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Key Points:

- The Puget Sound precipitation, temperature, snowmelt, and runoff are notably modulated by El Niño–Southern Oscillation (ENSO) and Madden-Julian Oscillation (MJO)
- ENSO mostly affects temperature-relevant processes, including snow drought, whereas MJO modulates extreme daily precipitation
- MJO modulations on extreme daily hydroclimate conditions are insensitive to how the ENSO signals are removed, except for temperature

Supporting Information:

Supporting Information may be found in the online version of this article.

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Impact of El Niño–Southern Oscillation and Madden-Julian Oscillation on the US Puget Sound Regional Hydroclimate

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Abstract El Niño–Southern Oscillation (ENSO) and Madden-Julian Oscillation (MJO) are two major modes of climate variability with global hydroclimate impacts. However, their impacts often depend on the local climate and geography, resulting in large regional differences. In this study, we examined the connection of ENSO and MJO to the hydroclimate conditions and extremes in the Puget Sound (PS) basin located in the US Pacific Northwest coast. The results indicate that ENSO significantly modulates the cold season temperature and temperature-mediated hydrologic processes. El Niño cold seasons feature less snow accumulation and intensified surface runoff, even if the precipitation amount is similar to La Niña cold seasons. Therefore, El Niño causes more snow drought (in the form of compound dry and warm snow drought) and shifts the surface runoff seasonality by reducing runoff in the subsequent warm season. MJO phases 6–7 trigger more extreme precipitation, temperature, snowmelt, and runoff in the PS region at 0–9-day lags, and such connections are robust regardless of how the ENSO signals are removed. Meanwhile, MJO modulates large-scale extreme weather systems (e.g., atmospheric rivers) with significant enhancement during phases 6–7. ENSO impacts have intensified in the 2001–2020 period, whereas MJO impacts showed some phase shift in this period. This study reveals ENSO and MJO phases 6–7 as useful predictors of the PS hydroclimate anomalies/extremes at seasonal and daily scales, respectively. Utilizing these findings holds the potential to improve regional water resources prediction and management.

Plain Language Summary El Niño and Madden-Julian Oscillation (MJO) are two important modes of climate variability that affect weather and hydrologic conditions. Their effects can vary greatly depending on the local climate and geography. In this study, we looked at how they influence weather and water conditions in the Puget Sound (PS) area, located on the US Pacific Northwest coast. We found that El Niño greatly impacts winter temperatures and temperature-related processes such as snowmelt. During El Niño winters, there is less snow and more surface runoff, even if the total amount of precipitation is similar to that in La Niña winters. This means El Niño winters result in less snow and lead to reduced water resources in the following warm season. MJO phases 6–7 are linked to more extreme weather events such as heavy precipitation, warm temperatures, intense snowmelt, and increased runoff in the PS area. Such impacts are notable in various experiments that remove the El Niño–Southern Oscillation (ENSO) impact with different methods. MJO phases 6–7 also strengthen extreme weather systems such as atmospheric rivers. Compared to the 1981–2000 period, ENSO modulations on hydroclimate conditions are enhanced in 2001–2020, whereas MJO impacts show a phase shift. Our findings could help improve the prediction and management of regional water resources.

1. Introduction

El Niño–Southern Oscillation (ENSO) is a major mode of climate variability and a recognized key hydroclimatic driver at regional to global scales (Bjerknes, 1969; Cai et al., 2020; Y. Chen et al., 2017; McPhaden et al., 2006). ENSO phases (El Niño, neutral, and La Niña) are usually defined using tropical Pacific sea surface temperature (SST) anomalies. These anomalies reflect the variability of large-scale ocean–atmosphere thermal conditions that induce diverse hydroclimate anomalies through atmospheric teleconnections on a global scale (Ault, 2020; Capotondi et al., 2020; Emerton et al., 2017; T. Le & Bae, 2020; Martens et al., 2018; Phillips et al., 2012; Sun et al., 2020; Trenberth et al., 2014; Ward et al., 2014; Yeh et al., 2018). Despite ENSO's global-scale hydroclimate signatures, its modulation has a regional dependence (Clark et al., 2001; Hernandez et al., 2022; Leung & Qian, 2009; Patricola et al., 2020; Rice & Emanuel, 2017). For example, Patricola et al. (2020) revealed opposite

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precipitation anomalies to ENSO in the western US: El Niño brings positive precipitation anomaly to California but average-to-negative anomaly to the Pacific Northwest (PNW); La Niña is associated with significant precipitation deficits in California but positive precipitation anomaly in PNW. Given the projected intensification of both El Niño and La Niña events, it is increasingly important to quantify the impact of ENSO on regional hydroclimate systems to understand future regional water resources (Cai et al., 2014, 2015; T. Le et al., 2021). Meanwhile, contrasting local hydrological responses to ENSO imply predictive skills from ENSO at local scales, which are worthy of further investigation.

Madden-Julian Oscillation (MJO) is another important tropical circulation pattern that has global-scale impacts (Bai et al., 2023; Jiang et al., 2020; Madden & Julian, 1994; Schreck III, 2021; Zhang, 2005). MJO is an effective predictor of climate variability and extremes on sub-seasonal time scales in many regions (Castellano et al., 2023; Jones, 2000; Jones & Carvalho, 2012; Li et al., 2018; Nardi et al., 2020; Peng et al., 2019). Within the extra-tropical climate, the enhancement of the PNW precipitation and flood patterns by MJO has also been revealed and established in previous studies (Bond & Vecchi, 2003; Wang et al., 2023). However, previous analyses did not separate the impact of ENSO, which is known to interact with MJO and complicate their hydroclimate signatures (Arcodia et al., 2020; Li et al., 2018). Additionally, the effect of MJO on snowpack and temperature is less well investigated (Barrett et al., 2015; Guan et al., 2012; Schreck et al., 2013), which leaves a gap in process-level knowledge on the flood responses to MJO in snow-fed watersheds. Meanwhile, these studies consider MJO less as an explicit predictor but rather as a modulator to other connections, such as the enhanced connection between North American 500 hPa geopotential, surface temperature, and snow depth during MJO phases 5 and 7 in March (Barrett et al., 2015).

Puget Sound is a watershed in the US PNW region with complex mountain-to-coastal terrain (Figure 1). The hydroclimate conditions of this region are modulated by: (a) large-scale circulation patterns such as the Aleutian Low over the Pacific Ocean; (b) local land-atmospheric interactions due to the complex topography; (c) human systems impacts such as urbanization and water management practices. This region shares similar large-scale drivers of extreme precipitation, snowmelt, and floods with the rest of the US West Coast. For example, extreme precipitation and floods in this region are often associated with atmospheric rivers (ARs), which are long and narrow bands of intense atmospheric moisture transport (Lamjiri et al., 2017; Newell et al., 1992). A better understanding of extreme precipitation associated with such large-scale features and their responses to ENSO and MJO can help advance the prediction of local climate extremes. For example, is ENSO modulation of hydroclimate conditions in the PS region similar to those in North America analyses (Cayan, 1996; Kunkel & Angel, 1999; Patten et al., 2003; Ropelewski & Halpert, 1986) or regional studies (Clark et al., 2001; Jin et al., 2006; Karanja et al., 2023; Tamaddun et al., 2017)? Will local human activities and local topography dominate the precipitation variability, overriding the modulation of these tropical forcings? Overall, PS provides a useful testbed to examine the responses of diverse regional hydroclimate extremes to large-scale climate variability. Although there have been some studies on the ENSO and MJO impacts on the hydrologic cycle in this region, a more comprehensive evaluation is still needed to understand how all the major hydroclimate variables (precipitation, temperature, snow, and runoff) are modulated in a single framework with integrated, physically consistent data (Leung et al., 1999). Meanwhile, as changes and shifts in ENSO and MJO have been observed in the past 40 years, it is also necessary to update our knowledge of these impacts and their implications (Alizadeh, 2024; Hu et al., 2020; McPhaden, 2012; Tan et al., 2024). For example, ENSO cycle variability has experienced a notable change in the 21st century, and how has it affected ENSO impacts on the regional hydroclimate? Similarly, how is the shifted MJO cycle connected to the changing hydroclimate in this region?

In this study, we focus on the ENSO and MJO impacts on the PS hydroclimate condition (including precipitation, temperature, snowpack, runoff, and AR) across daily, monthly, and seasonal timescales. By analyzing high-resolution regional hydroclimate modeling data from 1981 to 2020, we address the following questions: (a) What is the influence of ENSO on PS hydroclimate conditions at monthly-to-seasonal scales? (b) What is the influence of MJO on the PS hydroclimate extremes at the daily scale? (c) How are extreme hydroclimate conditions such as snow droughts and ARs affected by ENSO and MJO? (4) How are MJO signals affected by the removal of ENSO signals? This study will examine the distinct MJO impact on regional hydroclimate conditions through various methods of removing ENSO signals, and examine the roles of the MJO cycle in both its active and inactive periods. Lastly, we briefly investigate the ENSO and MJO changes in the recent decades and their hydroclimate impacts to motivate future research to understand the historical and future changes in ENSO and MJO and their regional hydroclimate impacts worldwide.

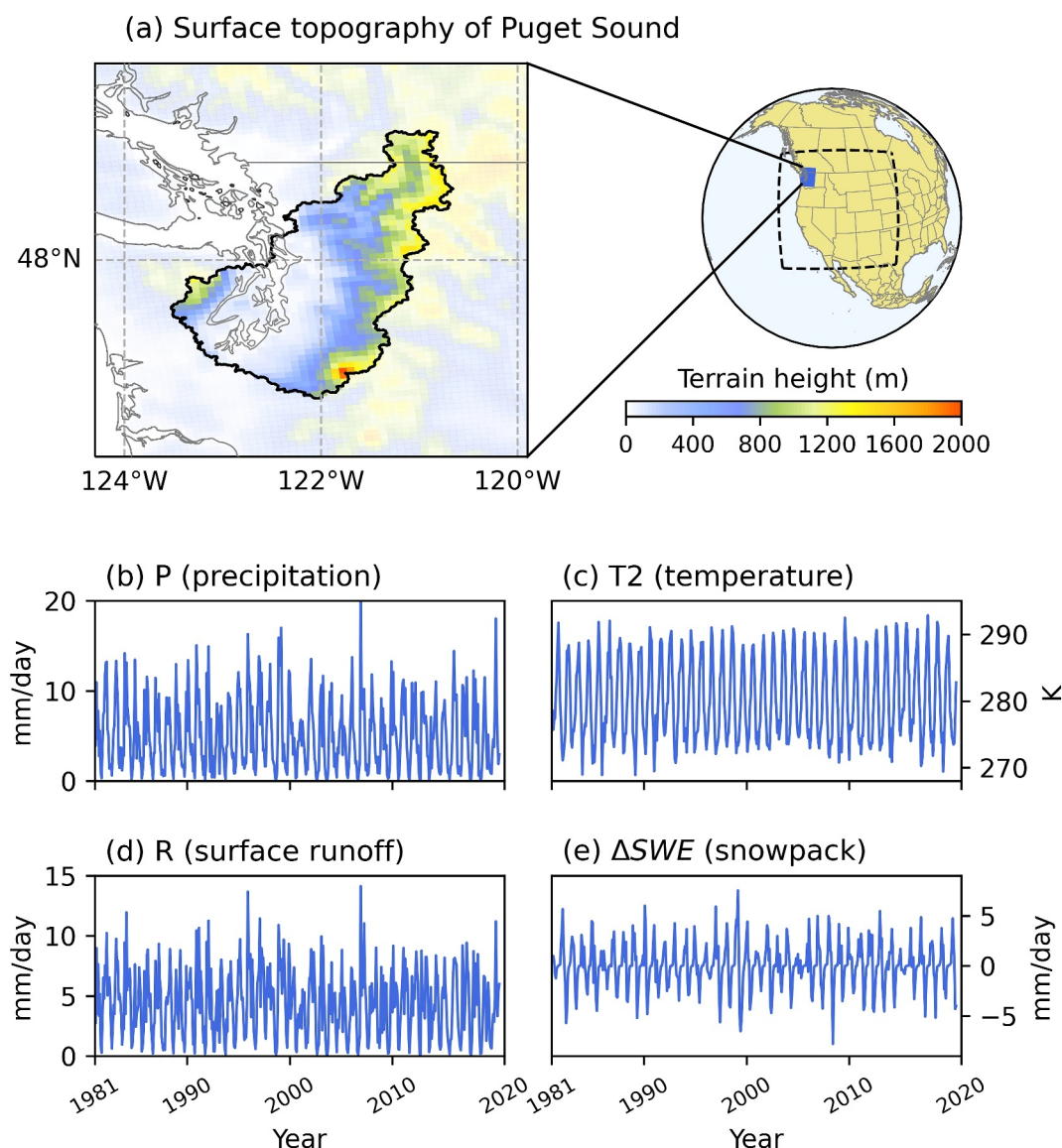


Figure 1. Overview of Puget Sound (PS) and the regional hydroclimate conditions. Panel (a) shows the surface topography of PS and the surrounding region, as well as the Weather Research and Forecasting hydroclimate simulation domain (dashed box). Panel (b–e) shows the PS-aggregated monthly precipitation (P), 2-m temperature (T_2), surface runoff (R), and snowpack change (ΔSWE) during 1981–2020.

2. Data and Method

2.1. Study Area

The PS basin is located in the US Pacific Northwest (Figure 1). It is in the west coast Mediterranean or Oceanic climate zone, featuring mild, wet winters and relatively cool, dry summers (Beck et al., 2018; Peel et al., 2007). About 70% of the annual precipitation occurs in the cold season (October–March), with most of the extreme precipitation and flooding events caused by ARs (Mass, 2021). Streamflow in the PS varies among snowmelt-dominated, transitional, and rainfall-dominated regimes (Beechie et al., 2006; Cao et al., 2016; Elsner et al., 2010; Stewart et al., 2005). The drainage area of PS is 31,440 km², and elevations range from sea level at the PS estuary to ~3,000 m in the major high-elevation mountains of the Cascade Range to the east of the PS region. Another high-elevation area is the Olympic Peninsula west of the PS region, as indicated on the western PS boundary in Figure 1.

2.2. Characterization of ENSO and MJO

The hydroclimate conditions of the PS region are well depicted by a regional climate simulation for 1981–2020 produced by the Weather Research and Forecasting (WRF) model V3.8 (Skamarock et al., 2008). This simulation at 6-km grid spacing covers the western US and northeastern Pacific Ocean (the dashed box in Figure 1a). The simulation is driven by the North American Regional Reanalysis (NARR) (Mesinger et al., 2006). Compared to the 32-km NARR data, the 6-km WRF outputs better capture the topographic impact and reflect the realistic PS hydroclimate condition. The simulated key hydroclimate components (precipitation, near-surface temperature, snowpack, and runoff) have been validated against various observations (Chen et al., 2019). More information on the model configuration including the physics parameterizations can be found in Gao et al. (2017) and Chen et al. (2018).

Daily precipitation (P), 2-m air temperature (T_2), snowpack change (as the change of snow water equivalent ΔSWE , or snowmelt as $-1 \times \Delta SWE$), surface runoff (R), integrated water vapor (IWV), and integrated vapor transport (IVT) are collected from this simulation for analysis in this study. ENSO condition is described by the Ocean Niño Index (ONI), and MJO is characterized by Real-time Multivariate MJO indices (RMM). Monthly ONI is generated by the Climate Prediction Center at the National Oceanic and Atmospheric Administration using the 3-month running mean of ERSST.v5 SST anomalies in the Niño 3.4 region (5°N – 5°S , 120° – 170°W) (Huang et al., 2017). RMM is generated using a combination of 850-hPa zonal wind, 200-hPa zonal wind, and satellite-observed outgoing longwave radiation in the equatorial region (Wheeler & Hendon, 2004). It includes two components (RMM1 and RMM2, which are the principal component time series from multivariate EOF of the MJO components above) and provides a mathematical description of the cloud and wind conditions at upper and lower levels of the atmosphere. When their combination ($RMM_C = \sqrt{RMM1^2 + RMM2^2}$) is greater than 1, that day is defined as an active MJO day; otherwise, it is an inactive or non-MJO day. During MJO days, the orientation of the vector (RMM1, RMM2) defines the 8 phases of MJO: positive RMM1 contributes to phases 3–6, and positive RMM2 contributes to phases 5–8.

2.3. Connecting ENSO and MJO to Regional Hydroclimate

The impact of ENSO phases on hydroclimate variables is examined by splitting the monthly/seasonal hydrological time series into subgroups to assess how the average responses of these variables differ during El Niño/neutral/La Niña months or cold seasons (October–March). The ENSO phase is defined using ONI: when ONI is beyond $+0.5^\circ\text{C}$ (below -0.5°C) for at least five consecutive months, it is defined as an El Niño (La Niña) event. If all months in a cold season are El Niño (La Niña) months, this cold season is defined as an El Niño (La Niña) season. On a continuous spectrum, the relationship between ONI and the hydroclimate variables is examined through wavelet analysis. Wavelet analysis transforms time series into time-frequency space (Daubechies, 1992; Torrence & Compo, 1998). Compared to other frequency analysis approaches (e.g., Fourier analysis), wavelet-based coherence analysis can identify both the coherence frequency and the timing/duration of coherence. The Morlet wavelet is selected due to its smooth features and wide applications in hydrological analysis (Brunner & Gilleland, 2020; Lafrenière & Sharp, 2003; Liu et al., 2011; Schaeffli et al., 2007). This study applies wavelet analysis to both raw and standardized monthly time series of hydroclimatic variables. In the standardized time series, the long-term monthly mean and standard deviation are removed to avoid any coherence caused by the repeating seasonal cycles.

The impact of MJO is examined at the daily time scale. Since the same hydroclimatic anomaly (especially temperature anomaly) can be caused by either ENSO or MJO, the ENSO impacts on the hydroclimatic variables are first identified and removed before the MJO impact analysis. For a daily time series $\{X_i | i = 1: N\}$ that contains N records in either warm (April–September, $N = 7,320$) or cold (October–March, $N = 7,290$) season during 1981–2020, all the records can be split into three groups based on the ONI of that month: the El Niño subset $\{X\}^E$, neutral subset $\{X\}^N$, and La Niña subset $\{X\}^L$. In this study, the ENSO impacts are considered and removed through the following four approaches:

1. The differences in the mean caused by different ENSO phases are considered. For a given day of a given month m , the mean in the same month during 1981–2020 and under the same ENSO phase can be computed as $\text{mean}(\{X \text{ in month } m\}^E)$, taking an El Niño month as an example. The residual on day i can then be computed as follows:

$$X_i^{\text{res}} = \begin{cases} X_i - \text{mean}(\{X \text{ in month } m\}^E), & (\text{if day } i \text{ is in an El Niño month}) \\ X_i - \text{mean}(\{X \text{ in month } m\}^N), & (\text{if day } i \text{ is in a neutral month}) \\ X_i - \text{mean}(\{X \text{ in month } m\}^L), & (\text{if day } i \text{ is in a La Niña month}) \end{cases}$$

2. The differences in both mean and standard deviation caused by different ENSO phases are considered. In addition to removing the mean($\{X \text{ in month } m\}^E$) during 1981–2020, we also standardize the series with $\text{std}(\{X \text{ in month } m\}^E)$ during 1981–2020:

$$X_i^{\text{res}} = \begin{cases} \frac{X_i - \text{mean}(\{X \text{ in month } m\}^E)}{\text{std}(\{X \text{ in month } m\}^E)}, & (\text{if day } i \text{ is in an El Niño month}) \\ \frac{X_i - \text{mean}(\{X \text{ in month } m\}^N)}{\text{std}(\{X \text{ in month } m\}^N)}, & (\text{if day } i \text{ is in a neutral month}) \\ \frac{X_i - \text{mean}(\{X \text{ in month } m\}^L)}{\text{std}(\{X \text{ in month } m\}^L)}, & (\text{if day } i \text{ is in a La Niña month}) \end{cases}$$

3. ENSO impacts are estimated through linear regression. Taking the warm season as an example, we regress the day i data X_i in month m to the ONI of the current and previous 5 months ($\text{ONI}_m, \text{ONI}_{m-1}, \text{ONI}_{m-2}, \text{ONI}_{m-3}, \text{ONI}_{m-4}$ and ONI_{m-5}): $X_i = \text{linreg}(\text{ONI}) = a_0 \cdot \text{ONI}_m + a_1 \cdot \text{ONI}_{m-1} + a_2 \cdot \text{ONI}_{m-2} + a_3 \cdot \text{ONI}_{m-3} + a_4 \cdot \text{ONI}_{m-4} + a_5 \cdot \text{ONI}_{m-5} + b$. Note that there is only one regression for all days in the warm season. The residual becomes:

$$X_i^{\text{res}} = X_i - \text{linreg}(\text{ONI})$$

This calculation is done separately for warm and cold seasons.

4. ENSO impacts are estimated through random forest regression. This approach is similar to approach #3, but with the linear model replaced by a non-linear random forest regression model $X = \text{RF}(\text{ONI})$. Similar to approach #3, ONIs of the current and previous 5 months are used. The residual is:

$$X_i^{\text{res}} = X_i - \text{RF}(\text{ONI})$$

From method #1 to method #4, the ENSO impact is considered with increased model complexities. By analyzing the MJO impact in these various types of residuals, we can reveal those MJO signatures that are insensitive to the ENSO removal methods.

Given previous studies suggesting a 5–9 days time lag for the MJO impact to propagate from the Indian Ocean and Pacific Ocean to the US West Coast (Hoskins & Karoly, 1981; Wang et al., 2023), here the connections between MJO and the hydroclimate response in the PS are examined with a 7-day lag, with sensitivity tests performed on varying lag durations. The frequencies of different MJO phases are not equal, and only 61% of days during 1981–2020 feature active MJO days (Figure S1 in Supporting Information S1). Therefore, in this study, the impact of MJO is examined using extended phases: When RMM_C is greater than 1 (i.e., active MJO period), the above-mentioned 8 phases are denoted as MJO 1–8; when RMM_C is smaller than 1 (i.e., inactive MJO period or non-MJO days), the corresponding 8 phases are denoted as RMM 1–8. The frequency of these 8 MJO and non-MJO phases is illustrated in Figure S1 in Supporting Information S1. Including the 39% non-MJO days allows a more comprehensive comparison of the MJO/non-MJO impact and identification of the key aspects of MJO (i.e., strength vs. phases) that control the PS hydroclimate conditions.

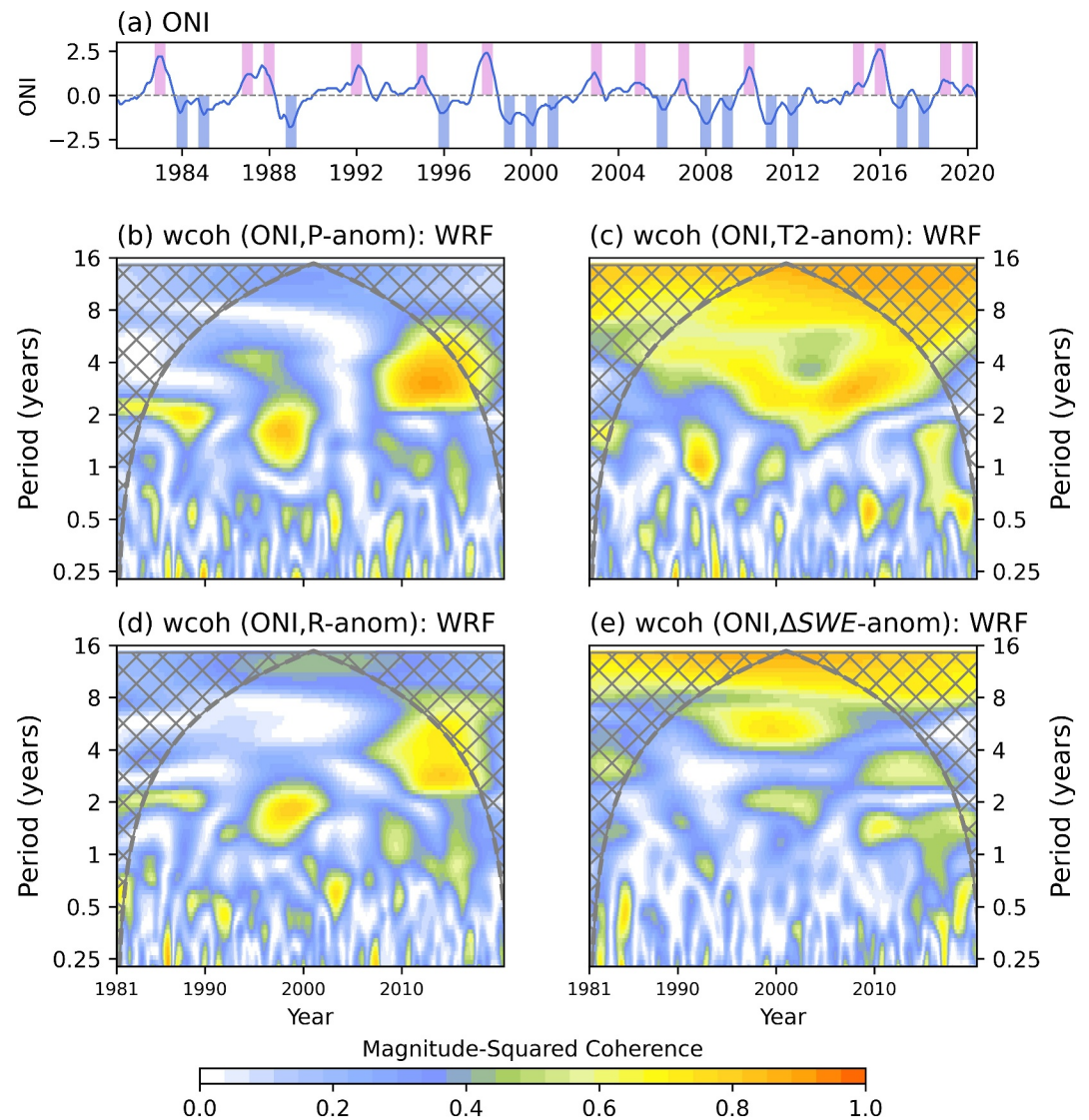


Figure 2. El Niño-Southern Oscillation condition and its correlations to Puget Sound hydroclimate conditions. Panel (a) shows the Ocean Niño Index (ONI) during 1981–2020. Panels (b–e) show the cross-spectrum of wavelet analysis between ONI and key hydroclimate variables: P , T_2 , R and ΔSWE . In panel (a), pink bands indicate the El Niño winters, and blue bands indicate La Niña winters, both of which are determined using the ONI anomalies. The wavelet analysis is conducted using standardized monthly series of each hydroclimate variables.

3. Results

In this section, we first present the ENSO impacts on the PS hydroclimate conditions, followed by an analysis of the MJO impacts. Then we analyze two types of hydroclimate extremes: snow droughts and ARs.

3.1. ENSO Impacts on Puget Sound Hydroclimate Conditions

Figure 2 illustrates the ENSO conditions and their correlation with the PS hydroclimate conditions represented by standardized monthly time series of key hydroclimatic variables (precipitation, temperature, ΔSWE , and runoff) during 1981–2020. Figure 2a illustrates the ONI time series, which is used to identify the El Niño (orchid) and La Niña (blue) cold seasons (October–March) when all of the 6 months between October–March are in the same ENSO phases. Figures 2b–2e show the magnitude-squared wavelet coherence between ONI and major hydroclimatic variables. It is worth noting that ENSO demonstrates a stronger connection to precipitation, temperature, and runoff after the year 2000 compared to the 1981–2000 period, with new correlations at a 4-year period

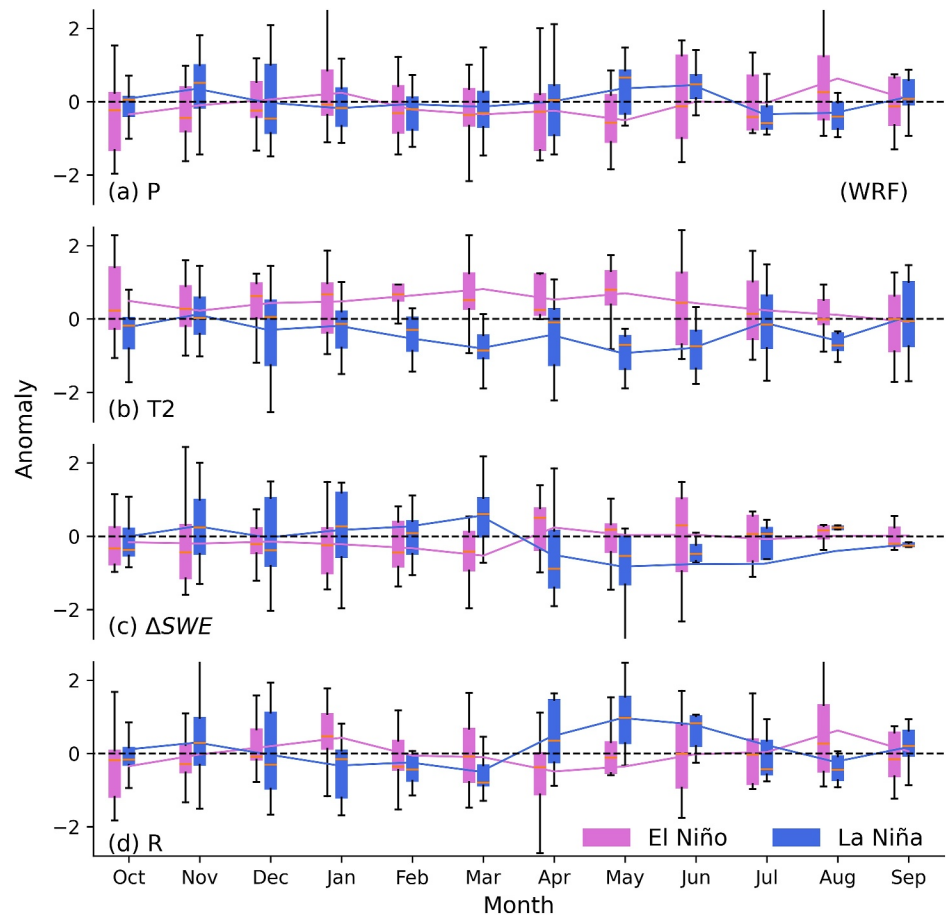


Figure 3. Response of hydroclimate conditions to El Niño-Southern Oscillation (ENSO) in each month. From top to bottom are the distribution of monthly precipitation (P), temperature (T_2), snowpack (ΔSWE), and runoff (R) grouped by ENSO phases. All values are standardized using the long-term mean and standard deviation of the same month. The raw monthly values of these variables are provided in Figure S2 in Supporting Information S1.

emerging after the year 2010. Most of the notable coherences show a periodicity of 1–4 years, though some longer-period coherence exists for temperature and snowmelt. This is reasonable as the original focus of ENSO is SST, which has an apparent influence on atmospheric thus regional thermal conditions.

Figure 3 shows the anomaly of monthly hydroclimate conditions as a function of ENSO conditions. In the cold season, El Niño leads to a delayed precipitation peak in January, compared to the La Niña precipitation peak in November–December (Figure 3a). This shifted precipitation peak, together with higher temperature (Figure 3b) causes a significant reduction in snow accumulation or more intense melt in the cold season. As reflected by the raw data (Figure S2c in Supporting Information S1), La Niña March still sees mostly snow accumulation, whereas El Niño March exhibits mostly loss in snowpack. Such an earlier melt, overlaid with increased precipitation in the middle of winter, leads to amplified runoff response in the late winter during El Niño (January–March). Figure 3d also shows the shifted peak timing of surface runoff during El Niño conditions in January as compared to the peak timing of May in La Niña phases. The raw data (Figure S2d in Supporting Information S1) also supports this finding, showing a significant runoff peak in January during El Niño, with a slightly higher magnitude than the peak during La Niña occurring in May. This shift of peak precipitation and runoff to late winter suggests a higher likelihood of reduced April 1st SWE driven by El Niño.

Aggregating these hydrological budgets at the seasonal scale across the region, Figure 4 illustrates their statistical responses to different ENSO phases. The April 1st SWE is significantly lower in El Niño cold seasons, whereas La Niña results in above-average SWE. Figure 4b compares the total SWE change during the cold season, and the response highly resembles the April 1st SWE contrast, suggesting that the initial SWE on October 1st plays a

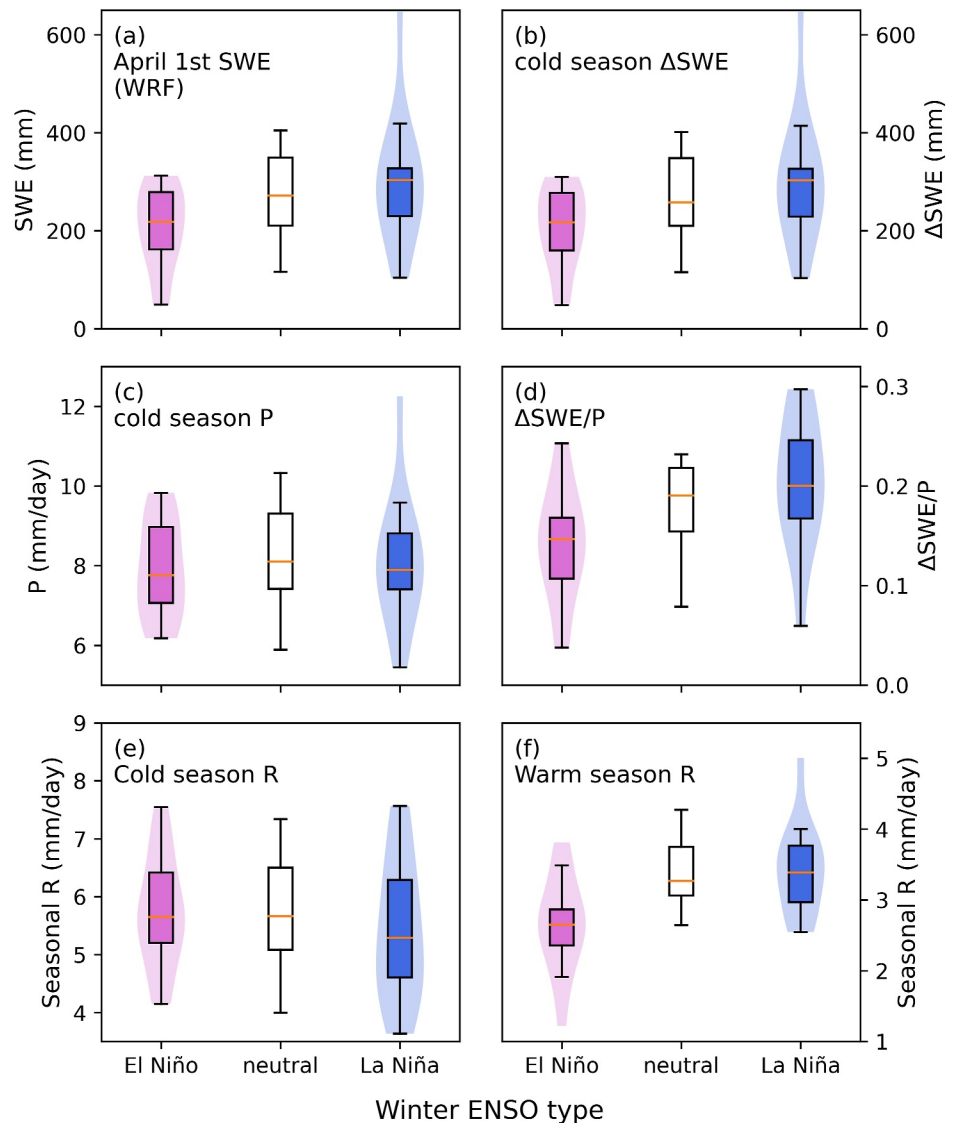


Figure 4. Impact of El Niño-Southern Oscillation on the seasonal surface water budget over the region. During the El Niño, neutral, and La Niña cold seasons, (a) the April 1st snow water equivalent (SWE), (b) the total change of seasonal SWE between October 1st and April 1st, (c) the seasonal mean precipitation, and (d) the fraction of cold season precipitation that is stored in snowpack by April 1st. Panels (e) and (f) show the seasonal mean runoff during cold and warm seasons, respectively.

limited role in the April 1st SWE. Figure 4c illustrates the seasonal precipitation response, where both El Niño and La Niña lead to similarly reduced precipitation compared to the neutral phase, though their peak timings differ as revealed in Figure 3. Driven by the significantly warmer conditions during El Niño, much less seasonal precipitation is stored in snowpack, leading to a notable reduction in Δ SWE/P. Overall, ENSO phases exhibit more control over the temperature and temperature-mediated hydrological processes such as snow accumulation and melting.

Given the strong dependence of warm season (April–September) runoff in the PS region on snowpack, warmer temperatures and delayed precipitation peaks during El Niño cold seasons indicate a modulated runoff split between cold and warm seasons. Figure 4 illustrates the cold season (Figure 4e) and warm season (Figure 4f) surface runoff. During El Niño cold seasons, seasonal runoff is comparable to neutral cold seasons and slightly higher than La Niña runoff. This is notable considering the reduced precipitation during El Niño cold seasons, as indicated in Figure 4c, highlighting a significant runoff contribution from warm-weather-induced snowmelt in the

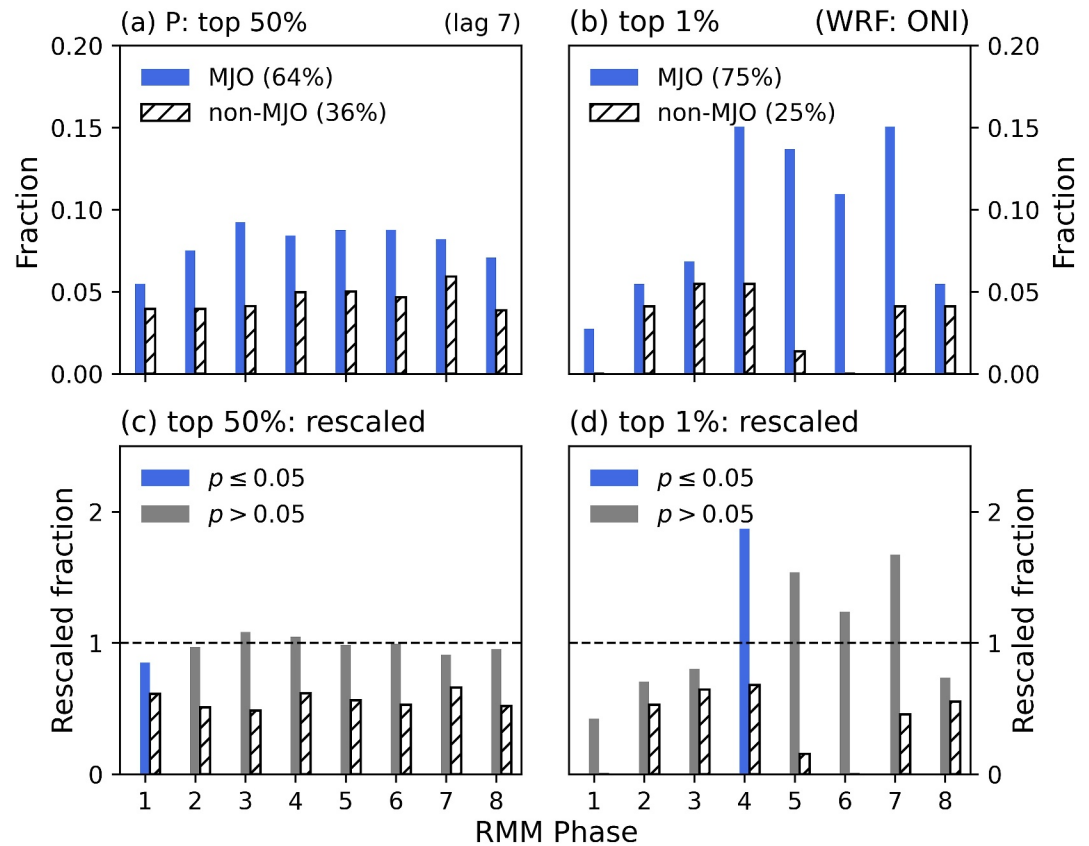


Figure 5. The distribution of the top 50% (i.e., greater than 50th percentile value) and top 1% (i.e., greater than 99th percentile value) precipitation days across Madden-Julian Oscillation (MJO)/non-MJO phases in the Puget Sound region during the cold season. Panel (a) shows the distribution of the top 50% P days across different real-time multivariate MJO indices phases during MJO (blue) and non-MJO (blank) periods. Panel (b) shows similar information but for the top 1% precipitation days. Panel (c) rescales the fraction in (a) with the MJO frequencies, and a value of 1 means they share similar frequencies (i.e., MJO does not enhance or inhibit the top 50% P days). Panel (d) shows similar information but for the top 1% P days. In panels (c) and (d), blue bars indicate statistical significance (in being different from 1) at $p = 0.05$ level.

El Niño cold season. In the warm season that follows an El Niño cold season, due to the significantly reduced April 1st SWE, there is a reduction in surface runoff. Further analysis suggests that the annual runoff under El Niño cold season is also lower than neutral or La Niña period (Figure S3 in Supporting Information S1). In brief, following El Niño cold seasons, total runoff in the same water year is reduced, yet a greater fraction is distributed in the cold season. This would cause increased challenges to summer water resource management.

3.2. Impacts of MJO on Puget Sound Hydroclimate Conditions

With the impact of ENSO on the hydrological conditions removed through linear regression, Figure 5 illustrates the impact of MJO activities on the PS precipitation condition during the cold season. The responses of temperature, snowmelt, and runoff are included in Figures S4–S6 in Supporting Information S1. Figure 5a shows the distribution of the top 50% (i.e., greater than 50th percentile value) days that approximate the climatology, highlighting that MJO phases 3–7 are related to a slightly higher frequency of top 50% precipitation days. Figure 5b shows the distribution of the top 1% extreme precipitation days in a similar way. There are ~73 days with top 1% cold season hydroclimatic extremes during 1981–2020, and these top 1% precipitation days occur notably more often around MJO phases 4–7. Given that MJO also exhibits uneven frequencies across different phases (Figure S1 in Supporting Information S1), a higher frequency shown in Figures 5a and 5b does not necessarily indicate a stronger connection between extreme precipitation days to certain MJO phases. Therefore, we rescale these frequencies with the MJO frequencies to derive the conditional probability $P(\text{hydroclimate}|\text{MJO phase})$, which is shown in Figures 5c and 5d. In these plots, bars higher than 1 indicate that

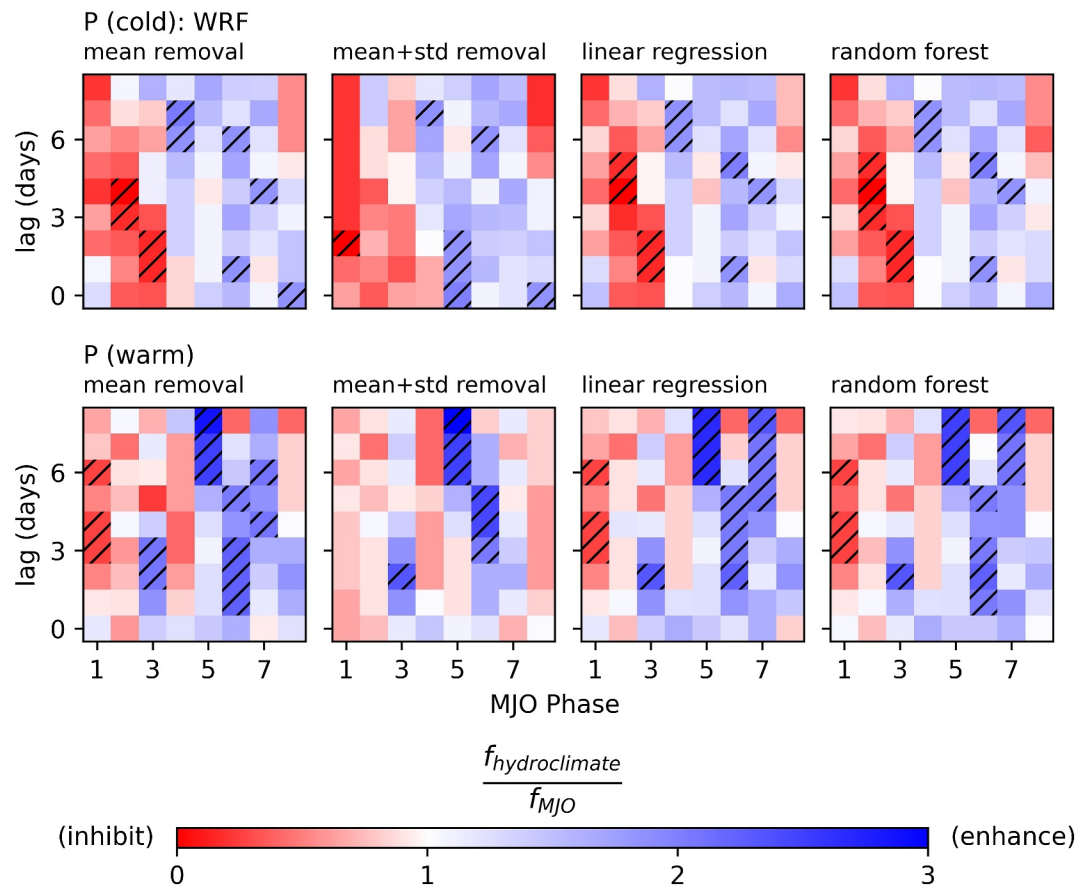


Figure 6. The Madden-Julian Oscillation (MJO) modulation on the top 1% precipitation days after the El Niño–Southern Oscillation impacts are removed. The results are shown separately for cold (upper) and warm (bottom) seasons. Values here are the ratio between the frequency of the top 1% precipitation days and MJO frequencies in each MJO phase (i.e., similar to Figure 5d). Hashed grids indicate statistical significance (in being different from 1) at $p = 0.05$ level.

a given MJO phase brings more hydrologic extreme events, whereas bars smaller than 1 indicate a decrease in the occurrence of hydrologic extreme events. Overall, MJO does not have strong modulation on the top 50% extreme days, whereas there are notable connections to the top 1% days: MJO phases 4–7 trigger more 1% extreme precipitation, with such enhancement from MJO phase 4 statistically significant at $p = 0.05$ level.

As described in the methods section, there are various methods of identifying and removing the ENSO impact on hydroclimate conditions. Figure 6 shows similar information as Figure 5d but now with various ENSO impact removal approaches and various lags considered. The 7-day lag results in the cold season “linear regression” panel resemble the results of Figure 5d. In the cold season, MJO phases 4–7 are more connected to the top 1% precipitation days, regardless of how ENSO signals are considered and removed. Such enhancement also exists in the warm season, though phase 3 also causes more extreme precipitation days at 1–3 days lags.

Figure 7 shows the MJO modulation on the top 1% temperature days. Different from the precipitation case where ENSO signal removal approaches exhibit negligible impact on the MJO modulations, here the MJO modulation is notably affected by how ENSO signals are removed. This is not surprising as ENSO’s impact is mostly on temperature, as described above. Under the simple approaches (of removing just mean or mean + std), MJO does not show statistically significant modulation on temperature. However, with a more comprehensive removal of the ENSO impact using linear and nonlinear (i.e., random forest) regression models, MJO phases 5–6 now show a significant enhancement in the top 1% temperature days. The linear and nonlinear results with ONI are similar, indicating that ONI is likely to have a linear control on PS temperature. The contrast between cold and warm seasons is also smaller in temperature than that in precipitation, with MJO phases 5–6 significantly enhancing extreme temperature days. Driven by the increased extreme precipitation days during phases 4–7 and increased

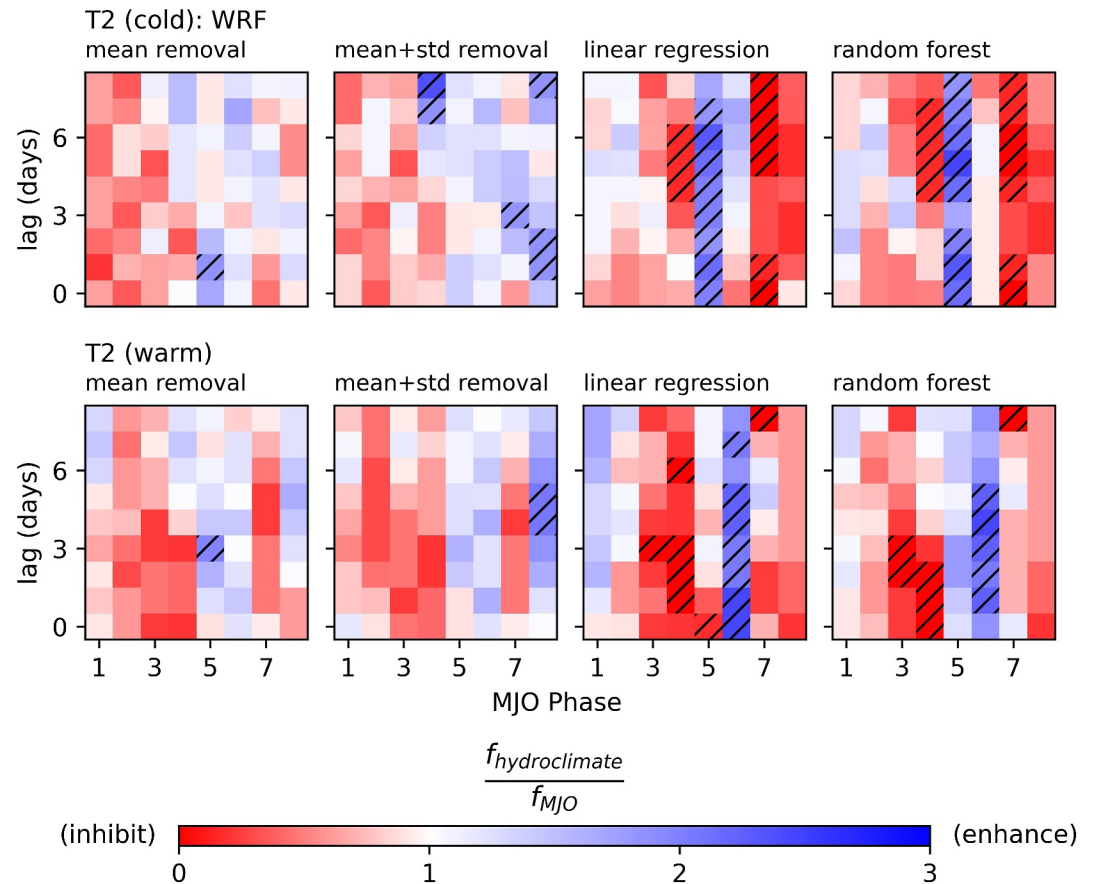


Figure 7. The Madden-Julian Oscillation modulation on extreme temperature after the El Niño-Southern Oscillation impacts are removed. This figure is similar to Figure 6 but for temperature.

extreme temperature days during phases 5–6, extreme snowmelt also occurs significantly more often during phases 6–7 in the cold season (Figure S5 in Supporting Information S1), resulting in more extreme runoff days (Figure S6 in Supporting Information S1). Meanwhile, extreme snowmelt and runoff responses show similar insensitivity to ENSO signal removal approaches, which is likely caused by the insensitivity of extreme precipitation. In brief, MJO exhibits notable controls on the hydroclimate extremes in the PS region, and its modulations on temperature, snowmelt (negative Δ SWE), and runoff are similar but slightly different from the modulation on extreme precipitation.

3.3. Snow Droughts

Snow drought is a significant driver of summer water shortage in the US West Coast. It is generally defined as periods when the snow condition is below the climatic average (Cooper et al., 2016; Hatchett et al., 2022; Huning & AghaKouchak, 2020). In this study, we focus on extreme snow drought, and a year is defined as a snow drought year if the April 1st SWE is below the 20th percentile. Figure 8 shows the cumulative distribution of annual April 1st SWE during 1981–2020. Based on this distribution, the bottom 20% of values, representing 8 years (2014, 2004, 1995, 1985, 1991, 2000, 2002, and 1992) with the lowest April 1st SWE, are defined as snow drought years (Figure 8a). Among these 8 years, El Niño, neutral, La Niña account for 4, 2, and 2 years, respectively. On the other end of the distributions, years with excess April 1st SWE (i.e., >80% percentiles) are either neutral or La Niña cold seasons. Snow drought can be caused by below-average precipitation in the cold season (i.e., dry snow drought) or above-average temperature that leads to less snow accumulation and/or earlier melt (i.e., warm snow drought) (Hatchett et al., 2022; Hatchett & McEvoy, 2018). Figures 8b and 8c further illustrate the co-distribution of mean precipitation and temperature in each cold season. Figure 8b shows the raw values of the mean precipitation and temperature, and Figure 8c shows their probability of exceedance in the 1981–2020 period (higher

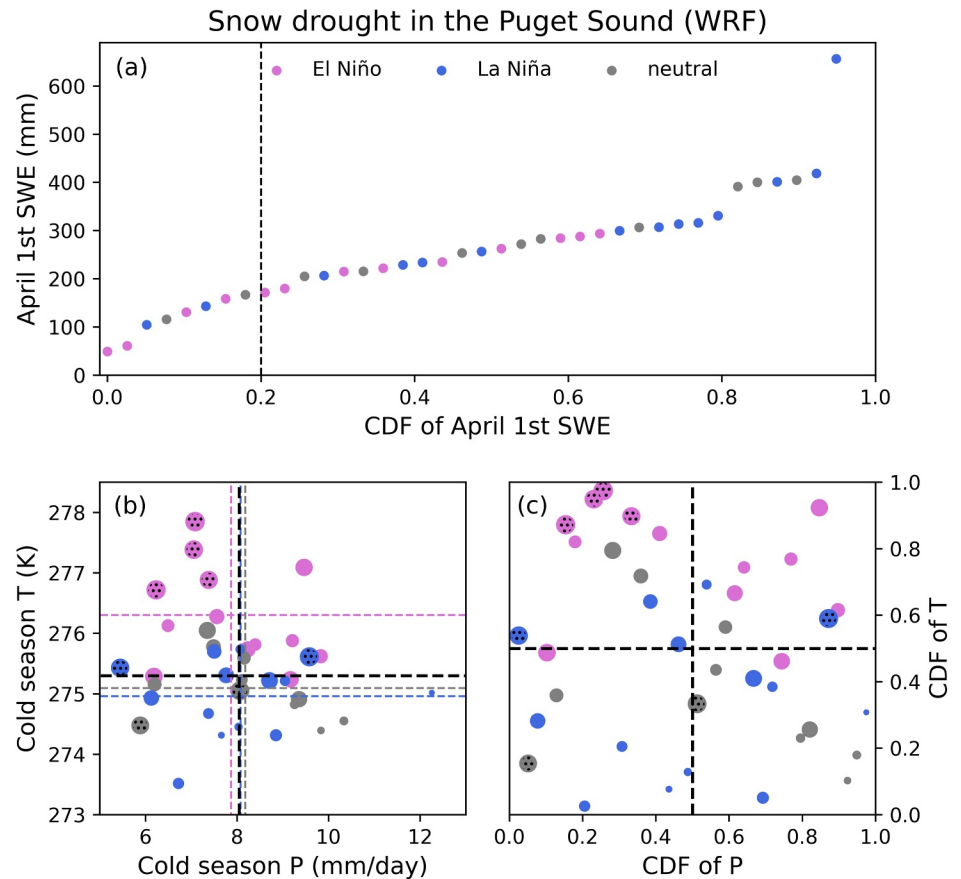


Figure 8. Snow drought and the relationship to El Niño-Southern Oscillation (ENSO): (a) the statistical distribution of the April 1st snow water equivalent (SWE) in the Puget Sound region. Snow drought years are defined as those with the bottom 20% April 1st SWE. (b) and (c) are the cold season precipitation and temperature condition in each year, in raw value and percentiles, respectively. The size of the dots denotes the rank number in panel (a), where larger dots denote lower April 1st SWE. The black dashed lines in panel (b) and (c) denote the 50th percentile levels, and the colored lines in panel (b) denote the mean precipitation and temperature under each ENSO phase. Dotted dots are the snow drought years. Across the plots, orchid, blue, and gray dots denote the El Niño, La Niña and neutral winters, respectively.

CDF indicates higher precipitation or temperature conditions). Snow drought events in the upper half of Figure 8c can be considered as warm snow droughts, and those in the left half are dry snow droughts. Most of the snow drought years (the dotted big dots in the two panels) feature high temperatures above the 50th percentile along with reduced precipitation, suggesting a combination of these two mechanisms in driving snow droughts in the PS region. Among the eight snow drought years, four El Niño droughts feature a very high temperature anomaly along with a less extreme precipitation anomaly, suggesting the dominance of the warm snow drought mechanism. In comparison, the two neutral events are both dry snow droughts, and the two La Niña droughts are either dry snow droughts or mild warm snow droughts.

Given the notable elevation range in the PS region, it is necessary to also examine the snow drought as a function of elevation (Figure 9). Eight local snow droughts are identified at each 6-km grid, and their distributions across ENSO phases are illustrated in Figures 6a–6c. Overall, local snow droughts are dominated by El Niño conditions, which resembles the PS-aggregated analysis. The elevation dependency of these contributions is summarized in Figure 9d, which reveals a shift from more El Niño-induced snow droughts at lower elevations (more sensitive to temperature) to more La Niña-induced snow droughts at higher elevations (more sensitive to precipitation). Meanwhile, the contribution of the neutral phase stays similar across the elevation range.

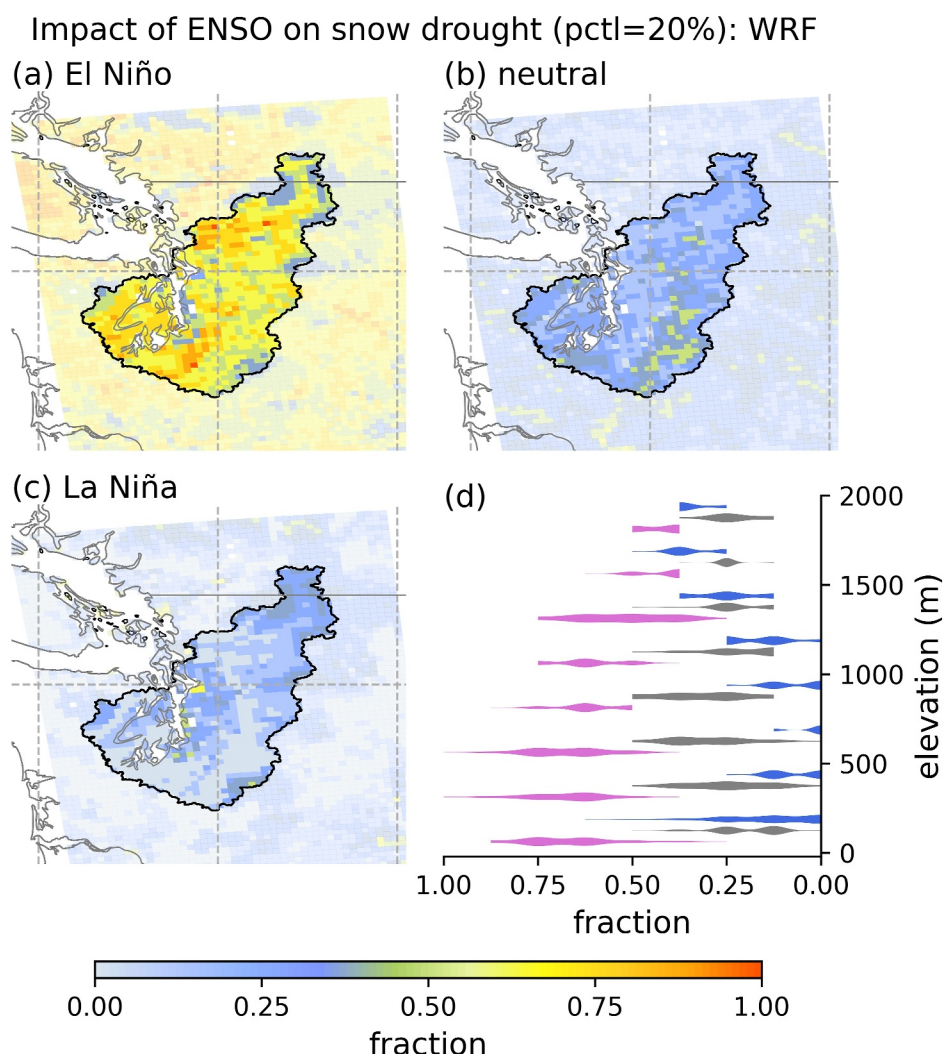


Figure 9. Response of local snow drought to El Niño-Southern Oscillation. The identification of local snow drought at each grid is the same as in Figure 8a but is based on the grid-level April 1st snow water equivalent records. Panels (a–c) show the fraction of snow droughts that fall into El Niño, neutral, and La Niña cold seasons, respectively. Panel (d) illustrates these fractions as a function of surface elevation (orchid–El Niño; gray–neutral; blue–La Niña).

3.4. Atmospheric Rivers

Since ARs bring most of the cold season extreme precipitation to the PS region, Figure 10 examines the distribution of PS-aggregated extreme IVT, which roughly approximates the occurrence of ARs (as many AR tracking algorithms use the 85th percentile IVT threshold). Similar to Figure 5, positive RMM2 (phases 3–6) leads to more extreme IVT, which results in a higher occurrence of extreme IVT during MJO phases 6–7 in the cold season, with the enhancement in Phase 6 statistically significant. The IVT response to MJO is similar to the P response (Figure 5), but differences are noticeable. Such differences may be due to: (a) the local topographical impact on P , which depends on the AR orientation relative to the mountain ranges and hence, the top 1% IVT may or may not lead to the top 1% P ; (b) the separate ENSO impact removal in P and IVT can lead to differing percentiles of P and IVT residuals on the same day.

Figure 11 shows the MJO modulation on IVT, which suggests a higher occurrence of the top 1% IVT days (which are very likely AR days) during MJO phases 6–8. This modulation is robust regardless of how ENSO signals are removed. Meanwhile, the MJO modulation on IWV is sensitive to the ENSO signal removal approaches (Figure S9 in Supporting Information S1). Such contrasts can be explained by the wind contributions to IVT, which is less affected by ENSO activities.

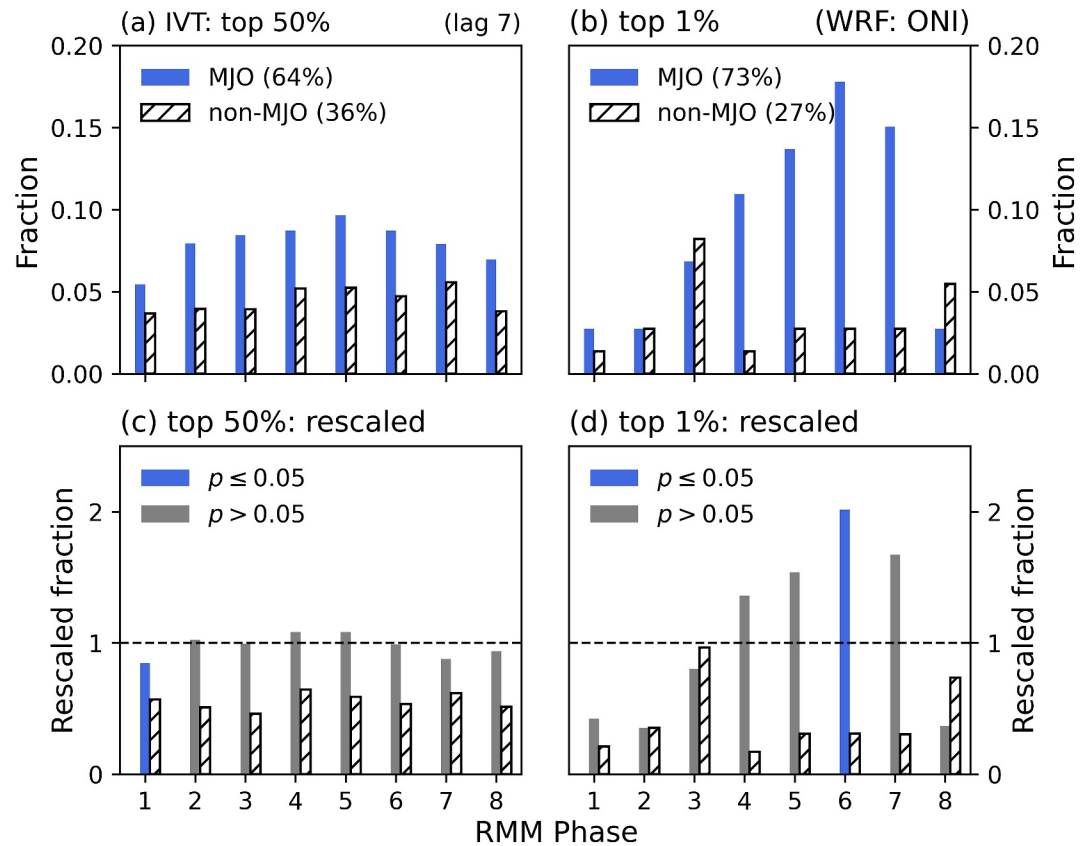


Figure 10. The distribution of the top 50% and top 1% integrated vapor transport (IVT) days across Madden-Julian Oscillation (MJO)/non-MJO phases in the Puget Sound region during the cold season. This figure is similar to Figure 5 but for IVT.

4. Discussions

4.1. ENSO and MJO Impacts on Puget Sound Hydroclimate Condition

The ENSO or MJO modulations on the western US hydroclimate have been found in previous observational and modeling studies, with their interaction also playing an important role (Arcodia et al., 2020; Lin et al., 2010; Moon et al., 2011; Yang et al., 2018). Chen et al. (2016) analyzed the ENSO modulation on MJO behaviors, whereas Moon et al. (2011) found that MJO teleconnection in North America is enhanced by El Niño. Arcodia et al. (2020) found that MJO can override the interannual ENSO signal during a specific ENSO phase, leading to opposite precipitation responses. The latter study suggests that MJO activities have a greater role in influencing extreme precipitation in the US. This is consistent with our findings on the similar seasonal precipitation between El Niño and La Niña during cold seasons (as depicted in Figure 4), when extreme precipitation occurs more frequently in this region. Further, this can explain the difficulty in using El Niño alone for seasonal hydrological predictions, which might benefit from an ENSO-MJO joint prediction (Cohen, 2016). In this study, we also took a hierarchical approach that separates the ENSO impact at monthly scales to reveal the additive MJO signals to facilitate such joint predictions.

ENSO is known to strongly modulate the hydroclimate conditions in the US West Coast, with differing impacts on the PNW region and California. For example, precipitation responds to ENSO differently between PNW and California, which suggests ENSO might exhibit better predictive skills at local scales than at regional/continental scales (Patricola et al., 2020). Such contrasts might be caused by a combination of different climatic factors (e.g., colder vs. warmer climate; different dominating precipitation systems) and different land features. For example, the relatively lower elevation of the Cascade Range compared to the Sierra Nevada can cause some opposite responses in snowpack under the same temperature perturbations (Chen et al., 2021). With a relatively colder climate compared to California watersheds, the PS region is a useful testbed to highlight such contrasting

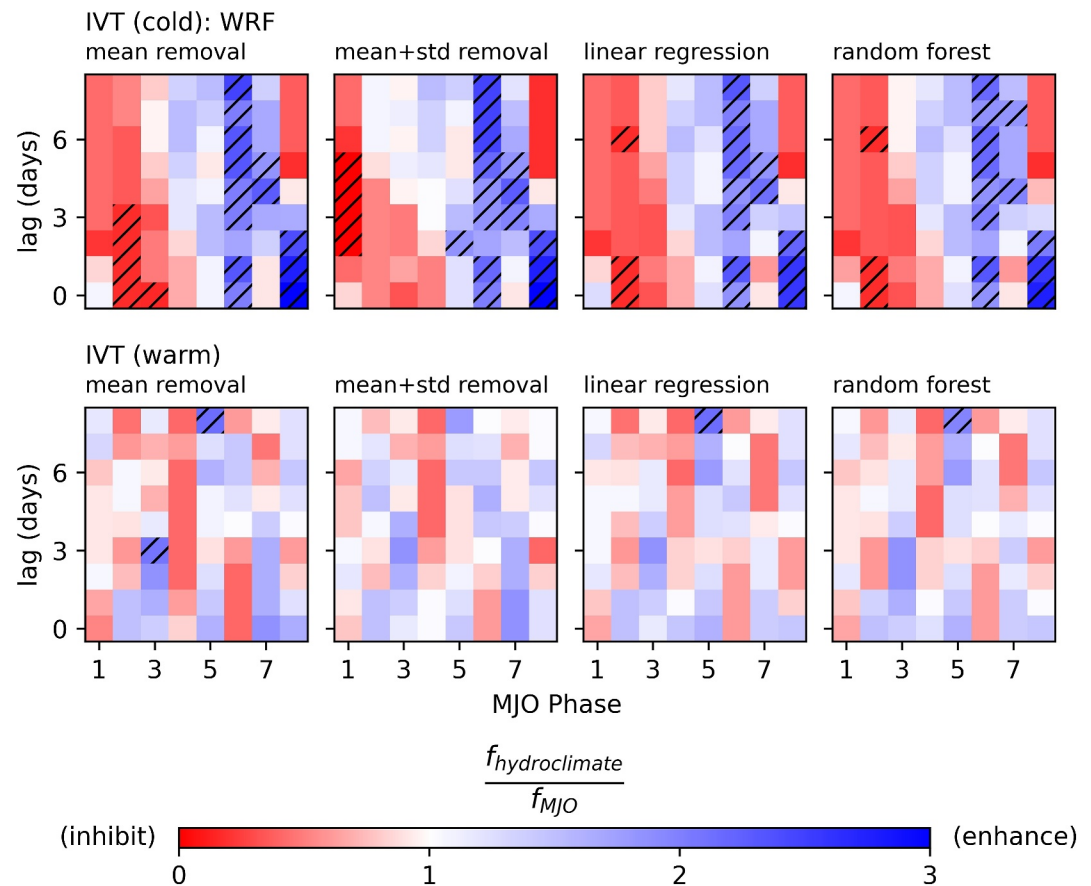


Figure 11. The Madden-Julian Oscillation modulation on extreme integrated vapor transport (IVT) conditions after the El Niño-Southern Oscillation impacts are removed. This figure is similar to Figure 7 but for atmospheric river IVT.

responses and understand the dependency of ENSO response on the local climate. The reduced PS regional cold season P (Figure 3c) as compared to the generally increased P in the PNW region (e.g., Patricola et al., 2020) also highlights the spatial scale-dependency of ENSO impact, as well as the roles of local geographical background (e.g., land-sea contrast, topography) in determining the fine-scale ENSO signature.

MJO is also widely analyzed for its impact on various environmental conditions (Yu & Ginoux, 2021). Given its notable impacts beyond the water cycle, such as on various ecological processes (Bai et al., 2023), an in-depth knowledge of MJO's hydrological impact is fundamental to understanding its multifaceted role in the Earth system. Extending the previous analyses that mainly focused on active MJO periods, this study examined both MJO and non-MJO periods. As shown in Figures S4 and S10 in Supporting Information S1, the RMM conditions during non-MJO can also exhibit some predictive power on PS hydroclimatic extremes. Figure S10 in Supporting Information S1 suggests that RMM phases 4–7 demonstrate consistent predictive power during MJO (blue bars) and non-MJO periods (hatched bars). This response highlighting the impacts of MJO phases 4–7 differs from other studies that show a symmetric impact of MJO phases in other regions (e.g., increased precipitation during phases 6–7 and reduced precipitation during phases 2–3). The lack of symmetry in the MJO phases in the PS region may be related to the impact of topography, which asymmetrically alters the precipitation response to changes in the winds impinging on the mountains. During phases 6–7, MJO rainfall moves eastward over the western Pacific; enhanced convection over the western Pacific can excite Rossby waves that modulate the frequency of extreme events in the northeast Pacific coast. During non-MJO periods, RMM phase 1 (cold season temperature), phase 2 (warm season snowmelt and IWV), phase 3 (warm season snowmelt and IVT), and phase 8 (warm season IVT and IWV) also exhibit some predictive power. Therefore, information outside the active MJO periods is beneficial for a more comprehensive understanding of their hydroclimate impacts. Meanwhile, how

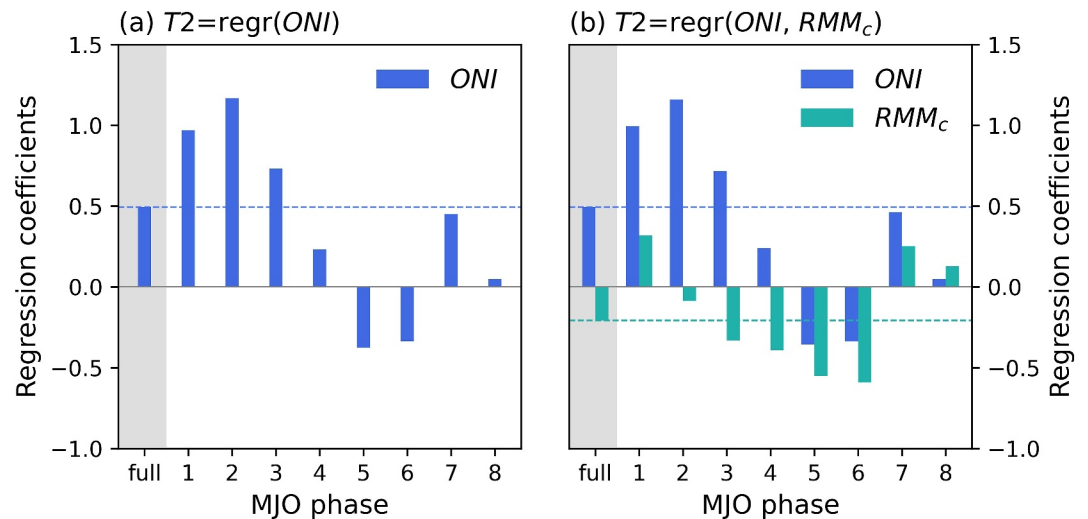


Figure 12. Linear regression experiment. Panel (a) shows the single-variate linear regression between daily T2 and the Ocean Niño Index (ONI) in the same month. The “full” bar denotes the regression using all the daily data, and the subsequent bars show the regression where only the specific days in the given Madden-Julian Oscillation phases are included. Panel (b) shows similar information but for multi-variate linear regression between daily T2 and: (1) ONI in the same month (blue bars); (2) RMM_c with a 7-day lead time (green bars).

well models simulate inactive/non-MJO activities should also be considered in evaluating MJO predictions (Kim et al., 2018; Savarin & Chen, 2022).

The MJO modulation on PS hydroclimate extremes also highlights the variability in the MJO impacts at fine scales. Regarding large-scale extremes such as ARs, Guan et al. (2012) found that MJO phase 6 is more relevant to the AR activities in California, whereas Zhou et al. (2021) revealed increased AR activities in MJO phases 6–7. Hagos et al. (2021) showed that by enhancing the background eastward moisture transport, MJO phases 6–7 favor landfalling ARs in the western US. These findings are consistent with our analysis in the PS region. Regarding more localized extremes, Schreck et al. (2013) found that MJO phase 5 usually leads to warm anomalies over eastern North America, whereas we reveal that phases 5 and 6 are both more relevant to the PS temperature anomalies (Figure S4 in Supporting Information S1). California snowpack accumulation reduces significantly during phase 8 (Guan et al., 2012), which is different from the dominance of phase 6 on snowmelt in PS. These differences suggest that the MJO impacts on local extremes are more diverse and may be affected by the strength and spatial distribution of the Rossby waves excited by MJO-induced enhanced convection. In this sense, analyzing the impact of MJO on regional weather patterns (instead of local extremes) may provide a more coherent understanding of MJO modulation at regional scales, with local land-atmospheric interactions isolated from the large-scale modulations (S. Zhou et al., 2012).

4.2. Impact of ENSO-MJO Interaction

MJO is known to interact with ENSO (Arcodia et al., 2020; Tang & Yu, 2008), so it is necessary to quantify the impact of such interaction on the presented results. A set of single- and multi-variate regressions was performed to relate daily hydroclimate conditions to ENSO (ONI) and RMM (RM12) in both active and inactive MJO periods. Taking a similar approach to those in Arcodia et al. (2020), we group days by MJO activity and then examine their statistical connection to ENSO. These regressions are separately established during each MJO period, and their regression coefficients are shown in Figure 12. A single regression (“full” in Figure 12) using all the days is also established as a baseline. Figure 12a shows the single-variate regression to just ONI. Compared to the baseline “full” regression, individual regressions in each MJO period show varying regression coefficients, and their pattern is similar to Figure 7. Figure 7 suggests that MJO phases 1–4 inhibit temperature and phases 5–6 enhance temperature. Similarly, in Figure 12a coefficients for ENSO are larger during MJO phases 1–4 and smaller than baseline during MJO phases 5–6. This suggests a consistency between our “ENSO impact removal first” approach and the approaches used in other studies. Figure 12b shows the multivariate regression using ONI and RMM_c, and the coefficients for ONI are highly similar to Figure 12a, suggesting that the interaction of ENSO and MJO does

not have notable impacts on the regression. Also, the enhancement from MJO phases 5–6 is clearly reflected by the increased regression coefficients of RMM_c during phases 5–6.

4.3. Impact of Historical ENSO and MJO Changes

Previous studies have shown a changing ENSO cycle variability after the turn of the 21st century (Hu et al., 2020; McPhaden, 2012; Tan et al., 2024). This change, related to the strengthening of zonal SST gradient along the equator as well as a shift from eastern Pacific El Niño to central Pacific El Niño, is likely to affect the ENSO teleconnection to the North American climate (J. Yu & Zou, 2013). Meanwhile, the MJO lifecycle has also been affected by the past warming, which can potentially also affect its teleconnection to the US West Coast hydroclimate (Roxy et al., 2019). To examine the potential impacts of these ENSO and MJO changes, we performed a comparison by splitting our analysis into the 1981–2000 and 2001–2020 periods. The results are presented in Figures S11, S12 (ENSO) and S13, S14 (MJO) in Supporting Information S1. The ENSO impacts in 2001–2020 are more consistent with the results based on the longer 1981–2020 period (Figure 4) showing the enhanced snowmelt in the El Niño cold season (Figure S12d in Supporting Information S1 and Figure 4d), and the notably reduced warm season runoff following the El Niño cold season (Figure S11f in Supporting Information S1 and Figure 4f), whereas the El Niño–La Niña contrast in 1981–2020 is less pronounced compared to 2001–2020 (e.g., Figure S11d and S11f compared to S12d and S12f in Supporting Information S1). After removing the ENSO signals with linear regressions in each period, Figures S13 and S14 in Supporting Information S1 illustrate the runoff response to the eight MJO phases. Madden-Julian Oscillation impacts also slightly differ between the two periods: a notable enhancement of cold season top 1% extreme runoff occurrence exists during MJO phases 4–7 with a 3–9 days lag in 1981–2000, in contrast with phases 4–7 with a 1–4 days lag in 2001–2020. In the warm season, the top 1% runoff occurrence is less affected by the specific MJO phases in 1981–2000 but is enhanced during phases 5–8 in 2001–2020, the latter is consistent with the 1981–2020 results (Figure S8 in Supporting Information S1). Overall, ENSO and MJO impacts during 2001–2020 are more similar to the overall 1981–2020 impacts, suggesting their intensification in the recent decades.

4.4. Robustness Check

To check the robustness of the presented ENSO/MJO modulations on the PS hydroclimate, multiple sensitivity experiments have been conducted:

1. To check the dependency on input data, we repeated the analysis using ERA5-land reanalysis product. The results (Figures S15–S18 in Supporting Information S1) well resemble the presented WRF-based findings (Figures 3, 4, 6 and 7), suggesting some skills of the WRF simulations in capturing the ENSO/MJO impacts on the PS hydroclimate and that the conclusions are independent of the data choice;
2. The 7-day lag used to determine the MJO hydroclimate impact is perturbed between 0 and 9 days, and the results based on some of these lags are included in Figures 6, 7 and 11, and Figures S7–S9 in Supporting Information S1. The extended analyses indicate that the relationship between MJO phases 6–7 and the PS top 1% hydrologic extremes still holds with a 0–9 days lag. More broadly, positive $RMM1$ (i.e., phase 5–8) possesses predictive skills with 0–9 days lags in the cold season;
3. Different approaches to identify and remove ENSO signals are examined, varying from simple mean removal to non-linear random forest regressions. The MJO modulations on daily hydroclimate extremes stay robust regardless of these ENSO signal removal approaches except for temperature, which is known to be more relevant to ENSO.

The presented ENSO/MJO impacts on the PS hydroclimate anomalies or extremes can be seen as part of ENSO/MJO teleconnections. Our analysis suggests the dominant roles of these teleconnections in the hydroclimate of this region, even in the context of local drivers such as intense urbanization and unique coastal mountain topography. Therefore, the ENSO and MJO teleconnections are important sources of predictability of hydro-meteorology and extremes in the PS basin at subseasonal-to-interannual timescales, and such teleconnections can provide useful metrics for climate model evaluation. The additive approach in separating the ENSO signal from the MJO analysis means the revealed MJO impacts can be directly added to the existing ENSO-based predictions. Meanwhile, the correct representation of the MJO hydroclimate signature in the PNW region requires realistic MJO teleconnection, which further requires that both the MJO representation and the basic hydroclimate conditions are reasonably simulated in global climate models (Henderson et al., 2017). Such diagnosis can serve as

part of the effective constraint or metrics for selecting models for forecasting and projection of MJO activities and MJO-induced extreme events such as extreme precipitation (P. V. V. Le et al., 2021; Liang et al., 2022).

5. Conclusions

In this study, we used regional high-resolution climate model output to provide a comprehensive evaluation of the ENSO/MJO impact on the hydroclimate conditions and extremes in the PS region. Our major findings are summarized as follows:

1. ENSO exhibits significant modulation on the regional temperatures and temperature-mediated hydrological processes. Although both El Niño and La Niña reduce the cold season precipitation, higher temperature during El Niño causes less snow accumulation or more rapid snowmelt, leading to significantly reduced April 1st SWE. Meanwhile, El Niño cold season triggers more surface runoff in the cold season but less runoff in the subsequent warm season, presenting a greater challenge for water resources during the low flow season.
2. Among the 8 snow droughts in the PS region, 4 snow droughts (50%) occur during El Niño cold season in the form of intense dry and warm snow drought. Two snow droughts (25%) occur in neutral cold season as dry snow droughts, whereas 2 droughts (25%) occur in La Niña cold season as mild warm droughts.
3. MJO activities are more relevant to hydroclimatic extremes in the region. A positive RMM2, which defines MJO phases 5–8, triggers more extreme precipitation, snowmelt, thus surface runoff extreme days in both cold and warm seasons. Among all the MJO phases, phase 6 is especially connected to hydrological extremes in the PS during the cold season: it accounts for more extreme precipitation, higher temperature, extreme snowmelt, and thus extreme surface runoff days. The MJO modulation on temperature extremes is notable even after the ENSO signals are removed.
4. ARs affecting the PS region occur more during MJO phases 5–8 (or positive RMM2) during the cold season.

This study identifies the El Niño phase and MJO phase 6 (and 7) as two useful predictors of the hydroclimate extreme in the PS region. MJO phases 6 and 7 both feature strong RMM2, suggesting the notable control of RMM2 on PS hydroclimate extremes. They may potentially have greater predictive power when combined with other climate indices or information. The physical mechanisms behind these connections are worthy of further investigation. For example, Chen et al. (2023b) found that heavy precipitation, warmer temperatures, snowmelt (including rain-on-snow), and runoff can each be tied to different types of weather patterns that are well connected to ENSO and MJO. Future studies may further verify and understand the ENSO/MJO relationships with surface hydroclimate conditions in the PS and other regions using simple models such as stationary wave models to elucidate the ENSO and MJO atmospheric teleconnections and weather patterns. Meanwhile, future studies can extend these impacts to the societal and engineering implications, which can potentially improve regional water and energy management. Given the limited samples of ENSO events in the study period and the ENSO diversity, future studies of the ENSO regional hydroclimate impacts may benefit from analysis of longer climate simulations combined with observations to establish more robust regional signatures and the underlying processes.

Data Availability Statement

Ocean Niño Index data are obtained from NOAA CPC (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). RMM data are obtained from the Australian Bureau of Meteorology (<http://www.bom.gov.au/climate/mjo/>). All the data and results from this study are available at Zenodo (Chen et al., 2023a, or Zenodo: <https://doi.org/10.5281/zenodo.8201861>).

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