

Investigation and Future Projection of Warm Rain During Winter Monsoon in Java Sea, Indonesia

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1. Introduction

Rainfall in tropical regions, including Indonesia, plays a vital role in hydrological and climatic systems, with warm rain contributing significantly to overall precipitation. Warm rain, primarily generated through the collision-coalescence process, accounts for 31% of total rainfall volume and 72% of the rain-affected areas in the tropics (Lau and Wu, 2003). Forming in clouds with temperatures above 0°C, it bypasses the ice-phase Bergeron-Findeisen mechanism (Tao et al., 2012). This process, driven by abundant moisture and strong updrafts, produces substantial rainfall, profoundly affecting regional water resources and weather patterns.

Climate change amplifies atmospheric dynamics, with global Sea Surface Temperature (SST) rising by ~2°C (IPCC, 2013), increasing water vapor capacity by 7% per 1°C (Clausius-Clapeyron relation). This warming boosts Cloud Water Content (CWC), including Cloud Liquid Water Content (CLWC) and Rain Liquid Water Content (RLWC), the key driver of precipitation. As a result, warm rain becomes more prevalent, intensifying the hydrological cycle and causing more frequent and intense rainfall events (Gao et al., 2021).

This study combines TRMM data with MRI-AGCM simulations to analyze warm rain changes in the Java Sea. Previously used for rainfall studies in Japan and East Asia (Mizuta et al., 2012; Osakada and Nakakita, 2018; Mori et al., 2021), MRI-AGCM offers valuable insights for the Indonesia region.

2. Research Location, Data, and Methodology

The study focuses on the Java Sea in Indonesia, a region heavily influenced by the winter monsoon (December, January, February; DJF), which often

brings heavy rainfall and floods to northern Java, including Jakarta. Using satellite observations (Tropical Rainfall Measurement Mission; TRMM), reanalysis data (ERA5), and Atmospheric General Circulation Model (AGCM) simulations by the Meteorological Research Institute (MRI), the research investigates warm rain dynamics and future projections.

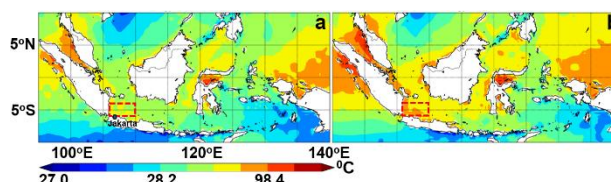
3. Results and Discussion**3.1. Increase in SST in the Indonesian Region**

Figure 1. Spatial increasing of SST in Indonesia, a. 1950-1979, b. 1980-2009 (The red square box is Java Sea).

Figure 1 illustrates the 30-year SST differences across the Indonesian region, including the Java Sea. A comparison between the first and second 30-year periods reveals a consistent increase in SST throughout the region, including the Java Sea. This SST rise is likely linked to climate change, which can significantly contribute to hydrometeorological disasters in surrounding areas of Java Sea such as Jakarta.

3.2. Correlation of SST and CLWC

The Correlation Coefficient (R) between SST and CLWC shows that annual climatology reveals low or negative R values in the monsoon pathway (Figure 2a), as warmer SSTs drive deeper convection, reducing lower-level CLWC (0.5–3 km). During DJF (Figure 2b), positive R values appear in northern Indonesia, with warm SSTs enhancing shallow convection and CLWC. However, Java Sea retains low R values, likely caused by factors such as stronger convection or changes in how clouds form and develop.

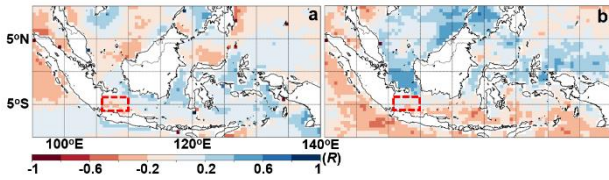


Figure 2. The spatial distribution of R between SST and CLWC at a height of 0.5–3 km for: a) annual climatology, and b) DJF climatology, over 17 years (1997–2014).

3.3. Warm Rain Analysis via CLWC

The spatial comparison of shallow (warm) rainfall and CLWC during DJF is shown in Figure 3. Warm rainfall, as observed by the TRMM, occurs when radar reflectivity is detected below the melting layer. The figure indicates that the distribution of warm rainfall closely resembles that of CLWC during DJF, suggesting that CLWC can serve as a reliable proxy for investigating warm rain.

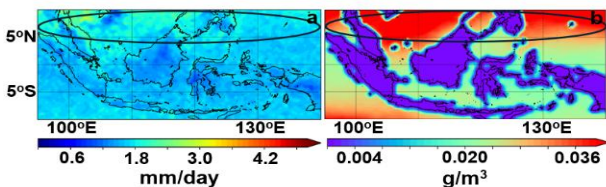


Figure 3. Comparison of a) shallow (warm) rainfall and b) CLWC observed by TRMM.

3.4. CLWC-TRMM vs. CLWC-AGCM

The R between CLWC observed by TRMM and CLWC simulated by AGCM for 1998–2014, covering the entire Indonesian region, including Java Sea is shown in Figures 4a and 4b for annual and seasonal climatology (DJF), respectively. Figure 4a demonstrates a good overall correlation ($R \sim 0.6$) across Indonesia, while Figure 4b shows that during DJF, high R values are concentrated in the western part of Indonesia. This suggests that the AGCM performs better in simulating CLWC during DJF, likely due to the increased CLWC resulting from higher water vapor levels during the monsoon.

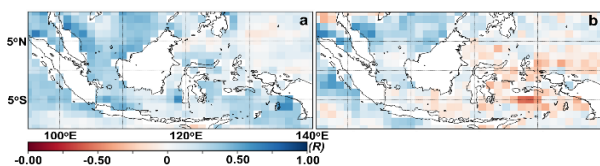


Figure 4. The R of CLWC-TRMM and CLWC-AGCM, a) annual climatology, b) Seasonal climatology.

3.5. Warm rain projection by AGCM

Figure 5 illustrates the projected increase in CWC at 850 hPa in the Indonesian region, including the Java Sea, during DJF in future climate scenarios. Since CLWC serves as a proxy for warm rain, this increase implies a likely rise in the occurrence of warm rain events in the future. This projection suggests that warm rain processes may intensify, potentially leading to more frequent or intense rainfall events and altering precipitation patterns and hydrological dynamics.

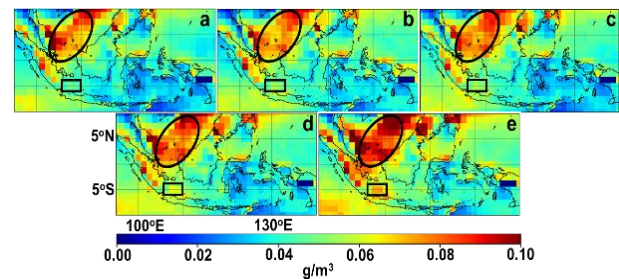


Figure 5. CWC-AGCM at 850 hPa in, a) 1950-1979, b) 1980-2009, c) 2010-2039, d) 2040-2069, e) 2070-2099.

4. Conclusions

Based on the investigation we reached the following conclusions:

- Climate change in Indonesia, including the Java Sea, is reflected in SST data, showing the highest increase during DJF.
- CLWC can serve as a proxy for warm rain occurrence due to its strong correlation with warm rainfall.
- The AGCM accurately simulates CLWC during DJF, as shown by the strong correlation with observed data.
- An increase in warm rain is projected for the future, as shown by the CLWC data from AGCM simulations.

References

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