season rainfall events would have suggested an earlier onset under conventional rainfall-only criteria, yet the weak NM moisture contribution and delayed wind reversal showed that large-scale monsoonal conditions had not fully established. Conversely, in certain La Niña years, the rapid intensification of NM moisture transport and earlier westerly onset at 850 hPa helped confirm an earlier transition into the wet season, even when local rainfall remained intermittent. These triangulated indicators therefore clarify ambiguous years, demonstrating that the integrated method not only follows the observed interannual variability but also corrects potential misclassification inherent in rainfall-only approaches.

Table 1. Onset date in Makassar along with the contribution of moisture sources.

Dates	NM	TM	Dates	NM	TM	Dates	NM	TM
10-Dec-1991	45.71	42.86	24-Nov-2001	54.29	34.29	26-Nov-2011	65.71	34.29
27-Nov-1992	51.43	48.57	12-Dec-2002	57.14	42.86	19-Dec-2012	71.43	28.57
18-Dec-1993	54.29	45.71	05-Dec-2003	65.71	34.29	21-Nov-2013	48.57	40.00
05-Dec-1994	80.00	20.00	03-Dec-2004	77.14	22.86	04-Dec-2014	34.48	13.79
30-Nov-1995	74.29	22.86	13-Dec-2005	62.86	31.43	21-Dec-2015	80.00	20.00
03-Dec-1996	60.00	40.00	27-Dec-2006	77.14	22.86	03-Dec-2016	48.57	34.29
08-Dec-1997	65.71	34.29	16-Dec-2007	57.14	42.86	20-Nov-2017	60.00	40.00
08-Dec-1998	60.00	40.00	20-Dec-2008	37.14	25.71	13-Dec-2018	51.43	28.57
24-Dec-1999	77.14	14.29	11-Dec-2009	60.00	40.00	17-Dec-2019	45.45	45.45
12-Nov-2000	62.86	34.29	03-Dec-2010	57.14	42.86	26-Nov-2020	54.55	45.45

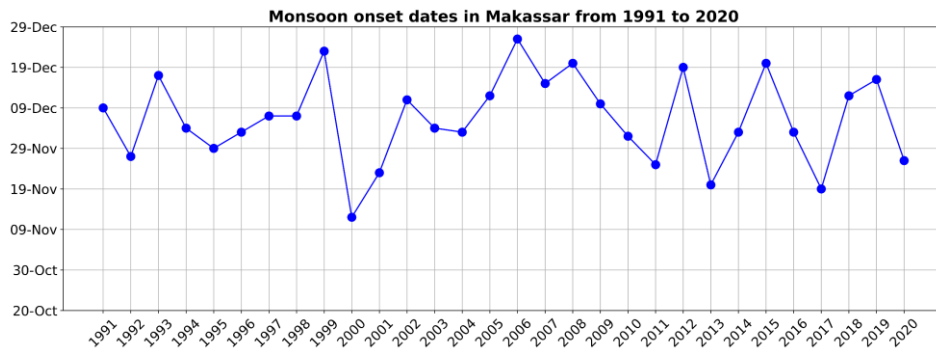


Figure 6. Time series of onset dates in Makassar from 1991 to 2020.

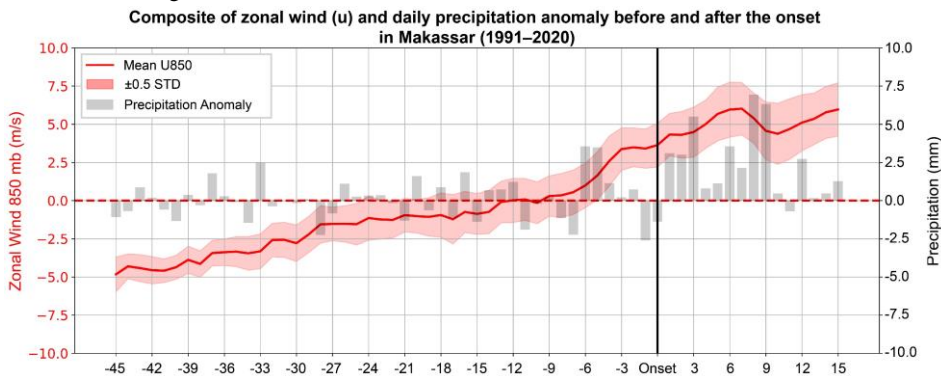


Figure 7. Zonal wind at 850 mb before and after the onset date. The gray bars indicate rainfall anomalies. The red dashed horizontal line marks the transition point from easterly to westerly winds. The black vertical line indicates the onset.

Figure 7 indicates that the onset of the rainy season is accompanied by a clear reversal of the 850 hPa zonal wind from easterly to westerly, concurrent with an increase in rainfall anomalies. This shift marks the transition from the dry to the wet phase, providing an independent dynamical indicator of monsoon onset and reflecting the establishment of cross-equatorial westerlies that enhance moisture convergence and convection [25]. Before the onset (day 0), the zonal wind is predominantly easterly (negative values), gradually weakening and then shifting to westerly (positive values) following the onset. This transition is marked by the red dashed horizontal line, signifying a shift in atmospheric circulation that supports sustained rainfall rather than the intermittent events often seen in pre-onset periods.

Importantly, the alignment between rainfall anomalies, zonal wind reversal, and NM moisture activation helps clarify why the integrated method improves onset detection. In several ENSO-affected years, rainfall-only criteria would suggest an onset up to 10–15 days earlier, but the absence of wind reversal and weak NM moisture contribution indicated that monsoonal conditions had not yet developed. Conversely, in some La Niña years, rapid strengthening of cross-equatorial flow and earlier NM moisture dominance (often varying by 30–40% across years) confirmed an earlier transition even when local rainfall remained sporadic. This phenomenon is consistent with moisture pathways entering Makassar predominantly from the west, with the NM region supplying the bulk of water vapor

during true monsoon onset [26]. These relationships illustrate that the integrated approach combining cumulative rainfall anomalies, backward moisture trajectories, and wind diagnostics filters out ambiguous rainfall signals and captures the dynamical structure of onset more reliably. Therefore, the onset dates determined using both local and regional criteria adequately represent significant atmospheric transitions, particularly wind direction shifts, and can serve as robust indicators of the beginning of the rainy season in Makassar [27].

To verify the previous findings, an experiment was conducted for 2024 by analyzing the relationship between zonal wind and rainfall in Makassar. Figure 8 shows daily rainfall observations and the 5-day running mean zonal wind at the 850 mb level throughout the year. Before the average onset date of December 6, zonal winds were predominantly easterly (red line, negative values), then shifted to westerly (blue line, positive values) concurrently with a marked increase in rainfall [28]. This east-to-west wind reversal provides a clear dynamical signal of the rainy season onset [29] and confirms that the identified date represents the atmospheric transition from dry to wet conditions in Makassar. The 2024 case study thus validates the robustness of the combined framework, as both rainfall anomalies and zonal wind shifts consistently captured the onset within the climatological range of 1991–2020. These results highlight the potential of the proposed criteria for real-time monitoring and early warning applications, in line with approaches used in other Asian monsoon regions.

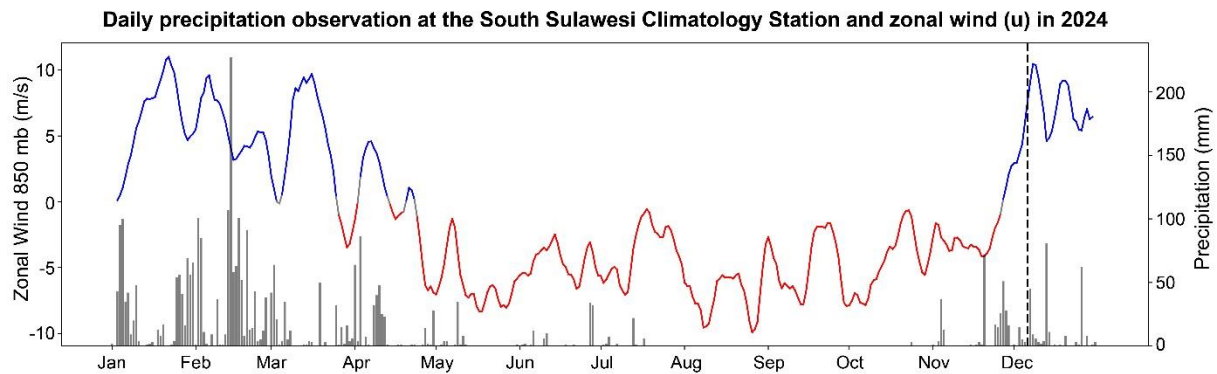


Figure 8. Daily rainfall (bars) and 5-day running mean of zonal wind (lines) in Makassar for the year 2024. Easterly zonal winds (red) and westerly zonal winds (blue). The black dashed vertical line marks the average onset date (6 December).

#### 4. Conclusion

This study determined the onset of the rainy season in Makassar by integrating local rainfall anomalies with regional moisture-source trajectories and dynamical indicators for the 1991–2020 period. This integrated approach directly addresses the limitations of rainfall-only onset definitions, which often struggle to capture the large-scale atmospheric processes governing monsoon transitions. By incorporating moisture-source information, the analysis demonstrates that rainfall increases during onset are consistently supported by enhanced moisture transport, particularly from the Northern Maritime Continent, which contributes more than 50% of the total moisture during peak months and responds sensitively to ENSO and other circulation anomalies. This provides a physical basis for interpreting early-season rainfall signals, reducing ambiguity in years when local precipitation is intermittent or suppressed.

The findings also show that the typical monsoon onset in Makassar occurs in November–December, even though with substantial interannual variability. A key dynamical marker identified in this study is the reversal of zonal winds at the 850-hPa level from easterly to westerly, which systematically coincides with the rainfall-based onset date. This alignment between rainfall anomalies, cross-equatorial moisture pathways, and low-level wind reversal illustrates the triangulation strength of the proposed framework. The 2024 case study further reinforces this consistency, demonstrating that all indicators converged on the same onset date 6 December highlighting the robustness of the method.

Overall, this research offers a clearer and more physically grounded definition of monsoon onset for Makassar by explicitly linking local rainfall behavior with regional atmospheric dynamics. The methodological contribution lies in demonstrating how moisture-source activation and dynamical transitions strengthen the interpretation of rainfall-based signals, producing a more representative and reliable onset estimate. Beyond Makassar, the

framework presented here holds potential applicability for other coastal monsoon regions where local rainfall alone may not adequately reflect larger-scale seasonal transitions. These insights provide valuable support for agricultural planning, water-resource management, and climate-related early warning efforts, while also offering a foundation for future operational or forecasting applications.

#### Suggestion

As a follow-up to this study, further research is recommended to explore the influence of global climate variability particularly ENSO on zonal wind dynamics and moisture advection affecting the rainy season onset in Makassar. Analyzing the relationship between SST anomalies in the Niño 3.4 region and local atmospheric parameters could provide a more comprehensive understanding of the global teleconnection mechanisms influencing regional monsoon systems. Additionally, the spatial scope of the analysis could be expanded to include other coastal areas in Sulawesi and eastern Indonesia to test the consistency of NM moisture contributions and zonal wind shift patterns in determining the rainy season onset. This approach could not only strengthen the generalizability of the findings but also provide a broader scientific basis for developing early warning systems based on atmospheric and oceanic dynamics in eastern Indonesia.

#### References

- [1] Zhang, S., & Wang, B. (2008). Global summer monsoon rainy seasons. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 28(12), 1563-1578.
- [2] Muttaqin, A. S. (2023). *Land-Atmosphere Interactions over the Indonesian Maritime Continent*. The University of Wisconsin-Madison.

- [3] Yang, D., Yang, Y., & Xia, J. (2021). Hydrological cycle and water resources in a changing world: A review. *Geography and Sustainability*, 2(2), 115-122.
- [4] Ahmed, M., Hayat, R., Ahmad, M., Ul-Hassan, M., Kheir, A. M., Ul-Hassan, F., & Ahmad, S. (2022). Impact of climate change on dryland agricultural systems: a review of current status, potentials, and further work need. *International Journal of Plant Production*, 16(3), 341-363.
- [5] Oyeboode, O. J., Oyerinde, A. O., & Oyeboode, F. A. (2023). Engineering Hydrology for Flood Control, Adequate Water Resources and Sustainable Environment in Nigeria. *Journal of Water Resource Engineering and Management*, 10(2), 1-10p.
- [6] Ulfiana, A., Arsyad, M., & Palloan, P. (2023). The Atmospheric Dynamics Related to Extreme Rainfall and Flood Events during September-October-November in South Sulawesi. In *Forum Geografi* (Vol. 37, No. 2, pp. 107-116).
- [7] Wainwright, C. M., Black, E., & Allan, R. P. (2021). Future changes in wet and dry season characteristics in CMIP5 and CMIP6 simulations. *Journal of Hydrometeorology*, 22(9), 2339-2357.
- [8] Ren, W., Tian, L., & Shao, L. (2021). Regional moisture sources and Indian summer monsoon (ISM) moisture transport from simultaneous monitoring of precipitation isotopes on the southeastern and northeastern Tibetan Plateau. *Journal of Hydrology*, 601, 126836.
- [9] Ferijal, T., Batelaan, O., Shanafield, M., dan Alfahmi, F. (2022). Determination of rainy season onset and cessation based on a flexible driest period. *Theoretical and Applied Climatology*, 148(1), 91-104.
- [10] Moron, V., Robertson, A. W., dan Boer, R. (2009). Spatial coherence and seasonal predictability of monsoon onset over Indonesia. *Journal of Climate*, 22(3), 840-850.
- [11] Wilks, D. S. (2011). *Statistical methods in the atmospheric sciences* (Vol. 100). Academic press.
- [12] Serrano-Vincenti, S., Condom, T., Campozano, L., Escobar, L. A., Walpersdorf, A., Carchipulla-Morales, D., & Villacís, M. (2022). Harmonic analysis of the relationship between GNSS precipitable water vapor and heavy rainfall over the Northwest Equatorial Coast, Andes, and Amazon Regions. *Atmosphere*, 13(11), 1809.
- [13] Schlegel, R. W., Oliver, E. C., & Chen, K. (2021). Drivers of marine heatwaves in the Northwest Atlantic: The role of air-sea interaction during onset and decline. *Frontiers in Marine Science*, 8, 627970.
- [14] Guo, X., Wang, L., Tian, L., Zhang, L., & Zhao, W. (2025). Quantitative identification of moisture sources over the Tibetan Plateau: spatial distributions and temporal variabilities. *Journal of Climate*, 38(1), 263-276.
- [15] Hu, Y., Stamnes, K., Vaughan, M., Pelon, J., Weimer, C., Wu, D., Cisewski, M., Sun, W., Yang, P., Lin, B. and Omar, A. (2008). Sea surface wind speed estimation from space-based lidar measurements. *Atmospheric Chemistry and Physics*, 8(13), 3593-3601.
- [16] Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., Nieto, R. (2012). Oceanic and terrestrial sources of continental precipitation. *Reviews of Geophysics*, 50(4).
- [17] James, P., Stohl, A., Spichtinger, N., Eckhardt, S., Forster, C. (2004): Climatological aspects of the extreme European rainfall of August 2002 and a trajectory method for estimating the associated evaporative source regions, *Nat. Hazards Earth Syst. Sci.*, 2004, 4, 733-746.
- [18] Rahmah, A., & Baeda, A. Y. (2024). PENGARUH MADDEN-JULLIAN OSCILLATION TERHADAP VARIABILITAS SUHU PERMUKAAN LAUT DI SELAT MAKASSAR. *Riset Sains dan Teknologi Kelautan*, 129-133.
- [19] Cheng, T. F., Lu, M., & Dai, L. (2021). Moisture channels and pre-existing weather systems for East Asian rain belts. *Npj Climate and Atmospheric Science*, 4(1), 32.
- [20] Stohl, A. dan James, P. (2004): A Lagrangian Analysis of the Atmospheric Branch of the Global Water Cycle. Part I: Method Description, Validation, and Demonstration for the August 2002 Flooding in Central Europe, *J. Hydrometeorol*, 5, 656-678.
- [21] Purwaningsih, A., Lubis, S. W., Hermawan, E., Andarini, D. F., Harjana, T., Ratri, D. N., ... & Sujalu, A. P. (2022). Moisture origin and transport for extreme precipitation over Indonesia's new capital city, Nusantara in August 2021. *Atmosphere*, 13(9), 1391.

- [22] Khan, S., Piao, S., Zheng, G., Khan, I. U., Bradley, D., Khan, S., & Song, Y. (2021). Sea surface temperature variability over the tropical Indian Ocean during the ENSO and IOD events in 2016 and 2017. *Atmosphere*, *12*(5), 587.
- [23] Bonazza, M. (2021). *Water vapor, precipitation and evapotranspiration isotopic composition in the tropical atmospheric boundary layer* (Doctoral dissertation, Dissertation, Göttingen, Georg-August Universität, 2021).
- [24] Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J. S., & Zhong, W. (2021). Changing El Niño–Southern oscillation in a warming climate. *Nature Reviews Earth & Environment*, *2*(9), 628-644.
- [25] Li, X., Hu, Z. Z., Tseng, Y. H., Liu, Y., & Liang, P. (2022). A historical perspective of the La Niña event in 2020/2021. *Journal of Geophysical Research: Atmospheres*, *127*(7), e2021JD035546.
- [26] Du, Y., Xie, Z., Wang, N., Miao, Q., & Zhang, L. (2022). Influence of zonal variation of the subtropical westerly jet on rainfall patterns and frequency of heavy precipitation events over East Asia. *Journal of Climate*, *35*(20), 6611-6626.
- [27] Rosalina, D., Suryadi, L. P. F., Rombe, K. H., Leilani, A., Irwana, I., & Haris, R. B. K. (2024). Salinity Distribution Pattern in Spermonde Waters Using Remote Sensing Data (Copernicus Marine Service) in 2022. *Jurnal Kelautan: Indonesian Journal of Marine Science and Technology*, *17*(1), 43-54.
- [28] Huang, L., Chen, J., Yang, K., Yang, Y., Huang, W., Zhang, X., & Chen, F. (2023). The northern boundary of the Asian summer monsoon and division of westerlies and monsoon regimes over the Tibetan Plateau in present-day. *Science China Earth Sciences*, *66*(4), 882-893.
- [29] Wang, Q., Wang, L., Huang, G., & Wang, T. (2023). Mechanism of the summer rainfall interannual variability in transitional climate zone in East Asia: roles of teleconnection patterns and associated moisture processes. *Climate Dynamics*, *61*(3), 1177-1192.