

Spatial Characterization of Rainfall, Convective Available Potential Energy, and Low-Level Relative Humidity across ENSO Phase Intensities over the Indonesian Maritime Continent Based on ERA5 Reanalysis

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Abstract

Rainfall over the Indonesian Maritime Continent (IMC) is strongly modulated by the El Niño-Southern Oscillation (ENSO), yet most previous studies have neither resolved ENSO intensity in detail nor examined rainfall jointly with atmospheric instability and low-level moisture. This study characterizes the spatial patterns of rainfall, Convective Available Potential Energy (CAPE), and 925 hPa relative humidity (RH925) anomalies across six ENSO intensity classes (weak, moderate, and strong El Niño and La Niña) over the IMC, using ERA5 reanalysis data for 1995–2025. ENSO phases were classified using the Oceanic Niño Index (ONI). The significance of the composite anomalies was assessed with a one-sample t-test and non-parametric bootstrap resampling (95% confidence interval, 1000 iterations), and the consistency between the two approaches was evaluated. Rainfall and RH925 responded uniformly but with opposite sign to the two ENSO phases, showing deficits during El Niño and surpluses during La Niña, with magnitudes that increased from weak to strong events. In contrast, CAPE anomalies did not vary monotonically with intensity but formed a west–east dipole that sharpened during moderate and strong phases. The two significance tests yielded highly consistent spatial patterns for all variables and phases. During strong events, rainfall and RH925 displayed an asymmetric response: the area of significant anomalies expanded under El Niño but contracted under La Niña, whereas the significant CAPE anomalies were spatially redistributed.

1 Introduction

The Indonesian Maritime Continent (IMC) is one of the world's largest centers of atmospheric convection, owing to its extensive warm ocean waters, which serve as the primary source of convective energy (Arsyandi et al. 2026). Rainfall over this region is strongly governed by complex ocean–atmosphere interactions and can be regionalized into several dominant patterns that respond differently to sea surface temperature (Aldrian and Susanto 2003). One of the most influential sources of interannual climate variability affecting these patterns is the El Niño-Southern Oscillation (ENSO), which modulates the distribution of sea surface temperature and atmospheric circulation across the Indo-Pacific region (Nur'utami and Hidayat 2016).

The influence of ENSO on Indonesian rainfall has been widely examined, from coastal and mountainous areas of Greater Jakarta (Aslama Afghani et al. 2025) and seasonal patterns across Indonesia based on station data from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) (Hamada et al. 2002) to satellite-based analyses of rainfall extremes (As-syakur et al. 2014; Kurniadi et al. 2021). Interactions between ENSO and other regional-scale variability, such as Cross-Equatorial Northerly Surges (CENS) and the Madden–Julian Oscillation (MJO), have also been shown to modulate atmospheric dynamics and rainfall over the IMC, in both case studies (Atmojo and Amri 2025) and long-term composite analyses (Adzan et al. 2025). However, several of these studies restrict the analysis to broad ENSO categories (El Niño, La Niña, or neutral) without distinguishing intensity levels, and generally focus on only one or two atmospheric variables without adequate statistical significance testing (Togatorop et al. 2025; Mulsandi et al. 2024).

Yet the atmospheric response of the IMC during ENSO is reflected not only in rainfall but also in atmospheric instability, represented by Convective Available Potential Energy (CAPE), and in the availability of lower-tropospheric moisture, represented by relative humidity (Hidayat et al. 2022). Both parameters have been reported to relate to rainfall in a non-linear manner, as shown by the complex relationship between CAPE and rainfall over Indonesian waters (Arsyandi et al. 2026). Relative humidity in the lower troposphere (925 hPa) also exhibits a dominant mode of variability that correlates with ENSO, indicating a substantial influence on lower-tropospheric water vapor availability over Indonesia (Fauziah et al. 2025).

This study therefore aims to characterize the spatial patterns of three parameters simultaneously namely rainfall, CAPE, and low-level relative humidity, across ENSO phase intensities (weak, moderate, and strong) over the entire IMC, using dual statistical significance testing based on the bootstrap method and the t-test. It should be emphasized that the study is exploratory and descriptive in nature: it maps and compares spatial patterns among phases and assesses the consistency of the two significance-testing approaches, rather than constructing or testing causal relationships among the variables.

2 Data and Methods

2.1 Study area and data

The study domain covers the IMC between 90°E -145°E and 10°N-15°S for the period 1995–2025. The data were obtained from the ERA5 reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al. 2020), available from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>). The variables analyzed were total precipitation, CAPE, and relative humidity at the 925 hPa level (RH925), taken from the ERA5 hourly data on single levels from 1940 to present, at a spatial resolution of 0.25° × 0.25° and a monthly temporal resolution.

It should be noted that ERA5 has relatively larger random errors over the tropics than over the mid-latitudes, including a tendency toward a wet bias in precipitation (Lavers et al. 2022). Accordingly, the rainfall anomaly patterns presented here represent reanalysis-model estimates rather than direct surface measurements.

2.2 ENSO phase classification

Monthly Oceanic Niño Index (ONI) data for 1995–2025 were used to classify ENSO phases. The ONI values were assigned to six classes based on the three-month running mean, following the granular ENSO classification thresholds derived from the historical ONI record (National Oceanic and Atmospheric Administration, Climate Prediction Center [NOAA CPC] n.d.), with the weak, moderate, and strong intensity categories following a commonly used scheme (Golden Gate Weather Services n.d.).

Months in the neutral phase were excluded from the analysis. The number of months in each phase is given in Table 1.

Table 1
Number of months (n) in each ENSO phase intensity class, 1995–2025

ENSO phase	Intensity	Number of months (n)	Percentage (%)
El Niño	Weak	46	22.8
	Moderate	13	6.4
	Strong	23	11.4
La Niña	Weak	83	41.1
	Moderate	30	14.9
	Strong	7	3.5
Note: Percentages are calculated relative to the total number of months in an active ENSO phase (n = 202); neutral months are excluded from the analysis.			

2.3 Anomaly calculation and compositing

The workflow of the study is summarized in Fig. 1. The ONI, CAPE, RH925, and precipitation data were first collected and subjected to quality control to ensure completeness, consistency, and validity. Once validated, the data were cropped to the study domain and synchronized to a uniform temporal resolution. Monthly anomalies of each variable were then computed relative to the climatological mean of the corresponding calendar month over the study period:

$$X'_{i,j,t} = X_{i,j,t} - \overline{X}_{i,j,m}$$

1

where $X'_{i,j,t}$ is the anomaly at grid point (i, j) and time t , $X_{i,j,t}$ is the value of the variable, and $\overline{X}_{i,j,m}$ is the climatological mean for calendar month m .

Based on the ONI, the data were classified into weak, moderate, and strong El Niño and weak, moderate, and strong La Niña phases. For each phase, a spatial composite of the anomalies was computed as the arithmetic mean of all months belonging to that phase. This compositing approach follows that used in a study of CENS–ENSO interactions and their effect on atmospheric dynamics over western Indonesia (Togatorop et al. 2025).

2.4 Significance testing

The statistical significance of the composite patterns was evaluated in parallel with two approaches. First, a grid-point-wise one-sample t-test was used to test whether the composite mean differs

significantly from zero ($p < 0.05$), with the test statistic

$$t = \frac{\bar{x} - \mu_0}{s/\sqrt{n}}$$

2

where $\bar{x}$ is the composite sample mean, μ_0 is the hypothesized mean (zero), s is the sample standard deviation, and n is the sample size. Second, non-parametric bootstrap resampling was performed with 1000 iterations for each grid point, and a composite was considered significant if its 95% confidence interval did not include zero. Using the two methods together was intended to strengthen the interpretation of the composite patterns, because analyses of spatial gridded data are prone to violations of the normality assumption and to sample-size limitations in certain phases. Grid points that were not significant were masked, the significant results were visualized as multi-panel figures, and the final output comprised composite maps of significant anomalies for each ENSO phase.

3 Results

The results are presented in two groups according to significance-filtering status: composite anomalies without significance filtering (Section 3.1) and composite anomalies after significance filtering with the one-sample t-test and bootstrap resampling, which are presented side by side for each variable (Section 3.2). Within each group, the three variables (CAPE, rainfall, and RH925) are described phase by phase, following the descriptive approach commonly used in reanalysis-based studies of IMC atmospheric dynamics (Togatorop et al. 2025; Adzan et al. 2025).

3.1 Composite anomalies without significance filtering

3.1.1 CAPE

Composite CAPE anomalies for each ENSO phase are shown in Fig. 2. The color scale represents CAPE anomalies from -150 to $\geq 150 \text{ J kg}^{-1}$, with red indicating a strengthening and blue a weakening of potential convective energy. During weak El Niño ($n = 46$), weak-to-moderate negative anomalies are evident around the Karimata Strait and the waters west of Kalimantan, whereas positive anomalies are confined to a single point or to small, thin, isolated patches, so the overall pattern is close to neutral. Weak La Niña ($n = 83$) shows a similar but weaker pattern, with anomalies close to zero over most of the domain.

The pattern changes markedly during moderate El Niño ($n = 13$), with strong positive anomalies approaching the upper limit of the color scale ($\geq 150 \text{ J kg}^{-1}$) over western Sumatra and the Malay Peninsula, directly adjacent to strong negative anomalies covering Kalimantan, the Java Sea, Sulawesi, and the Banda Sea. This two-pole pattern of opposing anomalies between the western and eastern parts of the domain (a west-east dipole) is clearly formed, with reversed polarity, during moderate La Niña ($n =$

30), when moderate-to-strong positive anomalies dominate the eastern region (Kalimantan, Sulawesi, and Papua) as well as the west coast of Sumatra.

During strong El Niño ($n = 23$), the dipole becomes more pronounced, with very strong negative anomalies extending from Kalimantan to the Banda Sea, adjacent to positive anomalies over Sumatra and the waters south of Java. Strong La Niña ($n = 7$) exhibits very extensive and strong positive anomalies, with most of the eastern part of the domain (from eastern Kalimantan to Papua) approaching or reaching the upper limit of the color scale, while negative anomalies remain concentrated in a small area south of Papua. These patterns indicate that the relationship between CAPE and ENSO phase does not increase or decrease monotonically with intensity; instead, it takes the form of a spatial redistribution of potential convective energy that sharpens as phase intensity increases.

3.1.2 Rainfall

Composite rainfall anomalies for each ENSO phase are shown in Fig. 3 (mm month^{-1}), with red denoting a surplus and blue a deficit relative to climatology. During weak El Niño, anomalies are close to neutral over almost the entire domain, with a slight negative tendency in southern Sumatra. Weak La Niña shows a similarly near-neutral pattern, with a slight positive tendency in the eastern part of the domain. Both weak phases also display a strong positive anomaly confined to a single point or small area near 140°E in the waters of West Papua. This signal appears consistently even when ENSO intensity is weak, and it most likely reflects local variability of that region rather than a pure ENSO response.

During moderate El Niño, negative anomalies of moderate intensity dominate nearly the entire domain, particularly around Kalimantan, the Karimata Strait, and the Java Sea. Moderate La Niña shows the opposite pattern, with positive anomalies extending across nearly the entire eastern and central parts of the domain, including the southern coastal areas of Kalimantan and Sulawesi. During strong El Niño, strong negative anomalies extend from western Sumatra to the Java Sea and the Karimata Strait. Conversely, strong La Niña exhibits very strong positive anomalies over almost the entire domain, especially along the equatorial band from Sumatra to Papua, with values approaching the upper limit of the color scale ($\geq 120 \text{ mm month}^{-1}$) in the waters south of Kalimantan and Sulawesi, and with the West Papua hotspot reappearing at greater intensity. Unlike CAPE, the pattern in Fig. 3 indicates a monotonic relationship between rainfall and ENSO phase, with opposite signs for El Niño and La Niña and anomaly magnitudes that increase with phase intensity from weak to strong (Aldrian and Susanto 2003; Nur'utami and Hidayat 2016; Hamada et al. 2002).

3.1.3 RH925

Composite anomalies of relative humidity at 925 hPa (RH925) for each ENSO phase are shown in Fig. 4 (%), with red denoting a moisture increase and blue a moisture deficit. During weak El Niño, weak negative anomalies are unevenly distributed over most of the domain, particularly from southern Java to

Nusa Tenggara. Weak La Niña shows a near-neutral pattern, with slight positive anomalies mainly in the southern waters of the domain.

During moderate El Niño, negative anomalies of moderate to strong magnitude are concentrated around Kalimantan, Sulawesi, and the Java Sea, forming a fairly extensive area of moisture deficit. Moderate La Niña shows the opposite pattern, with moderate-to-strong positive anomalies extending over the eastern and southern parts of the domain, especially from Nusa Tenggara to southern Papua. During strong El Niño, strong negative anomalies extend from Kalimantan to southern Java and Nusa Tenggara, with values approaching the lower limit of the color scale ($\leq -6\%$). Strong La Niña shows strong positive anomalies extending over most of the western part (northern Sumatra) and the southeastern part (Nusa Tenggara-Timor) of the domain, with values approaching the upper limit of the color scale ($\geq 6\%$) in the waters from south of Java to Timor. Like rainfall, the relationship between RH925 and ENSO phase is monotonic and of opposite sign for El Niño and La Niña, and its spatial pattern is consistent with that of rainfall in Fig. 3.

3.2 Composite anomalies after significance testing

Figures 5–7 show the composite anomalies after filtering with the one-sample t-test ($p < 0.05$; panel a) and bootstrap resampling (95% confidence interval, 1000 iterations; panel b). Areas that are not significant are left blank (white).

3.2.1 CAPE

Overall, both methods yield patterns similar to those in Fig. 2, but with a reduced spatial coverage that reflects the signal strength and sample size of each phase (Fig. 5). During the weak phases (El Niño $n = 46$; La Niña $n = 83$), the areas passing the significance tests are limited and confined to small areas, consistent with the weak anomalies in Fig. 2. During the moderate and strong phases, the significant areas expand clearly and follow the west-east dipole identified previously: the negative anomalies covering Kalimantan to the Banda Sea remain significant under both tests, as do the positive anomalies over northern Sumatra.

During strong La Niña ($n = 7$), the significant area in the western part of the domain is narrower than during moderate La Niña ($n = 30$). In the eastern part, however, a spatial redistribution occurs: some areas that were significant during moderate La Niña become non-significant during strong La Niña, while new significant areas appear elsewhere, including a strengthening of negative anomalies in the southern part of the domain. The smaller sample size in the strong phase therefore does not weaken significance uniformly but instead alters the spatial structure of the areas detected as significant.

3.2.2 Rainfall

Figure 6 shows the composite rainfall anomalies filtered with the t-test (panel a) and bootstrap resampling (panel b). The significant areas obtained with the two methods are very similar across all

phases. During El Niño, the significant negative area widens with increasing intensity, from around Kalimantan and the Java Sea during the moderate phase to western Sumatra and the Karimata Strait during the strong phase.

During La Niña, the pattern is reversed relative to El Niño. The significant positive area during moderate La Niña ($n = 30$) extends almost uniformly across the eastern and central parts of the domain, but it narrows and becomes more fragmented during strong La Niña ($n = 7$), even though the anomaly magnitudes in Fig. 3 remain large in these regions. The result is an asymmetric pattern: the significant area widens for El Niño but narrows for La Niña as phase intensity increases.

3.2.3 RH925

Figure 7 shows the RH925 patterns after significance filtering, with significant areas that are consistent between the t-test (panel a) and bootstrap resampling (panel b). In line with the significance patterns for rainfall, the significant negative area during El Niño also widens with increasing intensity, from a moderate coverage around Kalimantan during the moderate phase to a broader area encompassing Kalimantan, southern Java, and Nusa Tenggara during the strong phase. During La Niña, the significant positive area during the moderate phase extends over the eastern and southern parts of the domain but weakens slightly during the strong phase. The RH925 pattern again matches that of rainfall, which reinforces the association between the two variables as indicators of water vapor availability for rainfall formation.

4 Discussion

4.1 Spatial response to ENSO intensity

Rainfall and RH925 respond to ENSO in a monotonic manner, with opposite signs for El Niño and La Niña and anomaly magnitudes that grow with phase intensity. Their spatial patterns are closely matched, indicating that deficits or surpluses of lower-tropospheric moisture are associated with rainfall deficits or surpluses in the corresponding ENSO phases; this is plausible because RH925 represents the availability of water vapor, one of the prerequisites for the formation of convective clouds (Fauziah et al. 2025). CAPE, by contrast, does not change monotonically with intensity but is redistributed spatially into a west–east dipole that sharpens as intensity increases. This behavior is consistent with a shift of convection centers resulting from ENSO modulation of the Walker circulation (Aldrian and Susanto 2003).

4.2 Robustness across significance tests

The results of the t-test and bootstrap resampling in Figs. 5–7 are consistent across all variables and ENSO phases: the areas passing significance under both methods generally overlap in both location and extent. This indicates that the spatial patterns of CAPE, rainfall, and RH925 associated with ENSO phases identified here are robust to the choice of statistical method. The consistency agrees with an

earlier study of CENS over the Maritime Continent that likewise validated composite patterns with Monte Carlo bootstrap testing, in which the resulting significant patterns proved stable and physically interpretable (Dewi et al. 2023).

4.3 Limitations

Several limitations should be noted. First, the unequal sample sizes among phases ($n = 7$ to 83) result in different statistical power. Phases with small samples, such as strong La Niña ($n = 7$), tend to yield narrower significant areas despite large anomaly magnitudes, so results for these phases should be interpreted more cautiously than those for phases with large samples. This applies to rainfall and RH925, whereas for CAPE the sample limitation in the same phase appears as a spatial redistribution of the significant areas rather than a simple narrowing. Such caution is warranted because significance maps for spatial gridded data are prone to over-interpretation unless sample size and the associated multiple-comparisons problem are taken into account (Wilks 2016).

Second, this study is exploratory and descriptive, focusing on the mapping and comparison of spatial patterns among phases and between test methods; it does not aim to test causal or correlational relationships among the variables (CAPE, rainfall, and RH925). Third, the data come from a single reanalysis source (ERA5), so the composite results are affected by biases or uncertainties in the underlying data.

5 Conclusions

This study characterized the spatial patterns of rainfall, CAPE, and RH925 anomalies across six ENSO intensity classes over the Indonesian Maritime Continent, using ERA5 data for 1995–2025 and dual significance testing with a one-sample t-test and bootstrap resampling. Rainfall and RH925 respond uniformly but with opposite sign to the two ENSO phases, showing deficits during El Niño and surpluses during La Niña, with magnitudes that increase from weak to strong phases. CAPE shows a different relationship with ENSO, taking the form of a spatial redistribution in a west–east dipole pattern that sharpens during moderate and strong phases, with positive anomalies concentrated over northern Sumatra and negative anomalies extending from Kalimantan to the Banda Sea. The t-test and bootstrap resampling yield consistent spatial patterns of significant areas across all variables and phases. During strong phases, rainfall and RH925 show an asymmetric pattern, with a widening of significant areas for El Niño but a narrowing for La Niña, whereas CAPE shows a spatial redistribution of its significant areas.

The study is descriptive and exploratory, with limitations related mainly to the unequal sample sizes among phases and the use of a single reanalysis data source (ERA5). Future studies should perform further validation using independent data sources.

Declarations

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Conflict of interest/Competing interests. The authors declare that they have no conflict of interest or competing interests that could have influenced the work reported in this manuscript.

Ethics approval and consent to participate. Not applicable.

Consent for publication. Not applicable.

Data availability. The ERA5 reanalysis data are publicly available from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>). The Oceanic Niño Index (ONI) data are publicly available from the NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).

Materials availability. Not applicable.

Code availability. The code used for data processing, analysis, and visualization is available from the corresponding author upon reasonable request.

Author contribution. Mico Maulana: data collection, data processing, data analysis, results preparation, and manuscript drafting. Muhamad Asharul Awal, Krisna Dewi, and Daddykeyn Zui Watory: literature review, reference collection, results interpretation, and manuscript preparation. Sayful Amri: supervision, methodology, research guidance, and critical revision of the manuscript. All authors reviewed and approved the final manuscript.

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Figures

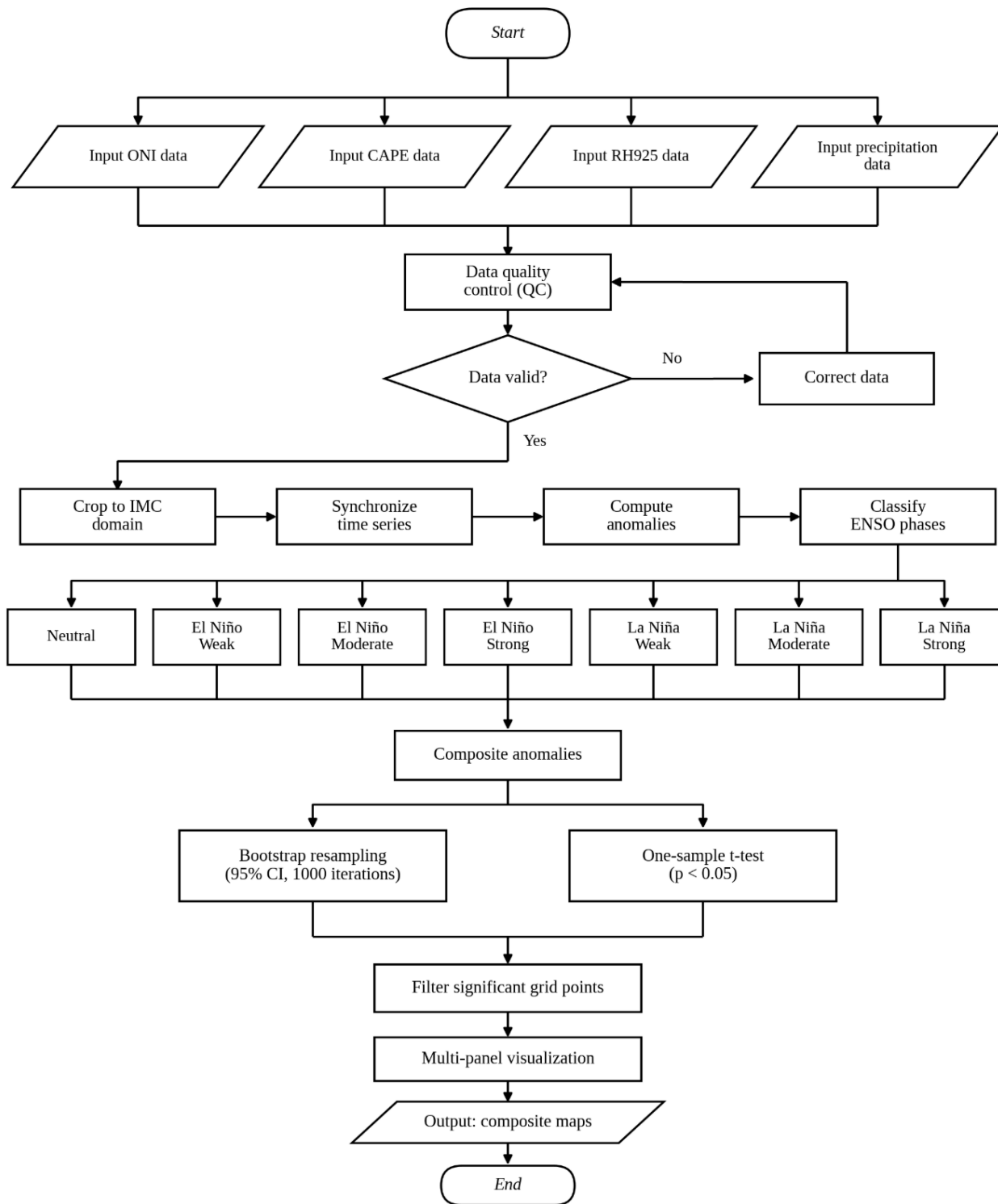


Figure 1

Flowchart of the analysis procedure. ONI, Oceanic Niño Index; CAPE, Convective Available Potential Energy; RH925, relative humidity at 925 hPa; QC, quality control; IMC, Indonesian Maritime Continent.

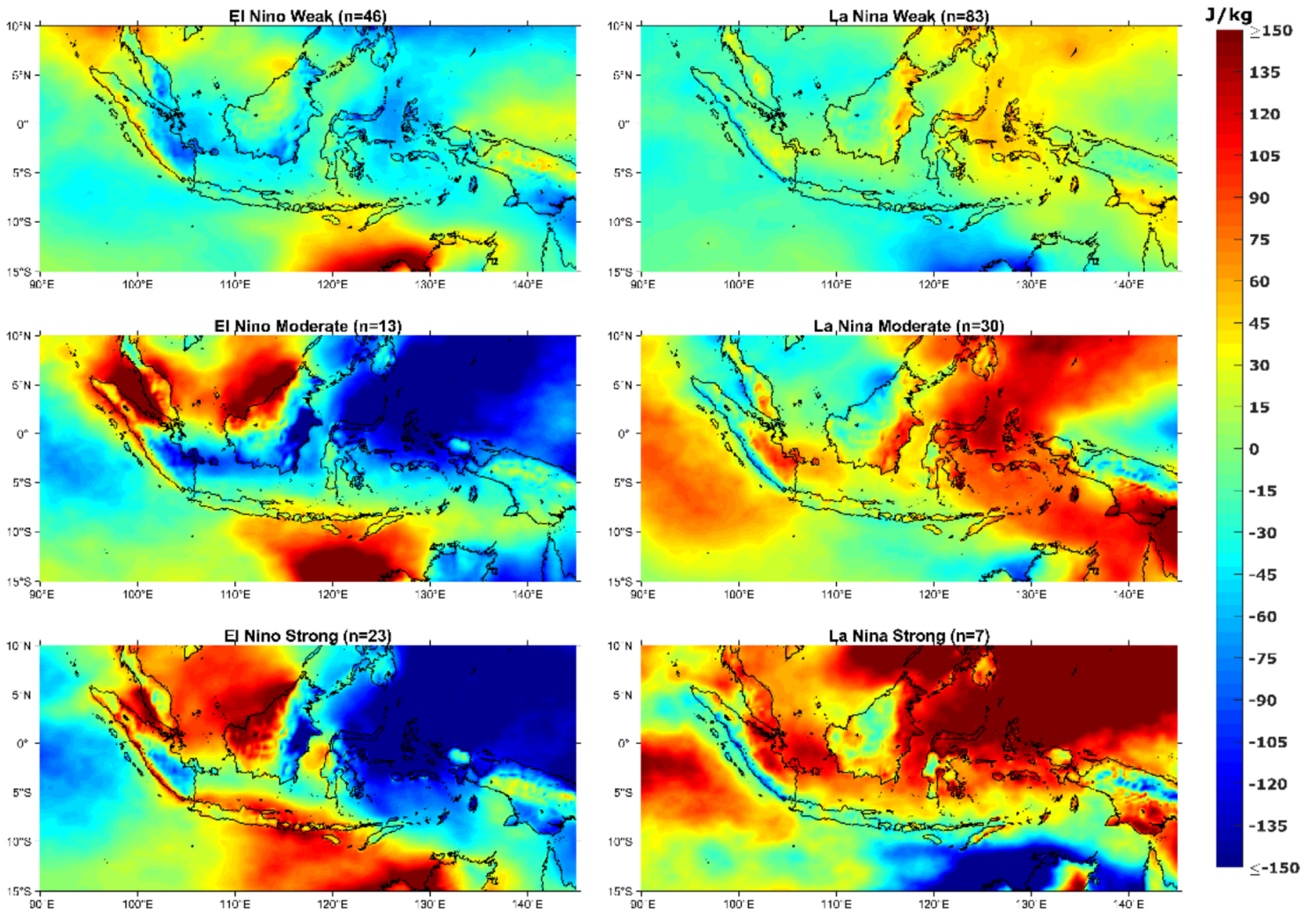


Figure 2

Composite CAPE anomalies (J kg^{-1}) for each ENSO phase intensity, without significance filtering. Panel titles give the ENSO phase and the number of months (n) in each composite.

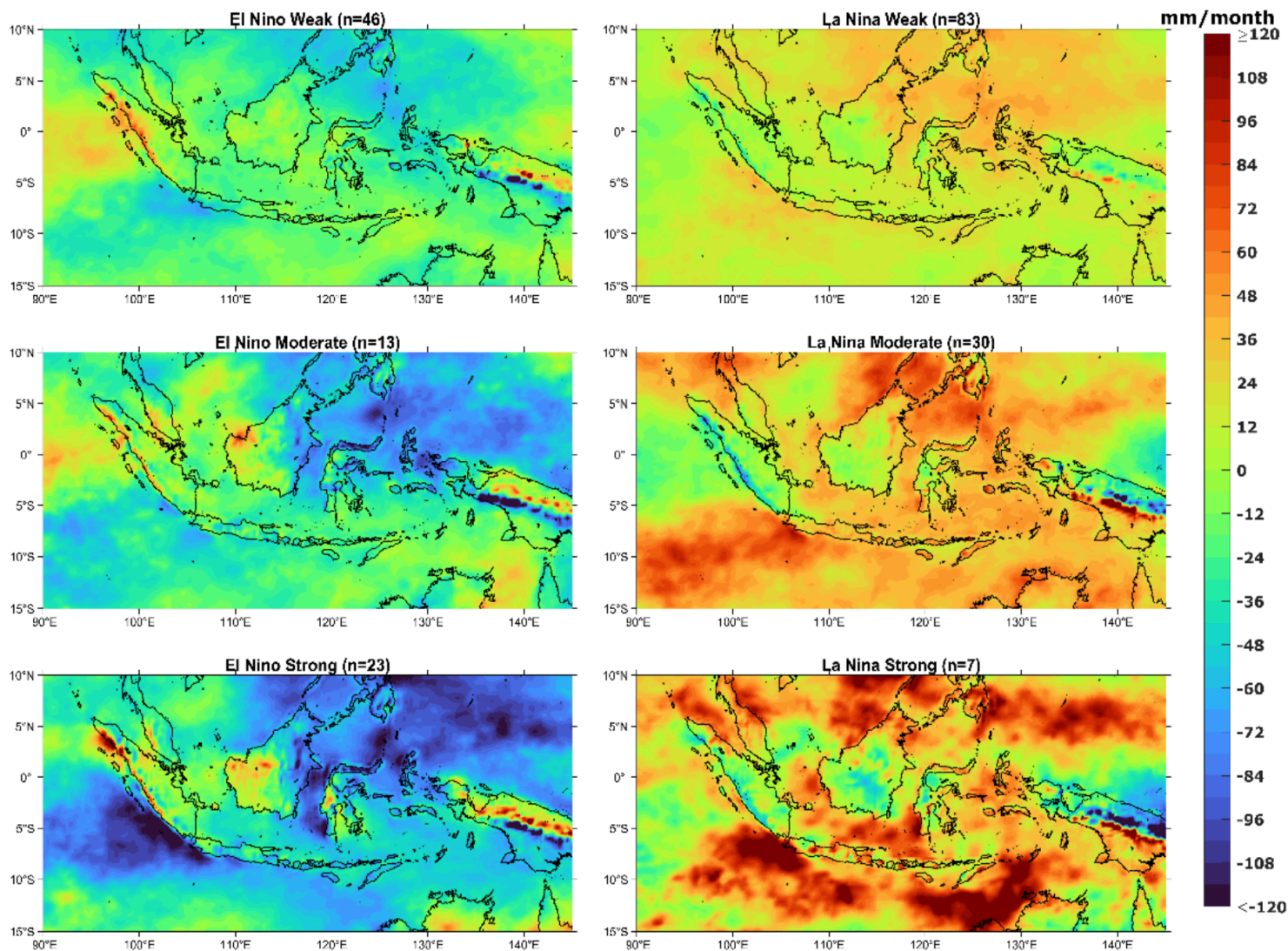


Figure 3

Composite rainfall anomalies (mm month⁻¹) for each ENSO phase intensity, without significance filtering. Panel titles give the ENSO phase and the number of months (*n*) in each composite.

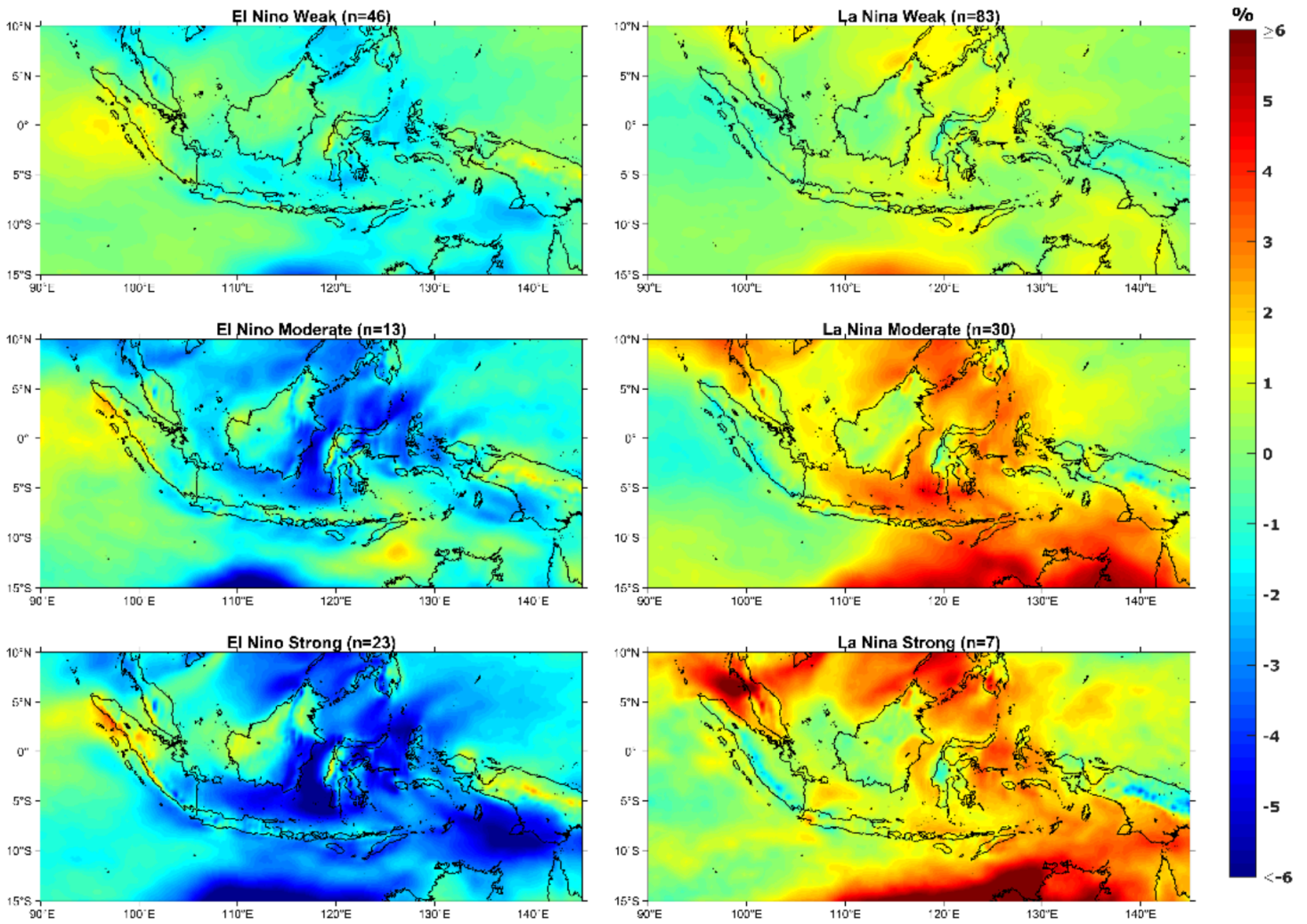
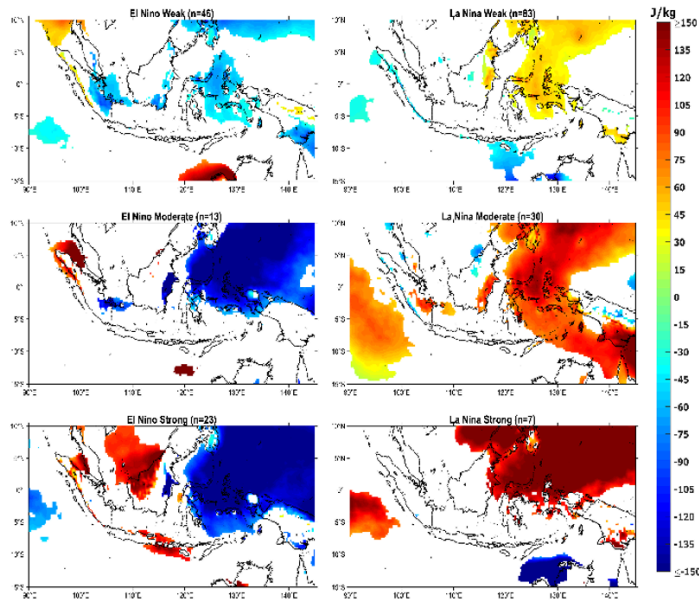
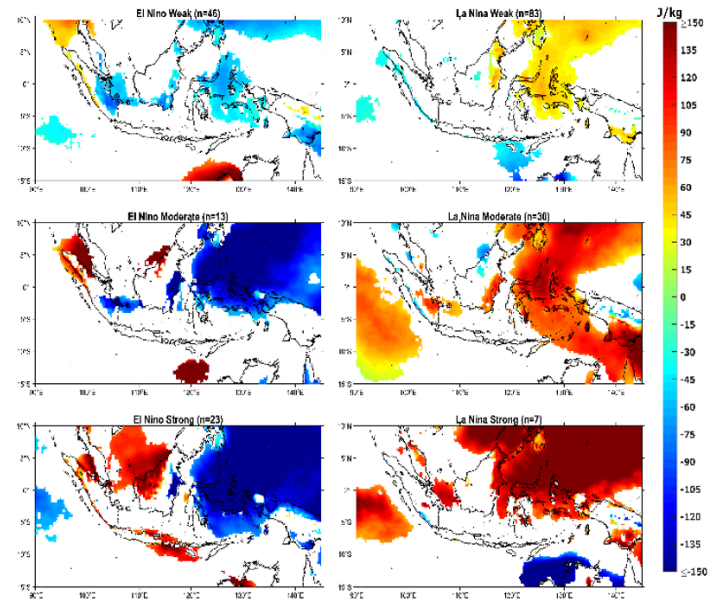


Figure 4

Composite anomalies of relative humidity at 925 hPa (%) for each ENSO phase intensity, without significance filtering. Panel titles give the ENSO phase and the number of months (n) in each composite.



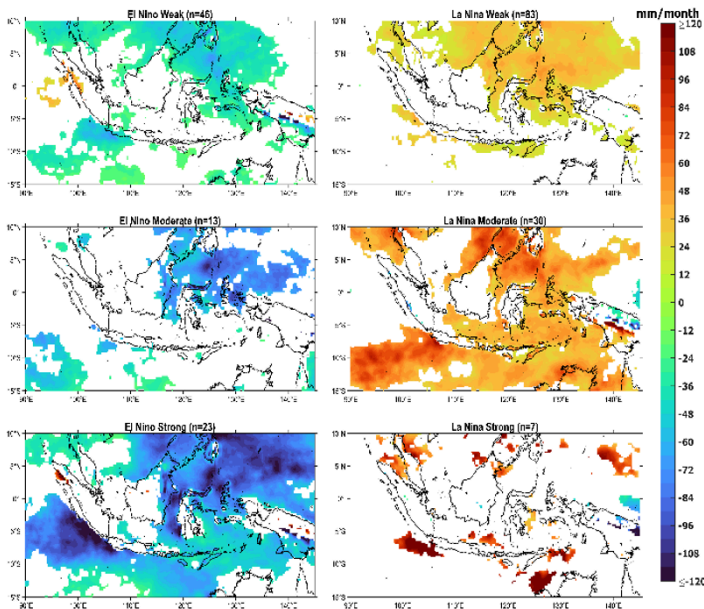
(a) One-sample t-test ($p < 0.05$)



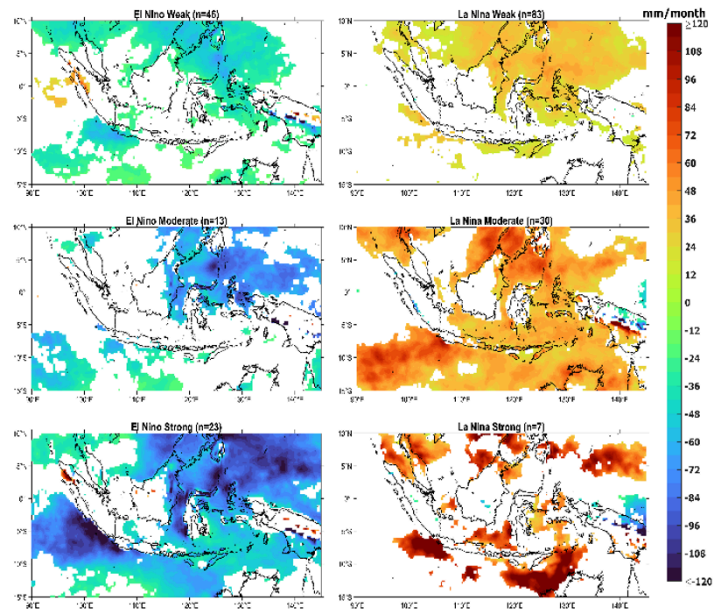
(b) Bootstrap resampling (95% CI, 1000 iterations)

Figure 5

Composite CAPE anomalies (J kg^{-1}) for each ENSO phase intensity after significance filtering with (a) a one-sample t-test and (b) bootstrap resampling. Non-significant areas are shown in white.



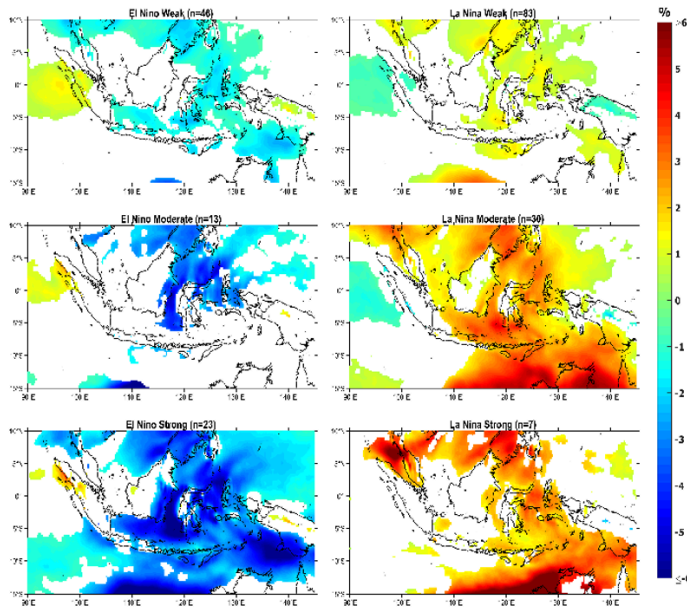
(a) One-sample t-test ($p < 0.05$)



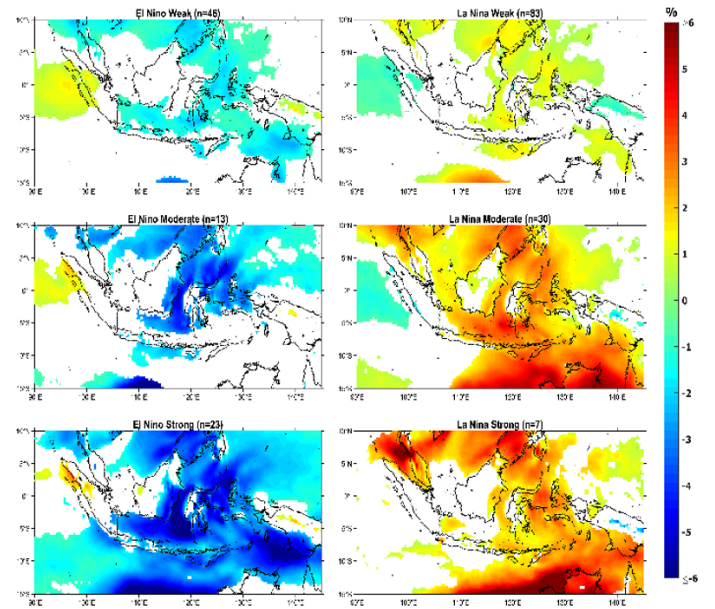
(b) Bootstrap resampling (95% CI, 1000 iterations)

Figure 6

Composite rainfall anomalies (mm month^{-1}) for each ENSO phase intensity after significance filtering with (a) a one-sample t-test and (b) bootstrap resampling. Non-significant areas are shown in white.



(a) One-sample t-test ($p < 0.05$)



(b) Bootstrap resampling (95% CI, 1000 iterations)

Figure 7

Composite anomalies of relative humidity at 925 hPa (%) for each ENSO phase intensity after significance filtering with (a) a one-sample t-test and (b) bootstrap resampling. Non-significant areas are shown in white.