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Effects of El Niño–Southern oscillation (ENSO) and Indian ocean dipole (IOD) on extreme temperatures in Indonesia

SUHADI[1*], JAMIATUL KHAIRUNNISA PUTRI[1], ISKHAQ ISKANDAR[2], MUHAMMAD IRFAN[2], HAMDI AKHSAN[3], MELLY ARISKA[3], EVELINA ASTRA PATRIOT[3] and SUPARI[4]

[1]*Physics Education Study Program, Universitas Islam Negeri Raden Fatah Palembang, Palembang 30126, Indonesia*

[2] *Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Inderalaya 302662, Indonesia*

[3] *Department of Physics Education, Faculty of Teaching and Education, Universitas Sriwijaya, Inderalaya 302662, Indonesia*

[4] *Meteorology Climatology and Geophysics Agency, Jakarta 3540, Indonesia*

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***Corresponding author's email: suhadi@radenfatah.ac.id**

सार – एक उष्णकटिबंधीय देश के रूप में, इंडोनेशिया भी जलवायु परिवर्तन के कारण अत्यधिक तापमान परिवर्तनों का अनुभव कर रहा है। यह शोध पिछले 45 वर्षों (1979-2023) में इंडोनेशिया में अत्यधिक तापमान की प्रवृत्तियों में हुए परिवर्तनों का मूल्यांकन करता है। इस तापमान प्रवृत्ति के मूल्यांकन में मान-कैंडल परीक्षण और अनुक्रमिक मान-कैंडल परीक्षण का उपयोग किया गया है, जो क्लाइमेट प्रेडिक्शन सेंटर (CPC) के अधिकतम और न्यूनतम तापमान डेटा का उपयोग करता है। प्रत्येक सूचकांक पर इन दोनों सूचकांकों के प्रमुख प्रभाव को निर्धारित करने के लिए हम Niño3.4 सूचकांक और डिपोल मोड सूचकांक (DMI) के साथ प्रत्येक सूचकांक का आंशिक सहसंबंध (Partial correlation) भी लागू करते हैं। परिणामों ने दैनिक अधिकतम तापमान के मासिक अधिकतम (TXx), दैनिक अधिकतम तापमान के मासिक न्यूनतम (TXn), दैनिक न्यूनतम तापमान के मासिक न्यूनतम (TNn), और DTR में क्रमशः 0.08°C/वर्ष, 0.18°C/वर्ष, 0.09°C/वर्ष और 0.19°C/वर्ष की वृद्धि दर्शाई है। इसके अलावा, दैनिक न्यूनतम तापमान का मासिक न्यूनतम (TNx) 0.16°C/वर्ष घट गया। दिन और रात के न्यूनतम तापमान, अधिकतम तापमान की तुलना में अधिक तेजी से बढ़ते हैं। स्थानिक रूप से, TNx को छोड़कर लगभग सभी क्षेत्रों में बढ़ती प्रवृत्ति देखी जा सकती है, जो अत्यधिक तापमान में वृद्धि की प्रवृत्ति को दर्शाती है। आंशिक सहसंबंध विश्लेषण से पता चलता है कि अत्यधिक तापमान पर हिंद महासागर डिपोल (IOD) की तुलना में अल नीनो-दक्षिणी दोलन (ENSO) का अधिक प्रभाव है।

ABSTRACT. As a tropical country, Indonesia also experiences extreme temperature changes due to climate change. This research evaluates changes in extreme temperature trends in Indonesia over the last 45 years (1979-2023). The evaluation of this temperature trend uses the Mann-Kendal test and the Sequential Mann-Kendal test, which uses maximum and minimum temperature data from the Climate Prediction Center (CPC). We also apply a partial correlation of each index to the Niño3.4 index and Dipole Mode Index (DMI) to determine the dominant influence of these two indices on each extreme temperature index. The results showed an increase in monthly maximum of daily maximum temperature (TXx), monthly minimum of daily maximum temperature (TXn), monthly minimum of daily minimum temperature (TNn), and DTR of 0.08 °C/year, 0.18 °C/year, 0.09 °C/year, and 0.19°C/year, respectively. Apart from that, monthly minimum of daily minimum temperature (TNx) decreased by 0.16 °C/year. Minimum daytime and nighttime temperatures increase faster than maximum temperatures. Spatially, the increasing trend can be seen in almost all regions, showing an increasing trend in extreme temperatures, except for TNx. Partial correlation analysis shows that El Niño–Southern Oscillation (ENSO) has more influence on extreme temperatures than the Indian Ocean Dipole (IOD).

Key words – Extreme temperature, Indonesia, Trend, Partial correlation, El Niño–Southern oscillation, Indian ocean dipole.

1. Introduction

One indicator of climate change is rising land and sea surface temperatures. Compared with pre-industrial times, the increase in surface temperature ranges from 30% to 70% (Lambert *et al*., 2011). So, it is natural that extreme temperature increases are predominantly caused by anthropogenic factors (Sun *et al*., 2022). Apart from these factors, changes in extreme temperatures, especially in the arid regions of northwestern China, are caused by geopotential factors (Pi *et al*., 2020). In addition, an increase in temperature in southern China occurred during a drought (Zhu *et al*., 2021). Regarding this increase in extreme temperatures, the Intergovernmental Panel on Climate Change (IPCC) shows that global temperatures have increased by 0.85 °C since 2012 (IPCC, 2012, 2018).

Several studies on extreme temperatures have been conducted in various world regions as a form of shared concern. The American region is experiencing an increase in extreme temperatures characterized by increases and decreases in hot and cold days (Lee *et al*., 2021). Research in China (Mo *et al*., 2022; Shan *et al*., 2022) shows that the intensity of extreme temperatures, specifically Daytime Maximum Temperature (TXx) and Nighttime Maximum Temperature (TNn), increased by 2.1 °C and 0.4 °C from 1959 to 2017. Research results (Zhou *et al*., 2021) also show extreme temperatures, especially in the Yangtze River in the 17th century and increased again in the mid-19th century. In relatively cold areas in China, especially in Beijing, Tianjin, and Hebei, there is an increase in the frequency of maximum and minimum temperatures, and even the maximum temperature and humidity in these areas will increase further in the future (Wang *et al*., 2022). Apart from these areas, desert areas such as Africa also show an increase in surface temperatures of 0.24 °C to 0.65 °C every decade (Ayugi *et al*., 2021; Kouman *et al*., 2022). The Australian region also shows an increase in maximum and minimum temperatures of 0.21˚C and 0.13˚C every decade (Duan *et al*., 2022). Apart from these regions, an increase in extreme temperatures is also occurring in Asia. Projections of extreme temperatures in the Central Asian region in the 2020 to 2099 range show an increase in Minimum Temperature (Tmin) (5.0 ºC) higher than Maximum Temperature (Tmax) (4.6 ºC) (Salehie, Ismail, Hamed, *et al*., 2022), and likewise occurred in the Egyptian region (Hamed *et al*., 2023). Seasonal increases in T_{min} and T_{max} also occur in Pakistan (Ahmad *et al*., 2023). This increase tends to occur in early spring. In addition, projections of maximum temperatures in Bangladesh from 2021 to 2100 also show an increase in Tmax of around 3 - 4.7 °C every 20 years (Das *et al*., 2023). Other desert regions, such as Iran in the period from 1961 to 2015, mainly experienced an increase in TXx, TNn, and Average Maximum and Minimum Temperature (Alavinia & Zarei, 2021; Asakereh *et al*., 2020; Zarrin *et al*., 2021).

In Southeast Asia, research on extreme temperatures has been carried out, especially in Malaysia (Tan *et al*., 2019). This research shows that from 1985 to 2015, the region experienced an increase in TXn and TNn of 0.31 °C and 0.65 °C every decade. Apart from Malaysia, in the 1983-2012 period, Indonesia itself experienced an increase and decrease in the frequency of hot days and cold nights, with an increase in average maximum and minimum temperatures of 0.18 °C and 0.30 °C respectively, every decade (Supari *et al*., 2017). Until 2024, only (Supari *et al*., 2017) has studied extreme temperatures, especially in Indonesia. Therefore, there is still a lack of recent research regarding extreme temperatures in Indonesia, so we conducted a study of extreme temperatures in this region. In addition, most previous studies have not linked several extreme temperature indices with ENSO and IOD conditions, so we calculated the correlation of each extreme temperature index with the ENSO index (Niño3.4 Index) and IOD index (DMI).

2. Data and methodology

This study area focuses on the area covering the Indonesian archipelago, precisely at a longitude of around 90° E-150° E, 15° S-10° N. As can be seen in Fig. 1, the Indonesian archipelago is located between the Indian Ocean and the Pacific Ocean. Globally, climate conditions, especially temperature, are strongly influenced by the IOD and ENSO phenomena in the Indian and Pacific oceans.

The data used in this research is the CPC Maximum Temperature (Tmax) and Minimum Temperature (Tmin) fromhttps://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html. The daily grid data has a resolution of 0.5° with time coverage from 1979 to the present. However, this study's data has a time range of 1979-2023 (45 years). CPC grid data with stable predicted values has the best

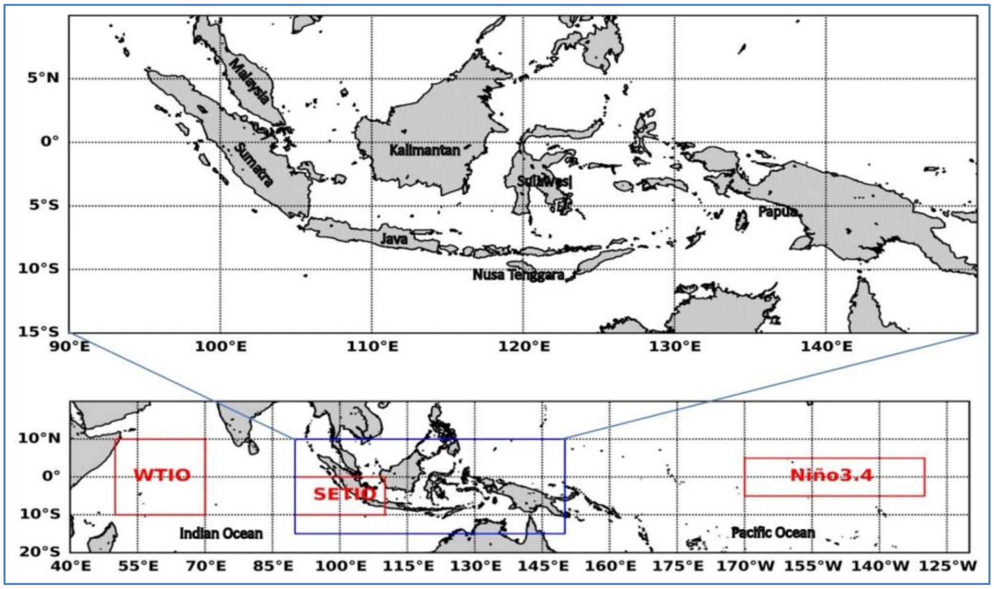

Fig. 1 Area of Interest

TABLE 1

Extreme Temperature index used in the research. Tx_{ij} and Tn_{ij} are the daily maximum and the daily minimum temperature in month i, period j

No	ID	Indicator name	Definitions	Calculations	Units
1	TXx	Max Tmax	Monthly maximum of daily maximum temperature	$TX_{ij} = max(Tx_{ij})$	°C
2	TXn	Max Tmin	Monthly minimum of daily maximum temperature	$TX_{ij} = min(Tx_{ij})$	°C
3	TNx	Min Tmax	Monthly maximum of daily minimum temperature	$TN_{ij} = max(Tn_{ij})$	°C
4	TNn	Min Tmin	Monthly minimum of daily minimum temperature	$TN_{ij} = min(Tn_{ij})$	°C
5	DTR	Diurnal temperature range	Monthly mean difference between TX and TN	$DTR = \frac{\sum_{i=1}^{I}(Tx_{ij} - Tn_{ij})}{I}$	°C

accuracy when compared to Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG) and Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis (TMPA), reanalysis-based (fifth generation of atmospheric reanalysis by the European Center for Medium Range Weather Forecasts (ERA5) (Jiang *et al*., 2023; Nashwan *et al*., 2019). Therefore, CPC data is widely used as material in temperature evaluation (Salehie, Ismail, Shahid, *et al*., 2022).

This study's evaluation of extreme temperatures is based on the index published by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang *et al*., 2018). Although there are at least 11 indices for extreme temperatures, this study uses five, as shown in Table 1.

The five extreme temperature indices indicate intensity (Mo *et al*., 2022). In general, the index defined by ETCDDI has been widely used to analyze climate extremes, both rainfall and temperature (Babaousmail *et al*., 2022; Chaney *et al*., 2014; Felix *et al*., 2021; Lopes *et al*., 2024; Nie *et al*., 2019; Supari *et al*., 2018).

Examination of the trend of each index decided by the Mann-Kendal (MK) test

$$Z_s = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}; & if \ S > 0 \\ 0; & if \ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}; & if \ S < 0 \end{cases} \quad (1)$$

with

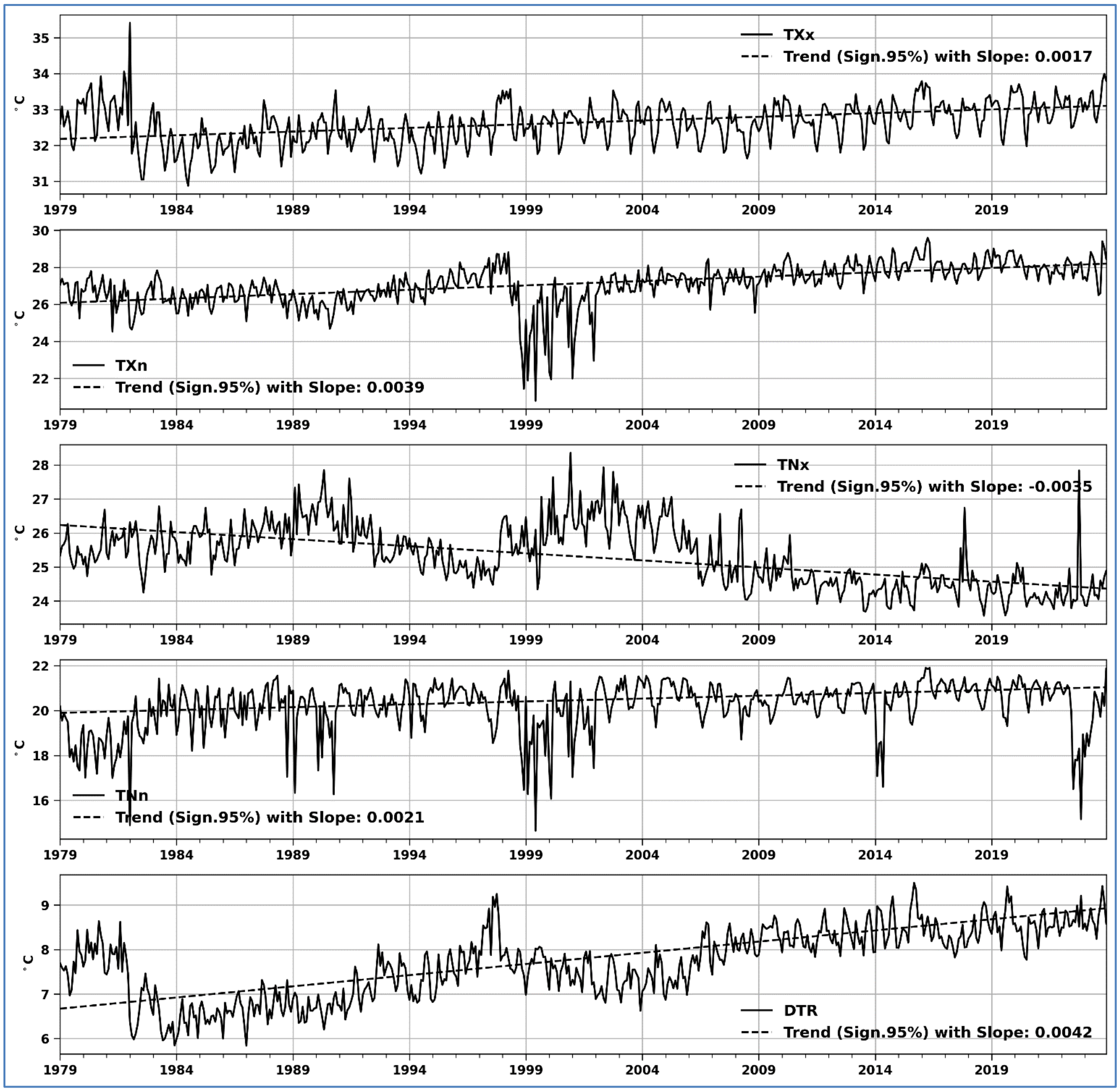

Fig. 2. Time-Series (solid line) and Trend (dashed line) of extreme temperature

$$VAR(S) = \frac{n(n-1)(2n+5)}{18}, \quad (2)$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i), \quad (3)$$

$$sgn(X_j - X_i) = \begin{cases} +1; if(X_j - X_i) > 0 \\ 0; if(X_j - X_i) = 0 \\ -1; if(X_j - X_i) < 0 \end{cases}. \quad (4)$$

Gradients of this trend are determined by

$$Q_i = \begin{cases} T_{\frac{n+1}{2}}; \; for \; n \; odd \\ \frac{1}{2}\left(T_{\frac{n}{2}} + T_{\frac{n+2}{2}}\right); \; for \; n \; even \end{cases} \quad (5)$$

with

$$T_n = \frac{X_j - X_k}{j-k} \quad (6)$$

for $n = 1,2,3, \ldots, n$; and X is the value of each index. In addition to the linear trend of each extreme temperature index, we also determined the period when the trend change occurred. Determination of these changes is based on the Sequential Mann-Kendall method (Dipak *et al*., 2014). To determine the relationship between each extreme temperature index, we applied a partial correlation of each index to the Niño3.4 index and Dipole Mode Index (DMI) (Iskandar *et al*., 2013). The DMI and Niño3.4 index we use are the results of calculations from previous research (Suhadi *et al*., 2024). It is just that we use this index from 1979 to 2023, which is according to analysis needs.

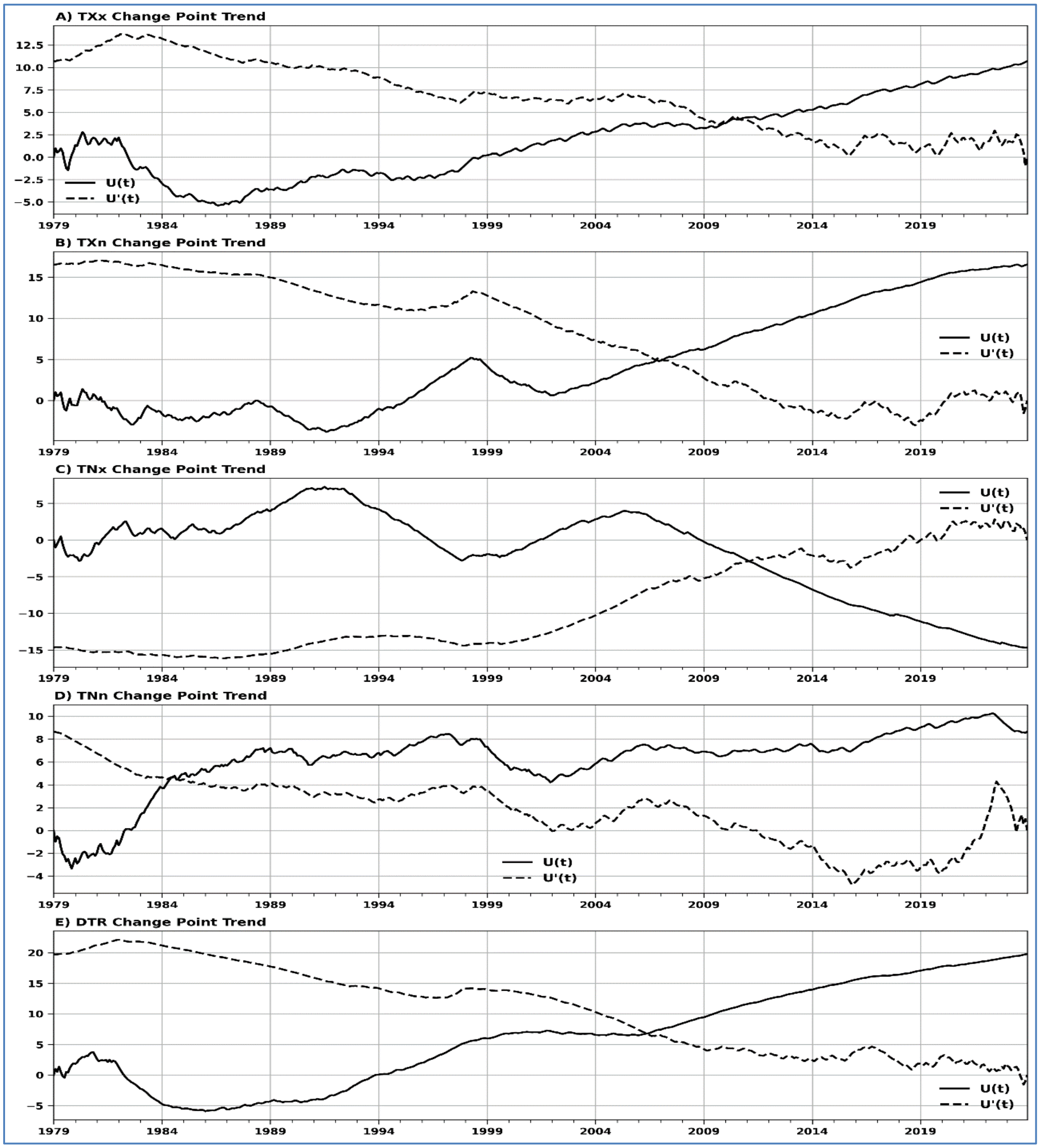

Fig. 3. Extreme Temperature Trend Change Point. Solid and Dashed Line are Forward U(t) and Backward U'(t) Sequential value. All of the Trend Change Point's Confidences Level is 95% with critical value is ±1,96

3. Results and discussion

The linear trend of extreme temperatures in Indonesia is shown in Fig. 2. Based on Fig. 2, it can be seen that over 45 years, TXx has increased by 0.0017 °C/45 years or around 0.08 °C/year. Additionally, TXn experienced an increase of 0.0039 °C/45 years or 0.18 °C/year. However, a decreasing trend in TXn was also detected in Mexico, especially from 1980 to 2013 (Ruiz-Alvarez *et al*., 2020). Even though there was an increase in maximum (TXx) and minimum (TXn) temperatures during the day, there was a significant decrease in minimum daytime temperatures around 1999-2002. In contrast to other extreme temperature indicators, the Maximum Nighttime Temperature (TNx) has decreased by 0.0035 °C/45 years or 0.16 °C/year. This result differs from previous research which showed an increase in nighttime temperatures around 2000 – 2022, especially in summer (JJA) (although it was not clearly stated whether TNx or TNn increased) (Sianturi *et al*., 2024). Based on Fig. 2, it can also be seen that TNn and DTR have increased by 0.0021°C/45 years and 0.0042 °/45 years (0.09 °C/year and 0.19 °C/year) respectively. Like daytime temperatures, fluctuations in minimum nighttime

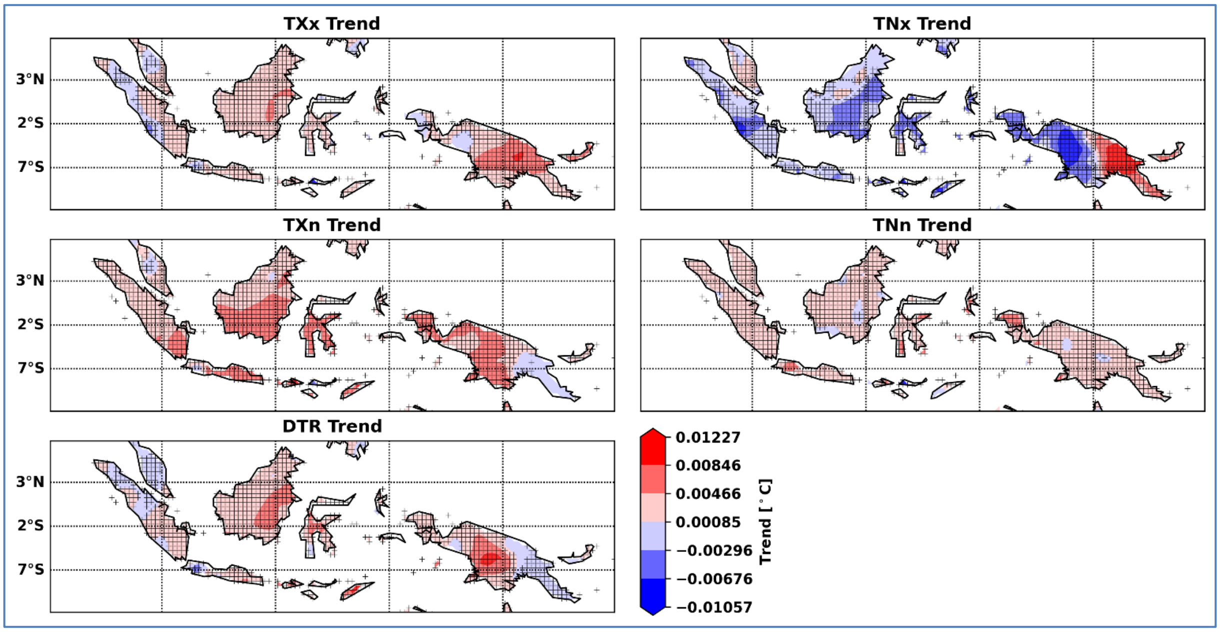

Fig. 4. Spatial Trend of Extreme Temperature. Plus (+) marked is Significance Level at 95%

temperatures also occurred around 1999-2002. These results confirm the increase in extreme temperatures, especially TXx and TNn, in other countries such as Iran (Alavinia & Zarei, 2021). This analysis also shows that minimum temperatures (both day and night) have increased more than maximum. These results have also been obtained based on previous research (Hamed *et al.*, 2023; Salehie, Ismail, Hamed, *et al*., 2022).

Fig. 3 shows the specific timing of changes in each extreme temperature index. Each index shows a different time of trend change. A significant change in TXx occurred in 2010, although TXx has consistently increased in previous years. Research results in China also show that an increase in TXx began to occur around 2000 (Mo *et al.*, 2022). Significant changes in TXn occurred in 2007. Although the linear trend of TNx decreased, based on Fig. 3.C, TNx experienced fluctuations before the TNx change point in 2011. In the frequency domain, a decrease in minimum temperature also occurred in the Chinese region (Pi *et al*., 2020). The observed decreasing trend in TNx in parts of Indonesia contrasts with the general global warming pattern, which typically shows increasing TNx trends. This regional anomaly may be driven by complex interactions between large-scale climate modes (ENSO and IOD) and local environmental conditions. For instance, stronger nocturnal cooling may occur during dry seasons under La Niña or positive IOD phases, which reduce cloud cover and enhance longwave radiation loss at night. Land-use changes, such as deforestation or differences in surface albedo, may also contribute to spatial heterogeneity in TNx trends (Supari *et al*., 2017). These findings highlight the importance of understanding regional climate dynamics in interpreting trends in extreme temperature indices. The significant increase in the TNn trend over 45 years was also confirmed based on the TNn change point detected in 1984. This result is also similar to previous research, especially in China, which showed that TNn began to increase around 1984 (Mo *et al*., 2022). Like the TXx, TXn, and TNx change points, the DTR change point also occurred after 2004, to be precise in 2006.

Spatially, the increasing and decreasing trends in extreme temperatures range from -0.01 °C to +0.01 °C over 45 years (Fig. 4). In general, increasing and decreasing trends are relevant to increasing and decreasing trends temporally (Fig. 2). The increase in the TXx trend was almost detected throughout Indonesia. Papua is the region experiencing the highest increasing trend, although several small parts in western Papua are experiencing a decreasing trend. The decline in the TXx trend is also visible in parts of Sumatra, especially the North Sumatra region and the island's west coast. The distribution of TXn increases appears to be more dominant than other extreme temperature indices. The TXn trend increase, higher than other regions, occurred in most of Papua, Sulawesi, southern Kalimantan, southern Sumatra and most of Java. Like the temporal trend, the spatial trend of TNx shows a decline in all regions of Indonesia. The most significant decline in TNx occurred in Papua, Central Sulawesi, southeastern Kalimantan and a small part of central Sumatra. Similar to TXn, the increase in TNn occurred in almost all regions of Indonesia, even on the Malaysian

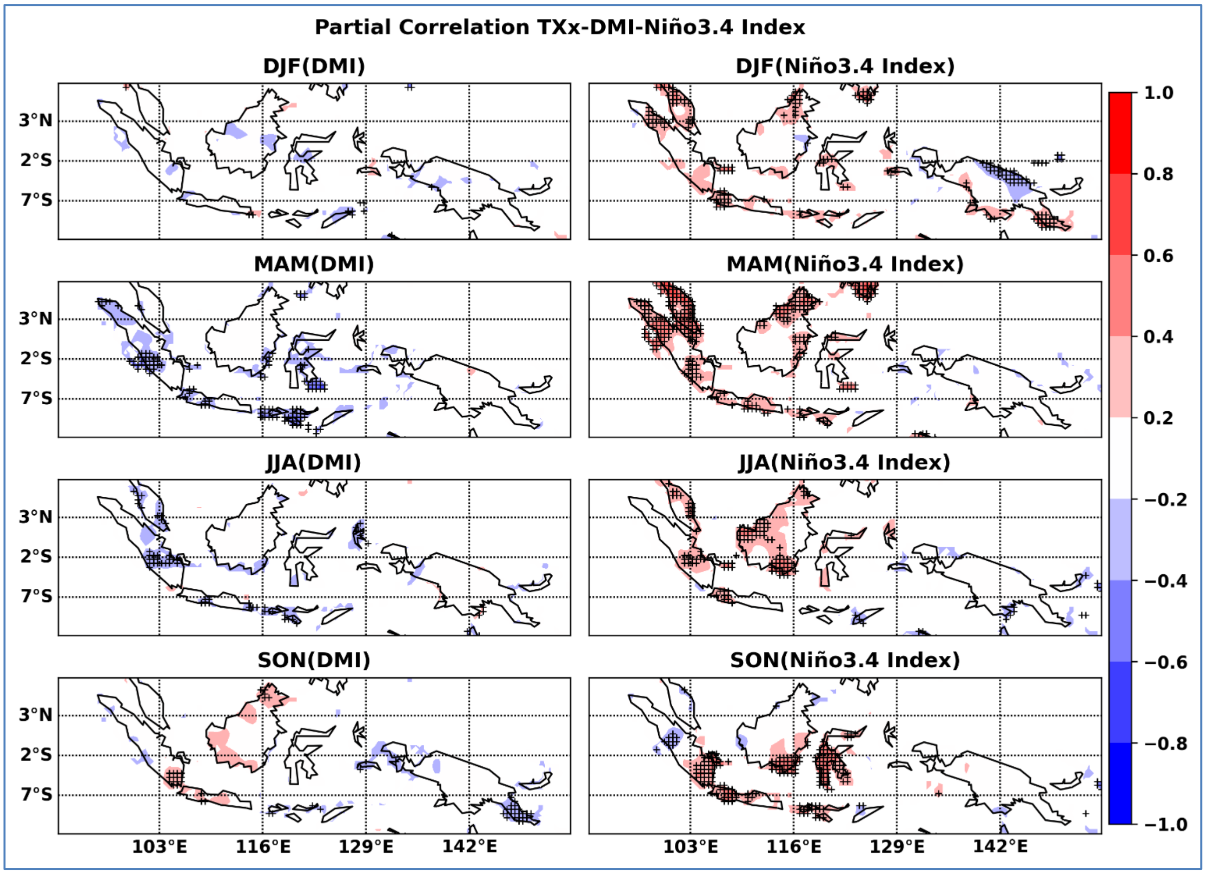

Fig. 5. Partial Correlation of TXx to DMI and Niño3.4 Index. Plus (+) marked is Significance Level at 95%

peninsula and Papua New Guinea. An increase in TXn and TNn in the Malaysian region was also shown in previous research (Tan *et al*., 2019). The increase in the DTR trend is almost the same as the increase in TXx; only the increase in DTR in southeast Kalimantan is more expansive than in TXx, especially for the increase in the trend, which is higher than in other regions, likewise with the increase in the central part of Sulawesi.

The correlation between TXx and IOD and ENSO is represented in the form of a partial correlation between TXx and DMI, the Niño3.4 index, and other extreme temperature indices (TXx, TNx, TNn, and DTR). The partial correlation of TXx with DMI and the Niño3.4 index is shown in Fig. 5. Based on Fig. 5, it can be seen that the positive influence of DMI is only visible at its peak, namely in SON, and even then, only in a small part of southern Sumatra, specifically in Lampung province. In SON, a positive influence of the DMI was detected in a small part of northern Kalimantan. The negative influence of DMI on TXx was detected in MAM and JJA, especially in 2° S in Sumatra, Nusa Tenggara Island, and small part of southern Sulawesi (MAM). Based on the correlation with the Niño3.4 index, ENSO has more influence on TXx in western to central Indonesia than in other regions. This influence moves from the northern hemisphere (in DJF) to the southern hemisphere (in SON). The peak influence of ENSO on TXx in the Northern Hemisphere occurs at MAM, while in the Southern Hemisphere, it occurs at SON.

Compared to TXx, IOD's influence on TXn is more visible. The positive correlation of DMI began to appear in MAM, especially in southern Sumatra, then weakened in JJA, and peaked in SON. As with TXx, ENSO has more influence on TXn in the same region (Fig. 6). In the DFJ to MAM period, the positive correlation of the Niño3.4 index is dominantly seen in the northern hemisphere, especially in the western to central regions of Indonesia. In JJA and SON, the positive correlation of the Niño3.4 index weakens in the northern hemisphere, spreading randomly to the southern hemisphere until it reaches Papua New Guinea. The correlation of the Niño3.4 index, which is more dominant with TXx and TXn than DMI, shows that ENSO plays a significant role in increasing extreme temperatures. The same was seen in previous research (Akhsan *et al*., 2023; Gershunov, 1998).

The partial correlation of TNx with DMI and the Niño3.4 index is shown in Fig. 7. Based on Fig. 7, it can

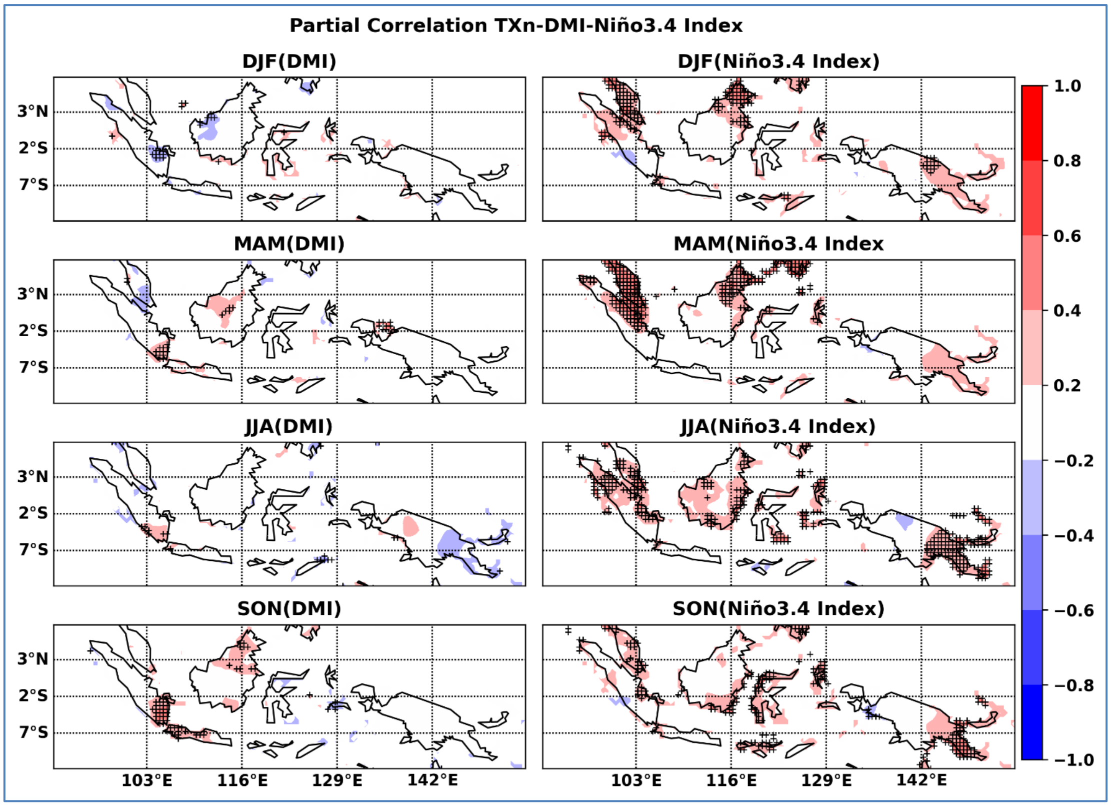

Fig. 6. Partial Correlation of TXn to DMI and Niño3.4 Index. Plus (+) marked is Significance Level at 95%

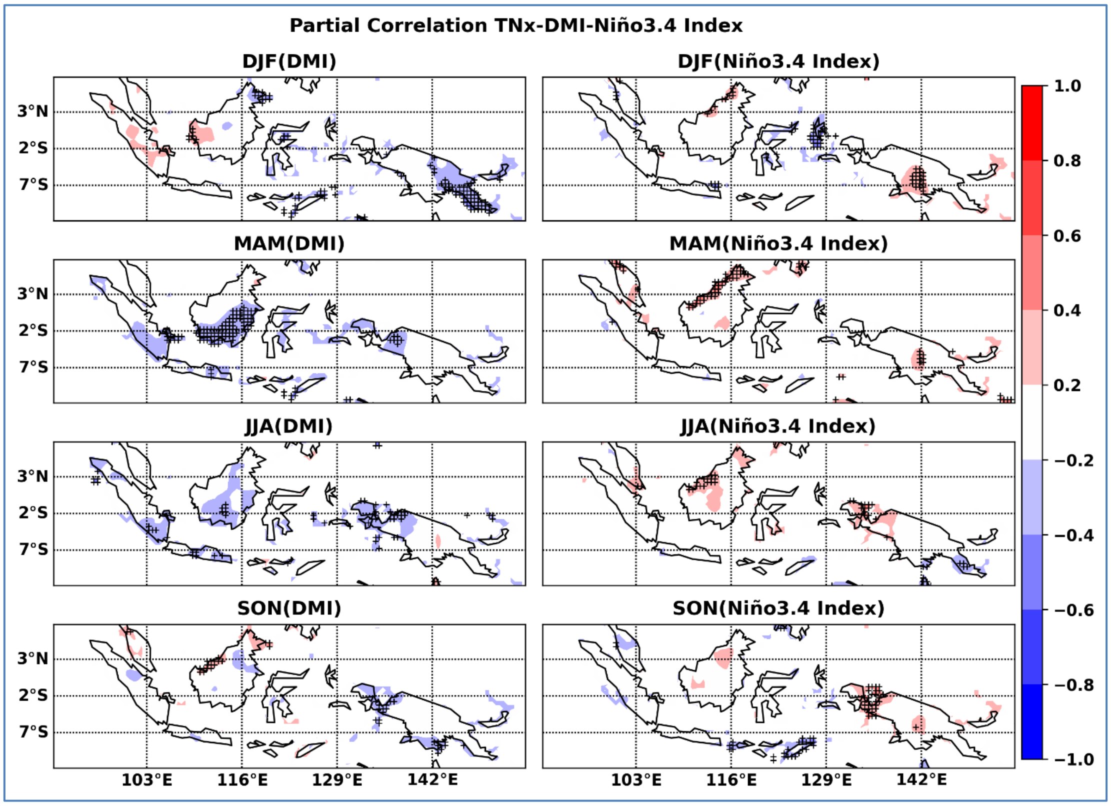

Fig. 7. Partial Correlation of TNx to DMI and Niño3.4 Index. Plus (+) marked is Significance Level at 95%

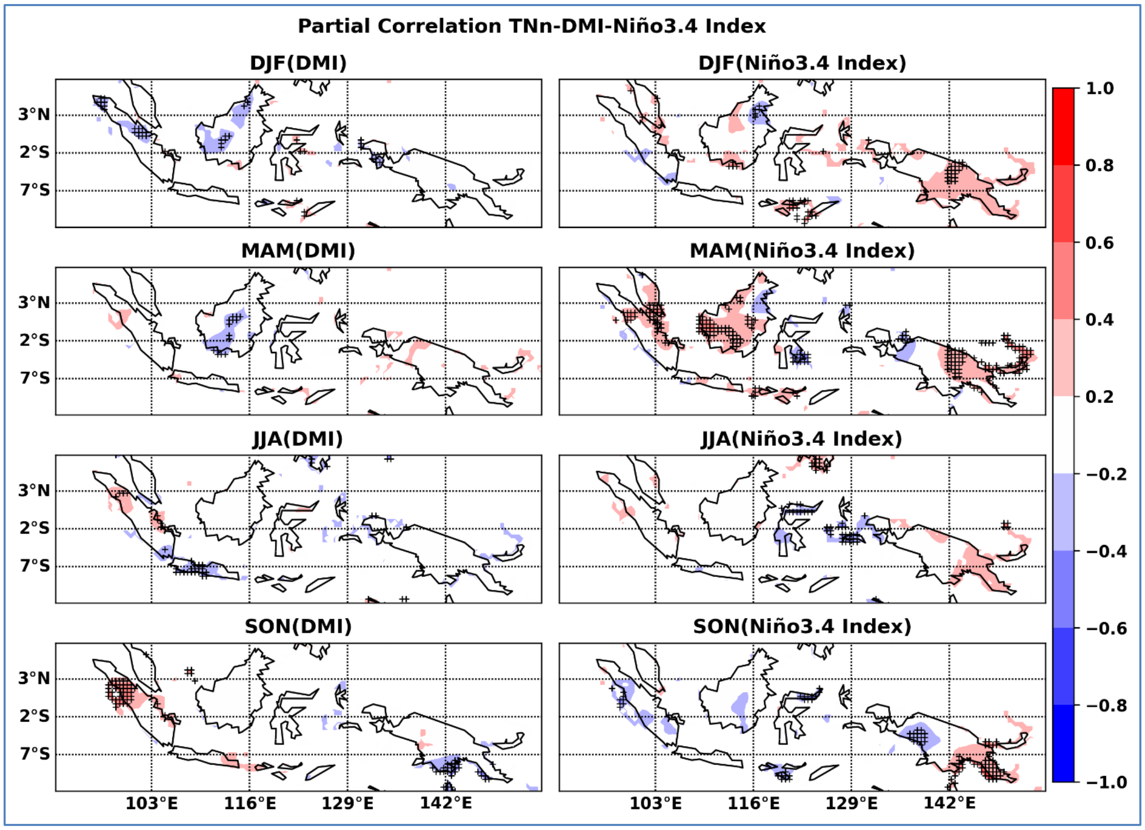

Fig. 8. Partial Correlation of TNn to DMI and Niño3.4 Index. Plus (+) marked is Significance Level at 95%

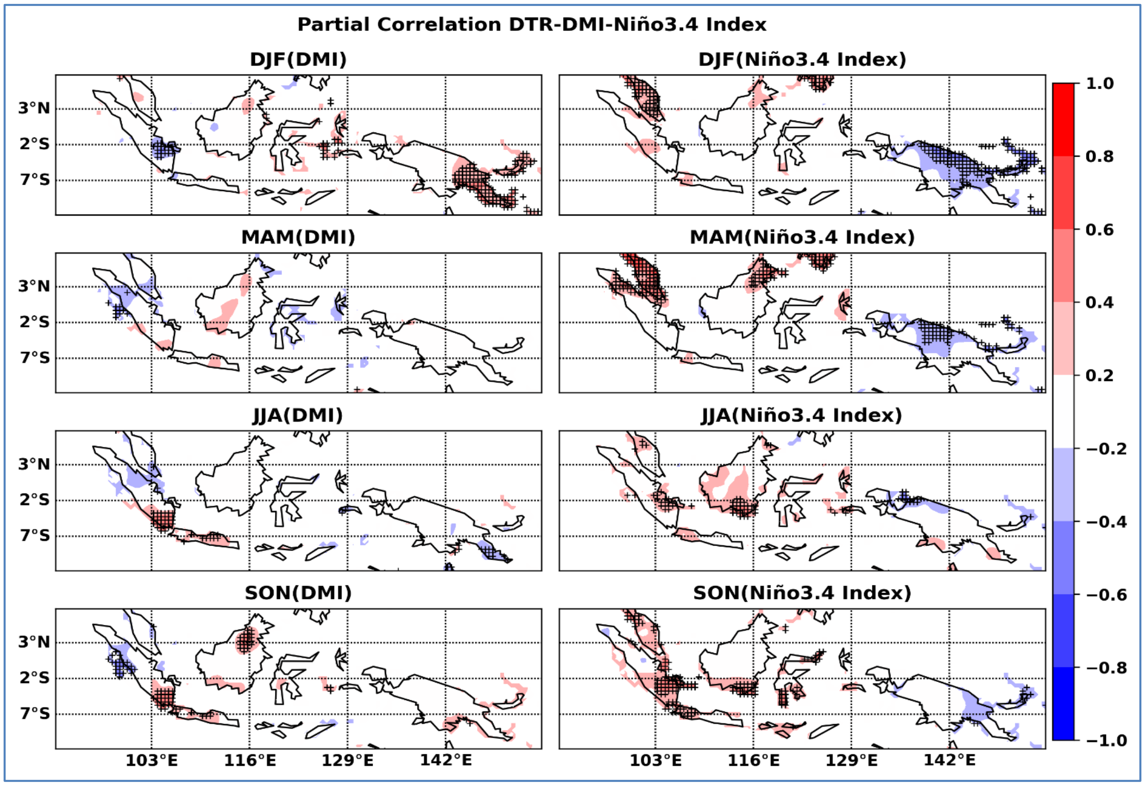

Fig. 9. Partial Correlation of DTR to DMI and Niño3.4 Index. Plus (+) marked is Significance Level at 95%

be seen that DMI is negatively correlated with TNx in a small part of Papua New Guinea in DJF and Southeast Kalimantan in MAM. Meanwhile, the positive correlation between TNx and DMI in DJF and SON only occurs in a small part of western Kalimantan. The positive correlation of TNx with the Niño3.4 index only occurs in several regions, namely in southern Papua in DJF, northwest Kalimantan in MAM and JJA, and western Papua in SON.

The partial correlation between TNn to DMI and the Niño3.4 index is shown in Fig. 8. Based on Fig. 8, it can be seen that in DJF, a positive correlation is only shown between TNn and the Niño3.4 index, especially in the eastern Papua province (142° E longitude), and the Nusa Tenggara islands as well as a small part of southern Kalimantan. Meanwhile, the negative correlation between TNn and DMI is only seen in several areas of Sumatra and Central Kalimantan. In MAM, the positive correlation of TNn with the Niño3.4 index is increasingly showing strengthening, especially in the Kalimantan region, the northern part of Sumatra, the east coast of Sumatra, reaching the Malaysian peninsula and east coast of Papua New Guinea. Apart from the positive correlation, in MAM, there is also a negative correlation between TNn and the Niño3.4 index in a small part of southern Sulawesi and western Papua province. This shows that ENSO affects TNn almost throughout the Indonesian archipelago (and Papua New Guinea), especially in MAM. In JJA, a positive correlation was only shown by TNn to DMI, especially in a small part of the east coast of Sumatra. Meanwhile, the negative correlation of TNn with DMI and the Niño3.4 index occurs in Java and small parts of Sulawesi and Maluku. In SON, the positive correlation of TNn with DMI occurs in the northern region of Sumatra, while for the Niño3.4 index, the positive correlation occurs in eastern Papua New Guinea.

The partial correlation of DTR to DMI and the Niño3.4 index is shown in Fig. 9. Based on Fig. 9, it can be seen that the positive correlation of DTR to the Niño3.4 index is dominantly seen throughout the year, moving from north to south in western to central Indonesia. Meanwhile, the positive correlation of DTR with DMI is only seen in southern Sumatra and Kalimantan in JJA and SON. The positive correlation of DTR with DMI also seen in eastern Papua New Guinea. Compared to other indices the increase in the DTR trend is the biggest thing. This trend is also experienced globally, although the most prominent increase occurs in desert areas (Zhao *et al*., 2021).

4. Conclusions

Like global temperatures, over the last 45 years (1979-2023), extreme temperatures in Indonesia have increased significantly, especially minimum day (TXn) and night (TNn) temperatures. These increases began to be detected in 2007 and 1984. This increase occurred evenly throughout Indonesia. The significantly increasing DTR trend is confirmed by a decrease in nighttime minimum temperatures, which shows that extreme temperatures in Indonesia occur during the day and at night. From an oceanographic perspective, the increase in extreme temperatures is predominantly influenced by the ENSO phenomenon, especially in Indonesia's western and central regions. This increase shows a teleconnection phenomenon of sea surface temperatures in the Pacific Ocean to the land areas of western and central Indonesia. These findings imply that Indonesia is experiencing broad and consistent climate warming, with both daytime and nighttime extremes becoming more frequent and intense. The increased diurnal temperature range suggests rising thermal stress on ecosystems, agriculture, and human health. Furthermore, the strong influence of ENSO highlights how oceanic conditions in the Pacific can significantly affect regional climate on land, demonstrating the interconnected nature of global climate systems. This underlines the importance of monitoring ocean-atmosphere interactions to better anticipate and respond to extreme temperature events in Indonesia.

Competing interests

The authors declare that they have no conflict of interest.

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Authors' contributions

Suhadi: Performed in the research process, main data analysis, interpretation of the results and prepared the initial draft of the manuscript.
Jamiatul Khairunnisa Putri: Contributed to interpretation of the results. (*email: jamiatulk hairunnisaputri_uin@uinradenfatah.ac.id*).
Iskhaq Iskandar: Contributed in main idea, supervised the research process, and contributed to the final review of the manuscript. (*email: iskhaq@mipa.unsri.ac.id*).
Muhammad Irfan: Contributed to the final review of the manuscript. (*email: muhammad_irfan@unsri.ac.id*).
Hamdi Akhsan: Contributed to the research process and interpretation of the results. (*email: hamdiakhsan @fkip.unsri.ac.id*).
Melly Ariska: Contributed to data collection, and research process. (*email: mellyariska@fkip.unsri.ac.id*).

Evelina Astra Patriot: Contributed to data collection. (*email: evelinaastrapatriot@fkip.unsri.ac.id*).
Supari: Supervised the research process, and contributed to the final review of the manuscript. (email: supari@bmkg.go.id).

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