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Key Points:

- Anthropogenic warming will increase the co-occurrence of extreme warm northeast Pacific and dry California conditions
- Controlling for trends, California drought co-occurs more frequently with marine heatwaves in the Gulf of Alaska but not in the California Current
- Shifts in distributions of associated sea surface temperature and soil moisture anomalies are consistent with changes in co-occurrences

Supporting Information:

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

Correspondence to:

H. Shi,
daisyhuishi@faralloninstitute.org

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Co-occurrence of California Drought and Northeast Pacific Marine Heatwaves Under Climate Change

Hui Shi¹ , Marisol García-Reyes¹ , Michael G. Jacox^{2,3} , Ryan R. Rykaczewski⁴ , Bryan A. Black⁵, Steven J. Bograd² , and William J. Sydeman¹

¹Farallon Institute, Petaluma, CA, USA, ²Environmental Research Division, NOAA Southwest Fisheries Science Center, Monterey, CA, USA, ³NOAA Physical Sciences Laboratory, Boulder, CO, USA, ⁴Ecosystem Sciences Division, NOAA Pacific Islands Fisheries Science Center, Honolulu, HI, USA, ⁵Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ, USA

Abstract Motivated by the uncommon yet highly impactful co-occurrence of California (CA) drought and a northeast Pacific (NEP) marine heatwave (MHW) during 2013–2016, we examined such compound extremes in Coupled Model Intercomparison Project Phase 6 projections, comparing the end of the 21st century with the preindustrial period, and separating effects of long-term trends from interannual variability. Here, we show that long-term trends due to anthropogenic climate change will dramatically increase the co-occurrence of extreme dry CA and warm NEP conditions. When trends are removed, the co-occurrence of CA drought and Gulf of Alaska (GOA) MHW will increase while the co-occurrence of CA drought and California Current (CC) MHW remains unchanged. A stronger link between GOA MHW and subsequent CC MHW as well as decreased persistence in CA drought are also projected under anthropogenic warming. These frequency changes are consistent with shifts in distributions of sea surface temperature and soil moisture anomalies associated with individual extremes.

Plain Language Summary From 2013 to 2016, an exceptional California drought co-occurred with extreme northeast Pacific (NEP) marine heatwaves (MHWs), leading to significant social-economical-ecological impacts. The evolution of this event led us to examine California drought co-occurring with MHWs in the California Current (CC) and in the Gulf of Alaska (GOA), as well as other relevant sequential events. To distinguish effects of long-term trends from year-to-year variability, we separately examine frequency changes in event occurrence with and without trends. Here, we show that under global warming, co-occurrence of extreme warm NEP ocean and dry California conditions will become dramatically more frequent by the end of the 21st century. This increasing frequency of co-occurrence is strongly driven by anthropogenic warming and drying trends. If these trends are removed, co-occurrence between GOA MHWs and California drought will increase, but co-occurrence of CC MHWs and California drought remains unchanged relative to cases with no warming. We also found stronger links between MHWs in the GOA and subsequent MHWs in the CC, and reduced frequency of persistent California droughts. Understanding changes not just in extremes but in their co-occurrence is critical to projecting the future impacts of multiple ecosystem stressors.

1. Introduction

From 2013 to 2016, the northeast Pacific (NEP) experienced unprecedented marine heatwaves (MHWs; Bond et al., 2015; Gentemann et al., 2017) concurrent with a record-breaking drought in California (Griffin & Anchukaitis, 2014). While California has experienced prior droughts and the NEP has experienced prior MHW (Cook et al., 2015; Jacox et al., 2016), their co-occurrence, specifically during hydrological years 2013–2015, was especially notable. These extreme events resulted in devastating economic and ecological consequences across both marine and terrestrial realms (e.g., Lund et al., 2018; Peterson et al., 2017; Santora et al., 2020). For example, a mass mortality event of nearly 1 million seabirds was recorded from Baja California to the Bering Sea (Piatt et al., 2020), while persistent harmful algal blooms along the US West Coast caused high marine mammal mortality and an estimated economic loss of ~\$170 million due to the closure of the Dungeness crab fishery (McCabe et al., 2016). Meanwhile, drought led to groundwater overdraft, land subsidence, loss of domestic water supply in the Central Valley (Bee, 2015; U.S. Geological Survey, 2015), and multi-billion dollar agricultural losses from reduced farmland productivity and additional groundwater

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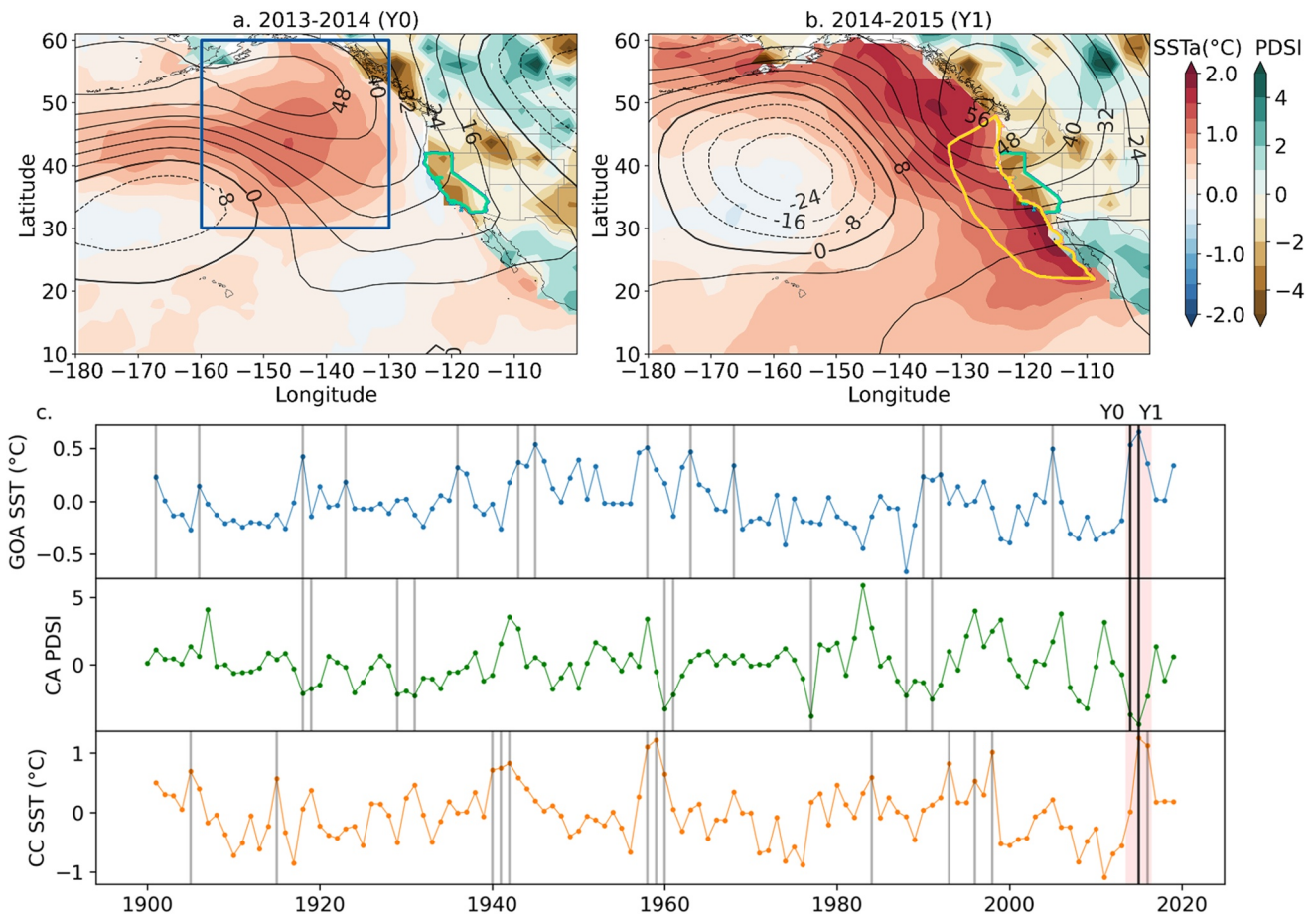


Figure 1. The co-occurrence of the northeast Pacific marine heatwave (MHW) and California (CA) drought during the hydrologic years (July–June) of (a) 2013–2014 (Y0) and (b) 2014–2015 (Y1). Contours are the 500 hPa geopotential height anomalies (m) relative to the 1981–2010 climatologies. Negative PDSI values indicate drought conditions. Outlined are regions of interest: open ocean Gulf of Alaska (blue), California Current Large Marine Ecosystem (orange), and the State of California (green). (c) Co-occurrence of NEP MHW and CA drought in instrumental records (1900–2019). Time series are calculated within the domains outlined in panels (a) and (b) with long-term trends removed. Gray bars indicate MHW or drought, identified with thresholds in 30-year rolling windows. Black bars mark the Y0 and Y1 co-occurrences of drought and MHW during the 2013–2016 event (light red column).

pumping costs (Howitt et al., 2014, 2015; Medellín-Azuara et al., 2016). This severe, extended drought has also been linked to the death of more than 100 million trees (USDA Office of Communications, 2016), which exacerbated the devastating 2015 fire season (Capital Public Radio, 2015), and remains a fuel hazard that continues to threaten public safety. At the same time, reduced streamflows and anomalously warm water threatened the survival of fish species including juvenile winter-run Chinook salmon and coho salmon (Bee, 2015; Jacox et al., 2018; San Francisco Chronicle, 2015). Although ~\$120 million was allocated for drought emergency ecosystem support from state and federal sources, lack of preparation compounded the effects of the drought in aquatic environments (Hanak et al., 2015).

Given these severe biotic and societal consequences, there is an urgent need to understand the potential for “compound extremes” (Zscheischler et al., 2020), in particular, (a) how frequent the co-occurrence of these events is, and (b) whether the frequency of co-occurrence might change in the future. During the 2013–2016 event period, persistent upper troposphere ridge events over the Gulf of Alaska (GOA) had prevented synoptic disturbances from reaching the West Coast and led to California’s extreme drought (Swain et al., 2014; Wang et al., 2014; Figures 1a and 1b). Surface high-pressure anomalies associated with the ridge weakened the surface winds, decreasing Ekman advection of cold water from the north, and reduced wind-generated upper ocean mixing, allowing a buildup of heat that caused the MHW in the central portion of the GOA during 2013–2014 (Y0) (Bond et al., 2015; Figure 1a). Following the open-ocean GOA warming in 2013–2014, the coastal GOA as well as coastal portions of the California Current (CC) experienced strong

warming in 2014–2015 (Y1), and the CA drought intensified (Figure 1b). The co-occurrence of CA drought and NEP MHW of these magnitudes with reference to modern climatology (1981–2010) had not previously been observed in the 20th century (Figures S1 and S2). Though the amplitude of warm and dry anomalies relative to a fixed climatology could be attributed in part to long-term trends (Figure S2), detrended time series indicate that CA drought has co-occurred only once with GOA MHW (1917–1918) and once with CC MHW (1959–1960) in the instrumental record (Figure 1c). Furthermore, the series of consecutive co-occurrences during the 2013–2016 event is unprecedented (Figure 1c), prompting questions of a possible link to climate change that extends beyond warming trends.

Typically, low precipitation years and drought in California are associated with a strong winter North Pacific High (NPH; Black et al., 2018) which, in late winter and spring, also drives strong alongshore winds, coastal upwelling (Huyer, 1983), and cold sea surface temperature (SST) anomalies in adjacent nearshore marine ecosystems. In contrast, an anomalously weak NPH and enhanced Aleutian low were associated with the recent 2019 NEP MHW (Amaya et al., 2020). The 2013–2016 event was notable in that the anomalous high-pressure system co-existed with warm ocean conditions during 2013–2015. Similar high-pressure associated MHW-drought co-occurrence has been observed recently in the South American sector as well (Rodrigues et al., 2019). MHW in CC has often been associated with El Niño events, which drive CC temperature through remote ocean forcing and atmospheric teleconnections (Jacox et al., 2015, 2016). However, El Niño events tend to enhance, not reduce, rainfall over California (Figure S3), especially southern California, through the Pacific North America teleconnection (Ropelewski & Halpert, 1987; Wallace & Gutzler, 1981), and their association with negative anomalies in NEP atmospheric pressure (Fiedler & Mantua, 2017). The absence of a fully developed El Niño event during the initiation (2013–2015) of the 2013–2016 NEP MHW (Di Lorenzo & Mantua, 2016; Jacox et al., 2018) likely facilitated the co-occurrence of NEP warming and CA drought. Thus, the co-occurrence of NEP MHW and CA drought runs counter to the typical El Niño Southern Oscillation (ENSO) teleconnection and motivates consideration of whether the abnormal nature and magnitudes of the anomalies may be associated with anthropogenic forcing.

In this study, we test the hypothesis that co-occurrence of NEP MHW and drought along the US West Coast will increase in frequency under future anthropogenic climate change. We use the ensemble of climate model outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6, Eyring et al., 2016) to compare the likelihood of co-occurring NEP MHW and CA drought under pre-industrial conditions with a late 21st-century climate projection under a fossil-fuel intensive development pathway.

2. Methods

2.1. Model Output

CMIP6 model outputs were obtained from the pre-industrial control (piControl) simulations (500 years) and compared with outputs at the end of the 21st century (2070–2099) from simulations that follow Shared Socioeconomic Pathway (SSP) 5-8.5, which represents a fossil-fuel reliant future (O'Neill et al., 2016). To investigate MHW, we examined spatially averaged SST in the GOA and CC regions (Figures 1a and 1b). For drought, we analyzed total soil moisture averaged over California (the area most impacted by the 2013–2016 drought) as an analog to the Palmer Drought Severity Index (PDSI; Palmer, 1965; Figure S4). Hydrological annual mean (July–June) time series were calculated to capture each fall-winter wet season in its entirety. We used 22 models (one realization per model) that had all the relevant variables and were available at the time of this analysis (Table S1).

2.2. Defining Extreme Events

Following earlier studies, we defined MHW as years with SST anomalies exceeding the 90th percentile threshold based on a reference time series (Hobday et al., 2016). When calculating SST anomalies and choosing thresholds to define MHW in a warming ocean, two distinct approaches have previously been applied (Jacox, 2019): (a) SST anomalies calculated relative to a fixed climatology, without removing the long-term warming trend (e.g., Frölicher et al., 2018), and (b) SST anomalies defined with respect to the contemporaneous climatology, separating the warming trend from variability (e.g., Jacox et al., 2020). We perform both analyses in this study, using 30-year climatologies from piControl and future runs, respectively, to

establish baseline conditions and thresholds. To avoid ambiguity, we use different terminology for analyses with and without warming trends. When applying the former method, in which SST exceedance of fixed thresholds in the piControl is driven primarily by warming trends, we refer to “extreme hot ocean.” We reserve the term MHW for the latter method, which identifies events that are above the 90th percentile of SST anomalies for the detrended 30-year contemporaneous periods, allowing interannual variability to be distinguished from the long-term trend. Drought was handled similarly, using a 10th percentile threshold of total soil moisture values, and we use “extreme dry land” and “drought” for results that include and remove the long-term trend, respectively.

2.3. Change in Co-occurrence of Extremes

Based on the above definitions for extremes, during the 2013–2016 event CA drought persisted for two hydrological years (2013–2014 and 2014–2015), co-occurring with a GOA MHW in 2013–2014 (Figures 1a, 1c and S1) and with both GOA and CC MHW in 2014–2015 (Figures 1b, 1c and S1). This progression occurred as the MHW evolved from the GOA “Blob” pattern to a coastwide arc warming pattern (Amaya et al., 2016; Di Lorenzo & Mantua, 2016). To ensure that our analysis captured this type of evolution, we examined CA drought co-occurrence with MHW in the CC and the GOA independently. We also examined lagged relationships between GOA and CC MHW (GOA leading CC by 1 year) as well as two-year persistence of CA drought, as these two components characterized the recent co-occurrence of CA drought and CC MHW. We describe all four combinations of extremes as “co-occurrence” for simplicity of terminology. For each of these pairs of extremes, we quantified long-term changes in the frequency of co-occurrence by comparing 30-year periods in the SSP5-8.5 simulation (2070–2099, hydrological mean calculated with data from July 2069 to June 2099) to the preindustrial period (piControl). When considering sequential events, we shift the period by 1 year to ensure 30 years of potential chances for combined extremes.

In addition to quantifying the frequency of co-occurrence, we also relate the occurrence of individual types of extremes (e.g., CA drought, GOA MHW) to probability distribution functions (PDFs) of SST and soil moisture anomalies under preindustrial and future conditions.

2.4. Attribution to Anthropogenic Climate Change

We use the fraction of attributable risk (FAR) metric (Lott & Stott, 2016) to quantify the fraction of increased risk of co-occurring extreme events attributable to anthropogenic climate change. FAR is defined as:

$$\text{FAR} = 1 - \frac{P_{\text{NAT}}}{P_{\text{ALL}}},$$

where P_{NAT} is the likelihood of the co-occurrence of events under natural climate forcing (here the piControl simulation), and P_{ALL} is the likelihood of co-occurrence of events under all climate forcing (here under the natural and anthropogenic forcing present in the SSP5-8.5 climate scenarios). The positive or negative signs of FAR represent increased or reduced risk that can be attributed to anthropogenic forcing, for example, when $P_{\text{ALL}} = P_{\text{NAT}}$, FAR = 0; when $P_{\text{ALL}} > P_{\text{NAT}}$, FAR > 0; when $P_{\text{ALL}} < P_{\text{NAT}}$, FAR < 0.

2.5. Robustness of Change

To quantify the robustness of change in frequency of co-occurring extreme events, we used the long piControl simulations. By dividing the 500-year piControl simulations into 16 non-overlapping 30-year periods, we obtained 352 30-year time series (16×22 models) with which to characterize the collective influence of internal variability in the multi-model ensembles (MMEs). We first calculated the change in the frequency of co-occurring extreme events in each model realization between the SSP5-8.5 and each piControl period and obtained 16×22 frequency differences. Then we averaged the frequency changes simulated by the 22 models to obtain 16 MME changes. The mean of the 16 MME changes was compared to the standard deviation across the 16 MMEs to estimate the robustness of the projected changes in the frequencies of co-occurring conditions. When the mean change exceeded the standard deviation across the 16 MMEs, we considered it a robust change. The one standard deviation across the 16 MMEs here represented the internal variability of the MMEs (Table 1). For the FAR analysis, because there were occasions when zero co-occurrence was

Table 1

Numbers of Co-occurrences per Century in the Preindustrial Control (piControl) and Future (SSP5-8.5) Simulations, Changes in Co-occurrence Frequency From piControl to Future and One Standard Deviation of the Change, and the Fraction of Co-occurrence Risk Attributable to Anthropogenic Forcing (FAR) With the 95% Confidence Interval in Brackets

	piControl (30-year period)	Future (SSP5-8.5 2070–2099)	Change \pm 1SD (future minus piControl)	FAR
Long-term trends retained/fixed climatology				
Hot GOA + dry CA	1.15	43.6	42.5 \pm 2.39	0.97 (0.97, 0.98)
Hot CC + dry CA	0.80	43.6	42.8 \pm 1.91	0.98 (0.98, 0.99)
Long-term trends removed/contemporaneous climatology				
GOA MHW + CA drought	1.11	1.67	0.56 \pm 0.30	0.34 (0.24, 0.43)
CC MHW + CA drought	0.73	0.61	−0.12 \pm 0.27	−0.20 (−0.45, 0.05)
GOA MHW leads CC MHW 1 year	1.06	1.97	0.91 \pm 0.42	0.46 (0.34, 0.58)
CA drought (2 years)	2.3	1.52	−0.78 \pm 0.30	−0.52 (−0.63, −0.41)

found in the 30-year period for one model realization, we summed the numbers of instances across 22 models first, and then calculated the FAR in the MME. After we obtained 16 MME FAR values, we calculated their mean and 95% confidence interval (Table 1). To evaluate the significance of changes in probability distributions of SST and soil moisture anomalies associated with individual extremes, we conducted Kolmogorov-Smirnov (K-S) and Mann-Whitney (M-W) tests and recorded the *p*-values (Table S3).

3. Results

3.1. Co-occurrence of Extremes in the piControl

Extreme events as defined in this study occur on average 10 times per century (10% of the time). Thus, the frequency of two extreme events co-occurring would be once per century if the events were independent. Co-occurrence at rates significantly different from once per century suggests that the extremes are dynamically coupled rather than independent. A coupling analysis (Table 1) shows that for the piControl simulation, the frequency of co-occurrence of CA drought and GOA MHW (and dry CA/hot GOA) and that of the GOA MHW leading the CC MHW by 1 year are approximately one, suggesting independence. In contrast, the frequency of co-occurrence for CA drought and CC MHW (and dry CA/hot CC) is below one (0.73 [0.80]; Table 1), suggesting that they are not independent and less likely to co-occur. The frequency of 2-year CA droughts also differed significantly from once per century, exceeding two events per century in the piControl simulation. This is generally consistent with the instrumental record during which three such droughts occurred (Figure 1c).

3.2. Changes in Extreme Hot Ocean/Dry Land and MHW/Drought Co-occurrence

Relative to the piControl simulations, the frequency of co-occurring hot ocean/dry land extremes will increase ~38-fold to 55-fold by the end of the century (Table 1). These changes are overwhelmingly due to the increase in frequency of individual extreme conditions related to mean state trends (Table S2). Specifically, the frequency of extreme hot ocean years in both the GOA and CC increases from 10% in the piControl simulation to 100% by end of the century under SSP5-8.5. Changes in CA extreme dry conditions are less dramatic but qualitatively similar, increasing from 10% in the piControl to 44% by end of the century.

The changes in co-occurrence of extremes are more nuanced when considering the anomalies defined relative to their contemporaneous climatologies. In comparison to the piControl simulations, the co-occurrence of CC MHW and CA drought does not exhibit robust change, while the co-occurrence of GOA MHW and CA drought increases 50% toward the end of the 21st century (Table 1). The frequency of GOA MHW leading CC MHW by 1 year almost doubles under the SSP5-8.5 future conditions relative to the piControl simulation. The frequency of 2-year droughts is projected to decrease by 34% in the future, declining to about 1.5 events per century from ~2 events per century in the piControl.

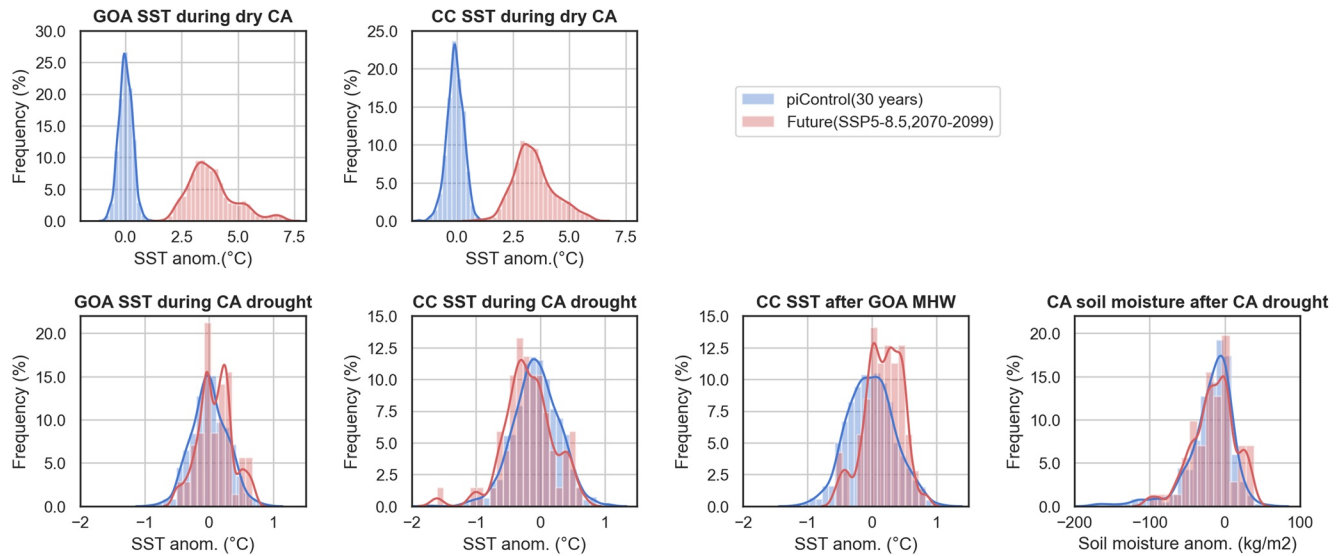


Figure 2. Sea surface temperature (SST) and soil moisture anomalies associated with co-occurrences of marine and terrestrial extreme events. Top panel shows probability distribution functions (PDFs) of SST anomalies (trends retained) in the Gulf of Alaska (GOA) and California Current (CC) during years of extreme dry CA conditions; bottom panel shows PDFs of GOA and CC SST anomalies (detrended) during years of CA drought; CC SST anomalies (detrended) in the year following a GOA MHW; and CA soil moisture anomalies (detrended) in the year following a CA drought. PiControl (blue) refers to 30-year periods in the pre-industrial control runs, future (red) is 2070–2099 in SSP5-8.5.

3.3. SST and Soil Moisture Anomalies Associated With Individual Extremes

To expand our analysis beyond binary co-occurrence metrics, we also examined changes in the distribution of properties associated with individual extreme events (e.g., the PDF of GOA SST anomalies associated with CA drought) (Figure 2). This analysis allows us to evaluate whether shifts in the full distributions of SST and soil moisture are consistent with frequency changes of co-occurring extremes. In piControl simulations, these distributions are in most cases near normal and centered around zero (blue bars in Figure 2). One exception is that the soil moisture anomaly in the year after CA drought is left-skewed (blue bars in Figure 2, bottom right), which is in agreement with the higher frequency of 2-year droughts in the piControl simulation (Table 1). The mean CC SST anomaly during CA drought is slightly negative, consistent with the lower frequency of combined CC MHW and CA drought (Table 1).

With warming and drying trends retained, the SST anomalies under dry CA conditions increase significantly by the end of the 21st century (Figure 2, top panel and Table 1), and all dry CA conditions co-occur with positive SST anomalies in GOA and CC. Compared with SST anomalies in the piControl run, nearly all future SST anomalies can be considered as extreme hot conditions.

When the long-term trends are removed, changes in SST anomalies are much smaller but still significant (Table S3) and more complex (Figure 2, bottom panel). During CA droughts, the probability distributions of SST anomalies show a right-ward shift in GOA, and a left-ward shift in CC. These changes are in agreement with the increased co-occurrence of CA drought with the GOA MHW and decreased co-occurrence of CA drought with the CC MHW (Table 1). In the year following the GOA MHW, the CC SST anomalies show a significant increase (Figure 2 and Table S3), consistent with the increase of instances when GOA MHW leads the CC MHW (Table 1). The distribution of CA soil moisture anomalies in the year following CA droughts shows a slight right-ward shift, consistent with the decreased frequency in 2-year persistent drought (Table 1), but the change in soil moisture anomalies is not significant (Table S3).

3.4. Attribution to Anthropogenic Climate Change

Changes in frequency of co-occurrences of hot ocean and dry land conditions are strongly attributed to anthropogenic forcing ($FAR = 0.97$ and 0.98) with great confidence (Table 1), as are the increased frequencies in individual extreme conditions (Table S1). However, these signals largely reflect the anthropogenic forcing

contributions through long-term trends: anthropogenic warming in the ocean causes increased extreme heat in the NEP, while warming over land is associated with drying trends and increases in extreme dryness in CA (Diffenbaugh et al., 2015; Williams et al., 2015).

On the other hand, FAR values for co-occurrence of extreme events defined relative to the contemporaneous climatology range from -0.52 to 0.46 , with relatively large uncertainties (Table 1), suggesting diverging and in some cases unclear contributions of anthropogenic forcing to the combined extremes. The increased co-occurrence of CA drought and GOA MHW in the future is partially attributed to anthropogenic forcing (FAR = 0.34 [$0.24, 0.43$]; Table 1). Given that the co-occurrence of CA drought and CC MHW does not show robust change in comparison to the piControl period, the attribution to anthropogenic climate change is also not significant. The increased frequency of GOA MHW leading CC MHW is attributed to anthropogenic forcing with a FAR of 0.46 ([$0.34, 0.58$]; Table 1). For the 2-year persistent drought, its frequency decreases in the future and can be partially attributed to anthropogenic forcing (-0.52 [$-0.63, -0.41$]).

4. Discussion and Conclusions

Our analysis indicates that in the future, even after removing trends, CA drought will co-occur more frequently with GOA MHW due to stronger coupling associated with anthropogenic forcing, and the SST anomalies in GOA associated with CA drought will significantly increase. Although drivers of these co-occurrences were not explicitly examined in this study, mechanisms underlying the recent heatwave and drought may elucidate the projected synchrony between CA drought and GOA MHW. In 2013–2014, extreme CA drought and GOA MHW were driven by persistent upper troposphere (500 hPa) atmospheric ridge events and associated sea level pressure anomalies over the NEP (Bond et al., 2015; Swain, 2015; Wang et al., 2014). Increasing trends in the frequency of strong upper troposphere ridge events in the twentieth century have been attributed to anthropogenic forcing (Swain et al., 2014, 2016), and increasing ridging events throughout the 21st century may be a common driver of more frequent co-occurring GOA MHW and CA drought.

In contrast, co-occurring CA drought and CC MHW did not show increased frequency under anthropogenic forcing, and the SST anomalies in CC during CA droughts significantly decrease in the future. The 2014–2015 co-occurrence of CC MHW and CA drought was not directly dynamically coupled by one system; rather it was mediated by the GOA MHW-CC MHW connection (Jacox et al., 2018), the persistence of the drought (Swain, 2015), and an El Niño event following the anomalous NEP ridge (Di Lorenzo & Mantua, 2016). Our results show a strengthening of the GOA MHW-CC MHW sequence due to anthropogenic forcing, consistent with the stronger coupling of NPGO-like and PDO-like modes (Joh & Di Lorenzo, 2017; Di Lorenzo & Mantua, 2016). At the same time, we found that the frequency of 2-year persistent drought will decrease under future anthropogenic forcing with respect to the piControl (Table 1). This reduced persistence of CA drought could be thought of in a statistical sense as preventing the increase of CA drought-CC MHW co-occurrence despite increases in CA drought-GOA MHW and GOA MHW-CC MHW coupling. Our results also show that the frequency of co-occurrence for CA drought and CC MHW is below once per century both in the piControl run and in the future (Table 1), indicating that they are not independent. We suspect that their relationship is mediated by ENSO teleconnections; El Niño events tend to weaken the NPH and strengthen the Aleutian Low while displacing it to the southeast of its climatological mean position (Fiedler & Mantua, 2017), bringing increased precipitation to CA (Figure S3) and warming to the CC; La Niña events tend to drive the opposite response. This canonical US West Coast response to ENSO likely makes CA drought and CC MHW co-occur less frequently than if they were independent. The lack of statistically significant changes in the future co-occurrence of CC MHW and CA drought relative to the piControl suggests that ENSO retains its dominant role in dictating the relationship between CA drought and CC MHW. Nevertheless, the strengthened linkage between GOA and CC MHW will likely facilitate the occurrence of CC MHW in the absence of an El Niño event.

The findings discussed above reflect the nuanced nature of coupled extreme responses to anthropogenic forcing based on event identification with respect to contemporaneous intervals to effectively remove the influence of long-term trends. In some cases, what may be of interest is change in the co-occurrence of conditions that are extreme relative to some historical threshold, whether due to changes in coupling or simply the influence of long-term trends. To that end, our analyses of extremely hot (in the ocean) and dry (over

land) conditions relative to constant pre-industrial conditions show future increases in co-occurrence that are both dramatic and clearly attributable to anthropogenic forcing.

Due to the relatively short (30 years) future period used to sample rare co-occurrences of extremes, the conclusions here are, by necessity, drawn from the MME means. However, one should bear in mind that individual models may not agree with the MME mean in terms of the magnitude, or even sign, of the change in co-occurring extremes.

The recent anomalies experienced in the NEP and western United States were unprecedented in the observational record, providing a climate “stress test” that impacted marine productivity, reduced terrestrial water supply in California, exacerbated fire seasons, and led to significant economic losses in fisheries and agriculture. Climate projections from the CMIP6 ensemble suggest that in some cases, the frequency of these compound extreme conditions is likely to increase in the late 21st century and that anthropogenic forcing is likely altering the dynamics in both marine and terrestrial realms. Understanding the mechanisms coupling these extreme events, and projecting their likelihood of occurrence in the future, is essential for societies to prepare for and adapt to climate change.

Data Availability Statement

The observational SST data were obtained from Met Office Hadley Center (<https://www.metoffice.gov.uk/hadobs/hadisst/>). The geopotential height data from NCEP Reanalysis 2 were provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their website at <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.pressure.html>. The 2-m soil moisture reconstruction was from NLDAS (North American Land Data Assimilation System, <https://ldas.gsfc.nasa.gov/nldas>). The Palmer Drought Severity Index was from NOAA NCEI (National Centers for Environmental Information, <https://www7.ncdc.noaa.gov/CDO/CDO-DivisionalSelect.jsp>).

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