Causal Impacts of El Niño–Southern Oscillation on Global Soil Moisture Over the Period 2015–2100

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Abstract Soil moisture is an important element of the Earth system that influences both mean and extreme climate, hydrological cycle, vegetation growth and agricultural production. Therefore, it is essential to understand the factors that drive soil moisture variability. Soil moisture variations have been shown to be affected by the El Niño–Southern Oscillation (ENSO) in several regions. However, the causal impacts of ENSO on global soil moisture remain elusive, particularly regarding the future periods under warming environment. Here we assessed the causal effects of ENSO on soil moisture at the global scale over the 2015–2100 period using data from Coupled Modeling Intercomparison Project Phase 6 (CMIP6) models. We find that ENSO is likely to have causal impacts on soil moisture over areas of northern Australia, parts of eastern and southern Africa, Southeast Asia, large parts of South America, middle and western Asia, and parts of southern North America. The results show low consistency between CMIP6 models for the causal impacts of ENSO over Southeast Asia while the models’ consensus is higher over eastern Africa, western Asia, Australia, south central North America, and South America. In addition, our results suggested an expansion in the spatial influences of ENSO on regional soil moisture for the future period 2015–2100 compared to the historical period 1915–2000. As soil moisture is an essential part of the water cycle and prediction of ENSO events is achievable, these results might have implications for regional water resources management in the future.

Plain Language Summary Here we evaluated the impacts of the El Niño–Southern Oscillation (ENSO) on global soil moisture during the 2015–2100 period using the latest outputs from climate models. Our results suggest that ENSO is expected to have impacts on regional soil moisture over northern Australia, parts of eastern and southern Africa, Southeast Asia, large parts of South America, middle and western Asia, and parts of southern North America. In addition, the results indicate that the regions influenced by ENSO are extended during the future period 2015–2100 compared to the past period 1915–2000. As soil moisture is an important part of the water cycle and prediction of ENSO events is achievable, the results of this study might be helpful for the sustainability of water resources management in the future.

1. Introduction

The El Niño–Southern Oscillation (ENSO; BJERKNES, 1969) is a major mode of climate variability with global impacts (Cai et al., 2020; Chen et al., 2017; Emerton et al., 2017; McPhaden et al., 2006). ENSO is known to cause the redistribution of winds, precipitation and evaporation (Le & Bae, 2020; Martens et al., 2018; Sun et al., 2020; Yeh et al., 2018) and affect drought, water storage, and water cycle extremes at the global scale (Ault, 2020; Emerton et al., 2017; Frappart et al., 2018; Phillips et al., 2012; Trenberth et al., 2014; Ward et al., 2014; Zambrano Mera et al., 2018). However, there is uncertainty for the causal impacts of ENSO on global soil moisture, particularly regarding the future periods under warming environment.

Soil moisture is an essential part of the water cycle that influences both mean and extreme climate and hydrological extremes (He et al., 2020; Legates et al., 2011; Samaniego et al., 2018; Seneviratne et al., 2010; Yoon et al., 2015). For instance, reduction in soil moisture leads to development and prolongation of heat waves and wildfire (Brey et al., 2021; Deb et al., 2020; Hirschi et al., 2014; Krueger et al., 2015; Lorenz et al., 2010; Miralles et al., 2014; Perkins et al., 2015). In addition, soil moisture may have influences on precipitation (Brocca et al., 2014; Fofoula-Georgiou et al., 2020; Moon & Ha, 2019) and plays a crucial role in land carbon uptake which affect future climate projection (Green et al., 2019; Humphrey et al., 2021). As soil moisture content reflects the hydrologic cycle and global warming is suggested to reduce soil moisture in many regions (Cook et al., 2020; Deng et al., 2020; Samaniego et al., 2018), it is important to understand the factors that drive future soil moisture variability.
While there are strong coupling between soil moisture and regional temperature and precipitation (Miralles et al., 2012; Seneviratne et al., 2010), the variations of soil moisture can be modulated by the main climate modes, including ENSO. For example, El Niño events caused declines in soil moisture over Amazon basin and an increase over eastern Africa (Solander et al., 2020; Van Schaik et al., 2018). While previous works focused on ENSO-induced changes of soil moisture and correlation between ENSO and soil moisture, causal analyses accounting for the confounding effects of other climate modes are lacking. Because ENSO variations and teleconnections are expected to change in the future (Cai et al., 2021), it is important to enhance our understanding of the causal effects of ENSO on global soil moisture. As the current global soil moisture products normally have coarse spatial resolution (Peng et al., 2017), the outputs from Coupled Modeling Intercomparison Project Phase 6 (CMIP6) models (Eyring et al., 2016) provide an opportunity for systematically investigating the response of soil moisture to ENSO.

In this study, we evaluate the possibility for the impacts of ENSO on soil moisture at the global scale. Climate models provide an important tool for evaluating the future impacts of ENSO on global soil moisture while ENSO teleconnections were shown to be better simulated in Coupled Modeling Intercomparison Project Phase 6 (CMIP6) models compared to those from CMIP5 (Planton et al., 2021). Furthermore, it is important to consider the concurrent effects of other modes of climate variability (e.g., the Southern Annular Mode (SAM), the Indian Ocean Dipole (IOD) and the North Atlantic Oscillation (NAO)) on soil moisture. We also discuss the consistency of the CMIP6 models in simulating the causal impacts of ENSO on soil moisture.

2. Data and Methods

2.1. Data

We utilized both future simulations of SSP5-8.5 (i.e., Shared Socio-Economic Pathway 5 and 2100 climate forcing level of 8.5 W/m²) and SSP2-4.5 (i.e., Shared Socio-Economic Pathway 2 and 2100 climate forcing level of 4.5 W/m²) to evaluate the impacts of ENSO on global soil moisture under different scenarios. SSP5 envisions optimistic and fossil-fueled development trends while SSP2 assumes a central pathway with continued historical trends (O’Neill et al., 2016). Different future emission scenarios may provide further insights and consistency across the models for the impacts of ENSO on global soil moisture. These data, which cover the period 2015–2100, are obtained from the Scenario Model Intercomparison Project (ScenarioMIP; O’Neill et al., 2016) of the CMIP6 (Eyring et al., 2016). The data from the historical simulations over the 1915–2000 period is used to estimate the changes in the future impacts of ENSO on soil moisture compared to the recent past. Table S1 in Supporting Information S1 lists the CMIP6 models employed in this study. The models selected provided accessible data for the historical simulations and the two future scenarios. Our analysis mainly used monthly surface soil moisture (upper 0–10 cm of soil, variable ‘mrso’) data. We also used total soil moisture (variable ‘mrso’) data to show the consistency of ENSO impacts on soil moisture of all soil layers. We used monthly sea surface temperature (SST, variable ‘ts’) and sea level pressure (SLP, variable ‘psl’) to define climate modes (see Section 2.2).

2.2. Methods

We followed the methodology employed in recent studies (Le & Bae, 2020; Le et al., 2021), and estimated the probability of no Granger causal effects of ENSO on global soil moisture. The probability value (p-value) is used as a metric to evaluate the likelihood of the causal impacts of ENSO on soil moisture. We use the following multivariate predictive model (e.g., Mosedale et al., 2006; Stern & Kaufmann, 2013) to estimate the causal links between the ENSO and soil moisture:

$$X_t = \sum_{i=1}^{p} \alpha_i X_{t-i} + \sum_{i=1}^{p} \beta_i Y_{t-i} + \sum_{i=1}^{m} \sum_{i=1}^{p} \delta_{ij} Z_{j,t-i} + \epsilon_t$$  \hspace{1cm} (1)

where $X_t$ is the annual mean (or seasonal mean) soil moisture for year $t$, $Y_t$ is the ENSO index, and $Z_{j,t}$ is the confounding factor $j$ for year $t$. In the predictive model shown in Equation 1, while estimating the influence of $Y$ on $X$ (i.e., the contribution of the term $\sum_{i=1}^{p} \beta_i Y_{t-i}$ in predicting $X$), the contribution of past $X$ events are already taken into account by adding the term $\sum_{i=1}^{p} \alpha_i X_{t-i}$. Thus, the causal influence of $Y$ on $X$, if detected, is robust and the contribution of past $X$ events are already considered in our analyses. Here, $m$ is the number of confounding factors and $p \geq 1$ is the order of the multivariate predictive model. The optimal order $p$ is an integer with units of
Our assessments considered the confounding influences of the IOD (Saji et al., 1999; Webster et al., 1999), the SAM (e.g., Cai et al., 2011) and the NAO (Hurrell et al., 2003). These modes of climate variability may have significant influences on regional climate and thus, may modulate the connection between ENSO and soil moisture. Our analysis uses three different confounding factors; thus, m is equal to 3. The noise residuals $\varepsilon_t$ and the regression coefficients $\alpha_i$, $\beta_i$ and $\delta_{ij}$ are the results of the multiple linear regression analysis using the least squares method. We detrend and normalize all the climate indices. We estimate the probability of no Granger causality by applying a test of Granger causality (Mosedale et al., 2006; Stern & Kaufmann, 2013) for the multivariate predictive model shown in Equation 1.

For computing the degree of uncertainty, we followed recent guidance (Stocker et al., 2013) and utilized the terms ‘very unlikely’, ‘unlikely’, ‘likely’ for the 0%–10%, 0%–33%, and 66%–100% probability of the likelihood of the outcome, respectively. For example, if the $p$-value is less than 0.33, the result indicates that ENSO is unlikely to display no Granger causality on soil moisture. In this instance, we conclude that ENSO has ‘causal effect’ on soil moisture.

We computed the ENSO index as the average boreal winter (December–January–February, DJF) SST anomalies over the Niño 3.4 region (120–170°W; 5°N–5°S). The DMI was given as the difference in boreal fall (September–October–November, SON) SST anomalies between two Indian Ocean regions of the western pole (50–70°E; 10°N–10°S) and southeastern pole (90–110°E; 0°N–10°S). The SAM (Cai et al., 2011) was calculated as the first empirical orthogonal function (EOF) of the boreal summer (June–July–August, JJA) SLP anomalies for the region of 40–70°S. The NAO index is computed as the EOF of boreal winter (DJF) SLP anomalies in the North Atlantic area (90°W–40°E, 20°–70°N).

3. Results

3.1. ENSO Impacts on Annual Mean Soil Moisture

Based on the multi-model analysis, Figure 1 presents the causal impacts of ENSO on global surface soil moisture for the future scenarios SSP2-4.5 and SSP5-8.5 over the 2015–2100 period. The regions dominated by ENSO for both scenarios include northern Australia, eastern Africa (regions close to the Horn of Africa) and limited area of south Africa, Southeast Asia, large parts of South America, middle and western Asia, and parts of southern North America. Specifically, for these regions, ENSO is unlikely to have no causal effects on soil moisture (i.e., $p$-value were lower than 0.33 (Stocker et al., 2013)). Details for the impacts of ENSO on soil moisture over these regions are shown in Figure S1 of Supporting Information S1. There is similarity in the patterns of ENSO impacts on surface soil moisture (Figure 1) and total soil moisture (Figure S2 in Supporting Information S1) for both future scenarios SSP2-4.5 and SSP5-8.5, suggesting the consistency of ENSO influences on regional soil moisture variability. We observe uncertain and nonsignificant response of soil moisture to ENSO in other areas comprising Europe, central, eastern and southern Asia, large parts of Africa and northern North America, suggesting the confounding influences of climate modes other than ENSO or the impacts of local climate conditions.

Figures 2a and 2b describe the multi-model mean map of annual mean surface soil moisture for the period 2015–2100 of the future scenarios SSP2-4.5 and SSP5-8.5, respectively. There is low agreement across models in simulating soil moisture over southwestern North America, Southeast Asia, and parts of central and western Asia. Figures 2c and 2d show the multi-model standard deviation of surface soil moisture for each future scenario. Higher spread between models is observed over high latitude regions of Eurasia and North America, parts of South Asia and parts of South America.

As soil moisture conditions have great influences on vegetation growth (Liu et al., 2020; Pereira et al., 2020) and agricultural production (Madadgar et al., 2017; Najafi et al., 2019), ENSO effects may cause risks to agriculture and cropland area of the affected regions (Heino et al., 2018). While the predictability of soil moisture might be improved even with limited predictions of precipitation (Esit et al., 2021), the results of this study suggest that past ENSO information are helpful for the predictions of future soil moisture for several regions. For example, ENSO information in the past can be used as a predictor of future soil moisture over eastern Africa, south
Figure 1. Map of multi-model mean probability for the absence of Granger causality from ENSO to annual mean surface (0–10 cm) soil moisture for the future scenarios SSP2-4.5 (a) and SSP5-8.5 (b) over the 2015–2100 period. Stippling shows that at least 70% of total models demonstrate agreement on the mean probability of all models at given grid point. The agreement of an individual model is defined when the difference between the selected model’s probability and the multi-model mean probability is less than one standard deviation of the multi-model mean probability. The cyan contour line specifies $p$-value $= 0.33$. Brown shades imply low probability for the absence of Granger causality. ENSO = El Niño–Southern Oscillation.
central North America, western Asia, and South America. In addition, as ENSO predictability is feasible (Ham et al., 2019), further predictions of ENSO-based soil moisture are achievable.

3.2. The Consistency of ENSO Impacts

We observe high agreement between models for the significant causal effects of ENSO on soil moisture over the regions of middle and western Asia, south central North America, South America, northeastern Africa and northern Australia (Figures S1a–S1c, S1e and S1f in Supporting Information S1). However, there is lower agreement between models in fractions of southern North America, Southeast Asia and fractions of southern Africa (Figures S1b, S1d and S1f in Supporting Information S1), indicating the spread of CMIP6 models in reproducing the link between ENSO and soil moisture over these areas. We observe high agreement between models for the weak response of soil moisture to ENSO over eastern Europe, limited areas of eastern Asia and Africa and northern North America.

The number of models exhibiting substantial causal effects of ENSO on soil moisture (i.e., p-value were lower than 0.33) is presented in Figure 3a. Consistent with Figure 1, more than 50% of all models indicate that ENSO is unlikely to have no causal effects on soil moisture (i.e., p-value were lower than 0.33) over the regions of Australia, eastern Africa, Southeast Asia, South America, middle and western Asia, southern parts of North America. In general, there is consistency between the two future scenarios SSP5-8.5 and SSP2-4.5 for the impacts of ENSO on soil moisture of these areas. However, additional analysis also reveals that different level of global warming may slightly affect the influences of ENSO on soil moisture (Figure 3b). For example, ENSO impacts on Australian regions and southcentral North America are extended in SSP2-4.5 compared to SSP5-8.5 while there are minor changes over Southeast Asia and middle and western Asia. Figure 3b indicates that different levels of warming may alter the impacts of ENSO on soil moisture in several regions, reflecting the confounding influences of various processes on regional soil moisture. Our results show that the regions with substantial agreement...
Number of models with Granger causality from ENSO to SOIL MOISTURE period 2015-2100 (p-value < 0.33)

(a)

MODELS MEAN OF ENSO - SURFACE SOIL MOISTURE: SSP245 MINUS SSP585

(b)

(c)

Fraction of land surface area influenced by ENSO

SSP5-8.5

SSP2-4.5

Fraction area (in percentage of land surface area)

Figure 3.
ENSO impacts on soil moisture account for ∼12% of land area for SSP2-4.5 and approximately 10% of land area for SSP5-8.5 (Figure 3c).

Figure 4 details the results of 15 individual models (Table S1 in Supporting Information S1) for the causal impacts of ENSO on global soil moisture for the future scenario SSP5-8.5 over the 2015–2100 period. The results of individual models from the future scenario SSP2-4.5 exhibit similar pattern compared to the future scenario SSP5-8.5 (not shown). In Figure 4, several models showed biases compared to the multi-model mean shown in Figure 1b. Notably, models CNRM_CM6_1 and CNRM_ESM2_1 (Figures 4g and 4h) shows weak connection between ENSO and soil moisture for most regions (e.g., Australia, middle and western Asia and large parts of South America), while model MIROC6 (Figure 4k) exhibits stronger soil moisture response to ENSO. The diversity of models’ response over Southeast Asia (Figure 4) contributes to the uncertainties of ENSO causal impacts on soil moisture in this region (Figure 1 and Figure S1d in Supporting Information S1). For instance, several models (i.e., models BCC_CSM2_MR and CNRM_CM6_1_MR – Figures 3c and 3f) showed weaker ENSO’s impact on soil moisture compared to others. The models CNRM_CM6_1, IPSL-CM6A-LR, MIROC6 and MRI_ESM2_0 (Figures 3g, 3j, 3k and 3n) have substantial biases in simulating the causal effects of ENSO on soil moisture over Australia compared to the mean of multi-model results. The model FGOALS_G3_L (Figure 4i) exhibited significant stronger ENSO impacts over much of western Africa, Asia and northern North America compared to other models. These discrepancies are associated with the performance of individual climate models in reproducing the variations of ENSO or the IOD and soil moisture (Gu et al., 2019; McKenna et al., 2020; Taschetto et al., 2014; Yuan et al., 2021; Yuan & Quiring, 2017). Despite these biases, the broad consistency between CMIP6 models described above over various areas suggest the confidence in the capability of the models in simulating the causal impacts of ENSO on global soil moisture.

3.3. ENSO Impacts on Seasonal Mean Soil Moisture

Natural hazards (e.g., drought and heat waves) might be very seasonally dependent, thus, further analyses for the impacts of ENSO on seasonal soil moisture are necessary. As ENSO peaks in boreal winter (DJF), its causal impacts are the most significant in the following boreal spring (MAM) and gradually weaken during following boreal summer (JJA), fall (SON) and winter (Figure 5). Specifically, ENSO at year t \([D(t)JF(t + 1)]\) is unlikely to exhibit no causal impacts on spring \([MAM(t + 1)]\) soil moisture (i.e., \(p\)-value were lower than 0.33) over northern Australia, Southeast Asia, large parts of southern North America, middle and western Asia, and parts of South America (Figure 5a). During following summer \([JJA(t + 1)]\), ENSO impacts might be found in limited areas of middle and western Asia, Southeast Asia and South America (Figure 5b). During following fall and winter \([SON(t + 1)]\) and \([D(t + 1)JF(t + 2)]\), ENSO is likely to show no causal effects on soil moisture (i.e., \(p\)-value were higher than 0.66 (Stocker et al., 2013)) for most regions (Figures 4c and 4d). These results demonstrate that ENSO-based predictability of seasonal soil moisture variations might be helpful in the following spring and summer while it is less effective in the following fall and winter.

3.4. Expansion of ENSO Impacts in the Future Periods

The causal impacts of ENSO on global surface soil moisture for the historical period 1915–2000 are described in Figure 6a. This baseline is used to evaluate the possible changes of ENSO impacts in the future scenarios SSP2-4.5 and SSP5-8.5. The results shown in Figures 1 and 6a indicate substantial changes in the spatial influences of ENSO on regional soil moisture for the future scenarios SSP2-4.5 and SSP5-8.5 compared to the historical period. Details for the difference between these two periods 1915–2000 and 1915–2000 are presented in Figures 5b and 5c. In particular, there is a decrease in the probability of no causal effects of ENSO on soil moisture in several regions, including South America, Southeast Asia, western and middle Asia and parts of eastern Africa. These results suggest possible intensification of ENSO impacts on these regions in the 21st century. Conversely, we observe minor reduction in the likelihood for the impacts of ENSO over southwestern Africa.

Figure 3. (a) The number of models (out of 15 in total) showing ENSO is unlikely to exhibit no causal effects on soil moisture (i.e., \(p\)-value < 0.33). (b) Difference of multi-model mean probability for the absence of Granger causality of ENSO on annual mean surface soil moisture between future scenarios SSP2-4.5 and SSP5-8.5 (i.e., SSP2-4.5 minus SSP5-8.5). Blue shades imply lower probability of no Granger causality in the scenario SSP2-4.5 compared to scenario SSP5-8.5. Red shades imply lower probability of no Granger causality in the scenario SSP5-8.5 compared to the scenario SSP2-4.5. (c) Fraction of land surface with probability for the absence of Granger causality from ENSO to soil moisture lower than 0.33 (i.e., \(p\)-value < 0.33). Fraction areas influenced by ENSO of future scenarios SSP2-4.5 and SSP5-8.5 are presented. ENSO = El Niño–Southern Oscillation.
eastern India, Australia and parts of North America, indicating possible increase in the confounding influences of other modes of climate variability (e.g., the NAO and the IOD). These climate modes in the Atlantic and Indian oceans may modulate the connection between ENSO and regional climate (Cai et al., 2019, 2020; Le et al., 2020). In addition, our results demonstrate that significant ENSO impacts on soil moisture during the historical period 1915–2000 only account for 8.1% of land area (i.e., 2.4% of total earth surface), implying the overall expansion of future ENSO effects on regional soil moisture (see also Figure 3c).

Figure 4. As in Figure 1, but for the probability for the absence of Granger causality of ENSO on annual mean surface (0–10 cm) soil moisture for the future scenarios SSP5-8.5 over the 2015–2100 period of 15 individual models (see also Table S1 in Supporting Information S1). The results are similar for the future scenarios SSP2-4.5 (not shown). ENSO = El Niño–Southern Oscillation.
4. Discussion and Conclusions

In this work, we assessed the causal effects of ENSO on global soil moisture over the 21st century using data from CMIP6 models. We showed that ENSO is unlikely to exhibit no causal influences on soil moisture (i.e., p-value were lower than 0.33) over northern Australia, eastern Africa (regions close to the Horn of Africa) and limited area of south Africa, Southeast Asia, large parts of South America, middle and western Asia, and parts of southern North America. These results are consistent between both future scenarios SSP2-4.5 and SSP5-8.5. In addition, we find an overall expansion of ENSO effects on regional soil moisture for the future period 2015–2100 compared to the historical period 1915–2000.

Our results emphasize the important role of the tropical Pacific in driving changes of surface soil moisture over many regions where more droughts are expected in the 21st century (e.g., Parsons, 2020). While precipitation is known as the input source of soil moisture, temperature may affect evapotranspiration processes and may cause the loss of soil moisture to the atmosphere (Legates et al., 2011). Changes in regional surface temperature and evaporation induced by ENSO lead to variations of atmospheric moisture transport and moisture advection (Algarra et al., 2020) and eventually influence regional soil moisture. Besides, changes in oceanic moisture supply induced by ENSO are expected to contribute to the variations of regional soil moisture. For instance, ENSO events cause an increase in precipitation in southwest central Asia region with additional moisture flux from tropical Africa and Arabian Sea (Mariotti, 2007).

The uncertainties in the response of soil moisture to ENSO in several regions (e.g., central and eastern Asia and northern North America) demonstrate the confounding influences of other climate modes and local climate conditions. For example, nonsignificant ENSO effects on soil moisture over western, central and southern Australian regions might be due to the confounding influences of the IOD and the SAM (Perkins et al., 2015; Ummenhofer et al., 2011). Besides, ENSO effects on soil moisture are dependent on soil moisture-atmosphere and soil moisture-temperature interactions (Fischer et al., 2007; Miralles et al., 2012).
Figure 6. (a) As in Figure 1, but for the multi-model mean probability for the absence of Granger causality between ENSO and annual mean surface (0–10 cm) soil moisture for the historical experiment over the 1915–2000 period. (b) Difference of multi-model mean probability for the absence of Granger causality of ENSO on annual mean surface soil moisture between future scenario SSP2-4.5 and historical experiment (i.e., SSP2-4.5 minus historical experiment). (c) Difference of multi-model mean probability for the absence of Granger causality of ENSO on annual mean surface soil moisture between future scenario SSP5-8.5 and historical experiment (i.e., SSP5-8.5 minus historical experiment). In (b) and (c), blue shades signify lower probability of no Granger causality in the future scenario SSP2-4.5 (and SSP5-8.5) compared to the historical experiment. Brown shades signify lower probability of no Granger causality in the historical experiment compared to the future scenario SSP2-4.5 (and SSP5-8.5). ENSO = El Niño–Southern Oscillation.
Our results show an agreement with previous study using observational data (Solander et al., 2020) which showed the important signature of ENSO on soil moisture variations over Southeast Asia, Amazon basin and eastern Africa. These results are consistent with the significant influences of ENSO on precipitation, surface temperature and evaporation over these regions (Cai et al., 2020; Dai & Wigley, 2000; Le & Bae, 2020). Moreover, the results support the conclusions of previous works for the impacts of ENSO on soil moisture and water cycle of the regions mentioned above. For instance, ENSO showed significant impacts on hydrological cycle of the Mekong River basin (Räisänen & Kummu, 2013) while western Asia climate was shown to have connection with ENSO (Mariotti, 2007; Molavi-Arabshahi et al., 2016). In addition, ENSO was shown to have impacts on drought over southeastern United States (Mo & Scherm, 2008).

The results show low consistency between models in reproducing the causal impacts of ENSO on soil moisture over Southeast Asian region, suggesting that the spread between models is substantial in this region and further studies are necessary. Because the Asian monsoon plays an important role in shaping the water resources of this region (Ha et al., 2020; Kripalani & Kulkarni, 1997), additional analyses considering the teleconnections between ENSO and the Asian monsoon are essential. As central Pacific and eastern Pacific (EP) ENSO might have different impacts (Cai et al., 2020), future works may consider investigating the effects of EP ENSO on soil moisture. Given the strong interaction between ENSO and the IOD under warming environment (Cai et al., 2019; Le & Bae, 2019; Le et al., 2020), it is crucial to investigate the causal influences of the IOD on regional soil moisture.

Data Availability Statement
Coupled Model Intercomparison Project Phase 6 (CMIP6) data can be accessed from the World Climate Research Programme (WCRP) ESGF website at https://esgf-node.llnl.gov/search/cmip6/.

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