The potential influence of falling ice radiative effects on Central-Pacific El Niño variability under progressive global warming

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Abstract

The impacts of falling ice (snow) radiative effects (FIREs) on simulated surface wind stress and sea surface temperature (SST) in Central Pacific El Niño (CP-El Niño) under a progressive warming climate are examined. Using controlled simulations with the CESM1 model, it is shown that the exclusion of FIREs (no snow: NOS) generates persistent westerly anomalies in surface wind stress relative to that with FIREs (snow on: SON). These anomalies subsequently lead to a weakening of the easterly trade winds associated with warmer SST anomalies in modeled life cycle. Results over three separated 40 year intervals (P1: 21–60 years; P2: 61–100 years; P3: 101–140 years) are compared with Coupled Model Intercomparison Project phase 5 (CMIP5) models without FIREs. Both NOS configuration and CMIP5 models simulate longer life cycles of CP-El Niño events with weakening easterlies and warmer SST anomalies on the equator, persistently propagating eastward from the mature to dissipating phases. Compared to NOS, SON, on the other hand, produces a shorter CP-El Niño life cycle together with stronger easterlies and colder SSTs over the eastern to central equatorial Pacific. The magnitudes of the simulated westerlies and warm SST anomalies tend to diminish without eastward shifting following the peak of the CP-El Niño activity. There are substantial differences in CP-El Niño characteristics from P1 to P3 between NOS and SON. During P1, both SON and NOS show patterns which are consistent with their present-day counterparts. In P2 and P3, SON exhibits a prolonged CP-El Niño life cycle, while NOS develops a double-peak El Niño evolution at the mature and decaying phases. Regarding El Niño diversity and the projections, the CMIP5 models have not reached a consensus. The inclusion of the FIREs would increase the confidence in simulating El Niño future behavior.

1. Introduction

The El Niño-Southern Oscillation (ENSO) is characterized by increases of central to eastern equatorial Pacific (EP) sea surface temperatures anomalies (SSTs) during the El Niño phase and vice versa during the La Niña phase, with significant impacts on worldwide climate systems through global atmospheric and oceanic teleconnections (McPhaden et al 2006, Guilyardi et al 2009). ENSO tends to have two distinct types of regime, which are often referred to as ‘EP-El Niño’ and ‘CP-El Niño’, with its largest anomalous SST warming in the eastern EP and central EP (CP), respectively (Larkin and Harrison 2005, Ashok et al 2007, Kao and Yu 2009, Kug et al 2009, Kim et al 2012).

In the past few decades, studies using Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIP5: Taylor et al 2012) model simulations did not find consensus projections in the 21st century responses of El Niño events composite to anthropogenic forcing (Meehl and Teng 2007, Yeh et al 2009, ...
et al (2012, 2014a), Kohyama et al (2017). However, there are some common features from CMIP3 and CMIP5 model simulations under greenhouse gas (GHG) forcing: (a) a weakening of the Pacific trade winds (Chen et al 2018), (b) a shoaling of the equatorial thermocline in the central and western Pacific (e.g. Yeh et al 2009, Collins et al 2010), (c) a clear trend towards an increased occurrence of CP-El Niño (Ashok et al 2007, Kao and Yu 2009, Kug et al 2009, Lee and McPhaden 2010), and (d) an increased intensity of CP-El Niño that results in distinct teleconnection patterns and hence climatic impacts (e.g. Wang and Hendon 2007, Kim et al 2009, Yeh et al 2014, Cai et al 2014, 2015). Previous studies have documented that, under GHG forcing, the various flavors of ENSO are associated with the tropical Pacific background states with increasing occurrences of CP-El Niño events due to a weakened surface wind stress. A weakened Walker circulation is also found favorable for a flatter oceanic thermocline and thus a more frequent occurrence of CP-El Niño events (Yeh et al 2009, Collins et al 2010).

A great deal of uncertainty, however, still exists on how CP-El Niño might change in the future climate with no clear consensus being reached thus far on, for example, the location and magnitude of the strongest SST anomalies and the temporal evolution among most models participating in CMIPs (e.g. Power et al 2013, Taschetto et al 2014, Yeh et al 2014). Given various model biases for the 20th century simulations and the lack of sufficient model agreements for the 21st century projection, whether the projected changes for CP-El Niño behaviors would actually take place remains largely uncertain. For example, one of the most frequently discussed topics is the El Niño diversity and the changes in the future (Capotondi et al 2015). The CMIP5 models are widely used in the related studies (Chen et al 2018, Feng et al 2020) but have not reached a consensus. One of the probable reasons is that all the CMIP3 and most CMIP5 models do not include the falling ice (snow) radiative effects (FIREs). Moreover, Fedorov and Philander (2000) pointed out that the models with unrealistic background mean state intend to simulate unrealistic El Niño modes. And a recent study suggested that there was a higher frequency of CP-El Niño in recent decades compared to past centuries (Freund et al 2020). One key question needs to be addressed is to examine the impacts of FIREs on projected El Niño evolution with and without FIREs.

In tropics, falling ice (or snow) mass is formed above melting level in the elevated detrained stratiform clouds through deep convection penetration, directly influencing upper level and near cloud-top radiation fields over Intertropical Convergence Zone/South Pacific Convergence Zone and Tropical Western Pacific (Li et al 2012, 2014a). While in trade wind regions, clouds most likely are water and warm clouds with less chance of high elevated falling ice mass. The potential importance of the FIREs on the tropical Pacific has been studied in a number of studies for present-day climate (Gettelman et al 2010, Li et al 2018, 2020, Michibata et al 2019). These studies showed a distinct Pacific Ocean pattern of radiation-circulation changes related to FIREs.

In terms of seasonal cycle and present-day CP El Niño activity, if FIREs are not included, models simulate persistent westerly anomalies of surface wind stress and low-level flow typically opposing the trade winds, decreasing surface wind stress leading to warmer SST over the central Pacific trade-wind regions. The lack of the FIREs biases simulations of radiation, SST and circulation in the Pacific present-day climate (Li et al 2014a, 2020) and produces an unrealistically seasonal cycle of surface wind and SST and a persistent eastward propagation of warm SST anomalies following the peak in CP-El Niño activity in the present-day climate (Li et al 2018). These biases in the seasonal variations are reduced with the inclusion of the FIREs, which would increase the confidence in simulating their future behavior.

Chen et al (2018) explored how FIREs contribute to simulated Pacific climate change via a pair of sensitivity experiments with FIREs (snow on, hereafter denoted as SON) and without FIREs (no snow, hereafter denoted as NOS) following CMIP5 1pctCO2 protocol using the National Center for Atmospheric Research and US Department of Energy (NCAR-DOE) Community Earth System Model version 1-Community Atmospheric Model version 5 (CESM1-CAM5) climate model (Gettelman et al 2008, 2010, Neale et al 2010, Lindvall et al 2013). Each simulation was initialized from the end of a preindustrial control (piControl) run and the model was then run with the atmospheric CO2 concentration increases at 1% per year for 140 years. The NOS and SON simulations were compared the results with the CMIP5 ensemble mean. They found stronger changes in convective activity and its eastward shift and a stronger zonal gradient of SST warming in the SON simulation than NOS. They also pointed out that the NOS patterns of change are similar to those in CMIP5 models that exclude FIREs, hinting that the future warming-driven changes in SSTs, surface wind stress, precipitation and circulation over the tropical south-central Pacific might be underestimated by most CMIP5 models. The present study uses the same CESM1-CAM5 output to extend the studies of Chen et al (2018) and Li et al (2018) to the seasonal variations as well as the occurrence and evolution of CP-El Niño under progressive global warming.

This study aims at exploring the potential influence of FIREs from progressive warming simulations on the changes of SSTs and surface wind stress in mean state and seasonal variability and on CP-El
Niño evolution in the SON and NOS simulations. The results are compared with the ensemble mean of CMIP5 simulations under the same 1pctCO2 protocol.

We describe the methodology for determining CP-El Niño in section 2. In section 3, model data are described. Results follow in section 4 and further discussion of the results is presented in section 5. Conclusions are drawn in section 6.

2. Methodology for determining CP-El Niño

After dividing the whole period into three 40 year periods (P1: 21–60 years; P2: 61–100 years; P3: 101–140 years), we subtracted the monthly climatology and the linear trend calculated separately for each grid point over each period to derive the monthly SST and surface wind stress anomalies. We then extracted the CP El-Niño index, which is the Niño index for CP events (hereafter denoted as NC_P) in each period following the Ren and Jin (2011) SST-based methodology. They proposed indices for warm pool El Niño (also termed as CP-El Niño) and cold tongue El Niño (also termed as EP-El Niño) based on a transformation of traditional Niño3 (5° S–5° N, 150° W–90° W) and Niño4 (5° S–5° N, 160° E–150°W) indices, and effectively delineate temporal variability and characterize spatial patterns for both El Niño types in present-day climate (equation (1) of Ren and Jin (2011)). Based on their concept, we obtained NC_P by testing and modifying the transformation coefficient as in equation (1) to effectively separate different clusters of El Niño events and limit the influence of EP-El Niño in warmer climate, which is not our main focus in this study.

An individual CP-El Niño event is identified based on the criterion that the normalized NC_P index exceeds a threshold value of 1 for five consecutive months. We develop a composite CP-El Niño life cycle by identifying and isolating 12 months before and 12 months after the local maximum in NC_P of the SST anomalies, summing up all individual CP-El Niño episodes, and dividing by the total number of CP-El Niño events. This method was applied for both the CESM1 sensitivity experiments (SON and NOS) and the other 14 CMIP5 models without FIREs. For those models that only simulate fewer than three CP-El Niño events in any of the three periods, they were excluded from the process of multi-model mean (MMM). Finally, we took an average of composite CP-El Niño pattern of the models which satisfy the criteria and obtain the MMM of the CMIP5 CP-El Niño

\[ NC_P \times N_4 = \alpha \times N_3, \quad \alpha = \begin{cases} 0.6, & N_3 N_4 > 0 \\ 0, & \text{others} \end{cases} \]

where \( N_3 \) and \( N_4 \) represent Niño3 and Niño4 indices, respectively.

3. Data sources

3.1. CMIP5 model output

Originally, 14 CMIP5 (Taylor et al 2012) models without FIREs are considered (table 1). Except for the sensitivity simulations SON by CESM1-CAM5, the other models listed in table 1 do not include FIREs. After CP-El Niño composite is calculated, those models that only simulate fewer than three CP-El Niño events in any of the three periods were excluded from the process of MMM. Finally, ten models were left, and we took an average of the composite CP-El Niño pattern to obtain the MMM of the CMIP5 CP-El Niño. The MMM is compared with CESM1 simulations to be described below. For each of the CMIP5 models listed in table 1, we use a single 1pctCO2 simulation, in which the atmospheric CO2 concentration increases at 1% per year for 140 years (simulation r1i1p1 in CMIP5 nomenclature). Each of the CMIP5 models is separately detrended for the monthly SST anomalies before the MMM of CMIP5 is obtained. All outputs were regridded on the same 1°×1° latitude–longitude grids.

3.2. CESM1 model and sensitivity experiments

To investigate the impact of the FIREs on simulated CP-El Niño under progressive warming, a pair of sensitivity experiments are performed with the CESM1. The CESM1-CAM5 is a fully-coupled global climate model (GCM), including atmosphere, ocean, and sea-ice components, developed and maintained jointly by the NCAR and DOE. Detailed descriptions of CESM1-CAM5 components and physical parameterizations can be found in Morrison and Gettelman (2008), Gettelman et al (2010), Neale et al (2010), Lindvall et al (2013) and also at www.cesm.ucar.edu/models/cesm1.0. The simulations are run with a horizontal atmospheric grid of 1°×1°.

For the two sensitivity experiments (SON and NOS), the effect of FIREs is turned on or off in Community Atmosphere Model version 5 (CAM5), the atmospheric component of CESM1. We follow the 1pctCO2 CMIP5 protocol, in which the simulation is initialized from a piControl run and the atmospheric CO2 concentration increases at 1% per year for 140 years, by which time the atmospheric CO2 concentration has quadrupled. This is not a realistic scenario analogous to recent climate warming since other factors such as aerosols also play an important role. But this is useful for understanding a high-emission scenario where the anthropogenic radiative forcing change is dominated by that of CO2.
Table 1. List of CMIP5 models used in this analysis. Only CESM1-CAM5 includes the FIREs.

| Model name       | Modeling center or group                                                                 |
|------------------|-------------------------------------------------------------------------------------------|
| ACCESS1-0        | The Centre for Australian Weather and Climate Research, Australia                         |
| bcc-csm1         | Beijing Climate Center, China Meteorological Administration, China                       |
| bcc-csm1-m       | Beijing Climate Center, China Meteorological Administration, China                       |
| CCSM4            | National Center for Atmospheric Research, US                                               |
| CESM1-CAM5       | National Center for Atmospheric Research, US                                               |
| CESM1-BGC        | National Center for Atmospheric Research, US                                               |
| CNRM-CM5-2       | Centre National de Recherches Météorologiques/Centre Européen de Recherche et             |
|                  | Formation Avancée en Calcul Scientifique                                                   |
| Inmcm4           | Institute for Numerical Mathematics                                                       |
| IPSL-CM5A-LR     | Institut Pierre-Simon Laplace, France                                                     |
| IPSL-CM5B-LR     | Institut Pierre-Simon Laplace, France                                                     |
| MRI-CGCM3        | Meteorological Research Institute, Japan                                                   |
| MIROC5           | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute      |
|                  | for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology,     |
|                  | Japan                                                                                        |
| MIROC-ESM        | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute      |
|                  | for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology,     |
|                  | Japan                                                                                        |
| NorESM1-M        | Norwegian Climate Centre, Norway                                                           |
| NorESM1-ME       | Norwegian Climate Centre, Norway                                                           |

Figure 1. The spatial patterns of composited mature warm phase SST anomalies (°C) averaged from 2 months before the mature peak (−2) to 2 months later (+2) for P1, P2 and P3 over the 140 year integrations for the SON simulation (a), (d), (g) and the NOS simulation (c), (f), (i). Panels (b), (e) and (h) show the CP-El Niño indices for SON (blue lines) and NOS (orange lines) from P1 to P3, respectively. The CP-El Niño peak phases of the SON and the NOS simulations are highlighted with yellow triangles and green circles, respectively.

4. Results

4.1. Differences in the strength and variability of CP-El Niño in CESM1 sensitivity experiments

Similar to Kug et al. (2009), who defined the mature warm phase of CP-El Niño as an average from December to the following February, we defined the mature phase as an average from 2 months before to 2 months after the mature peak of each warm event. Figure 1 shows the composite of SST anomaly patterns during the CP-El Niño mature phase for SON (left column) and NOS (right column) over P1 (figures 1(a)–(c)), P2 (figures 1(d)–(f)) and P3 (figures 1(g)–(i)), respectively, and the corresponding monthly $N_{cp}$ indices (middle column) based on equation (1) for SON (blue lines) and NOS (orange lines) simulations.

Generally, the CP-El Niño SST anomalies are warmer in NOS than in SON in most of the periods. Yet, distinct evolutions from P1 to P3 are found in SON and NOS simulations. In P1, SON (figure 1(a)) and NOS (figure 1(c)) show an evident difference in that the maximum SST anomalies in NOS are about 0.6 K warmer than in SON. The
apparent difference between the SON and NOS simulations is consistent with the findings of CP-El Niño events in Li et al. (2018) for present-day simulations. In P2, an abrupt warming behavior occurs in the SON simulations, while a slight reduction occurs in the NOS. The maximum SST anomaly difference between SON and NOS is reduced to only about 0.2 K. Moreover, the SST anomaly pattern of SON appears to spread eastwards to \( \sim 100^\circ \) W. Such opposite variations reduce the difference of the maximum SST anomalies between SON and NOS. In P3, the maximum SST anomalies remain unchanged but broaden slightly in SON, while reduce a little bit continuously in NOS. Noting that from P1 to P3, the maximum SST anomalies area is found to broaden between the dateline and 100\(^\circ\) W in SON, while continuously shrink to 170\(^\circ\) W in NOS. Such different development from P1 to P3 in these two simulations suggests that some important features might be overlooked if we merely analyzed the changes between P1 and P3 and only detrended for the entire 140 years period. In addition to the mature phase, the life cycle would be needed to see the whole picture of how CP-El Niño evolves in SON and NOS.

Figure 2 demonstrates the composite CP-El Niño life cycle averaged over the equatorial band of 5\(^\circ\) S–5\(^\circ\) N for SST, for each of P1 to P3 periods and the entire 140 years integration (\(P_{\text{all}}\)) of SON and NOS simulations. These Hovmöller diagrams cover 25 months (12 months before and after the peak \(N_{cp}\) indices) in time and from 150\(^\circ\) E to 90\(^\circ\) W in longitude. For SON in P1 (figure 2(b)), the composite CP-El Niño SST evolution shows an initial propagation of the warm SST anomalies, which decrease in magnitude and continue to propagate westward. In contrast, a component of SST anomalies for the NOS in P1 (figure 2(g)) propagates eastward following the peak stage, in addition to the westward propagation from the initial to the mature stages. This eastward-propagation component results in late-cycle warm SST anomalies of 0.2 K–0.8 K, which explains the 5 to 6 months longer CP-El Niño life cycle relative to SON.

The CP-El Niño SST evolution during P2 exhibits a warming behavior (figures 2(c) and (h)) in SON, while a double-peak CP-El Niño evolution appears in NOS. In NOS simulation, on the other hand, the single mature phase in P1 is found to split into
two warm peaks, which appear to situate around the dateline and 140° W, respectively. This might be why we observe a slight reduction of the maxima SST anomalies for the mature peak stage in P2 (figure 1).

Particularly for SON, the peak SST anomalies, which are weakened with westward propagation in P1, prolong the mature phase and slightly spread eastwards around 100° W with maximum SST anomalies reaching 1.4 K around 6 months after the mature peak in P2 and with a 3 month longer life cycle than in P1. For NOS, the eastward-propagation component enhances earlier, and the maxima SST anomalies reach another peak around 5 months after the original peak stage. Such warming behavior during P2 results in a prolonged CP-El Niño life cycle in SON but a double-peak CP-El Niño evolution in NOS.

During P3, the maximum SST anomalies in SON increase to ~1.4 K (figure 2(d)), but the slight eastward-propagation features around 100° W from P2 strengthen and result in a life cycle that is 5 months longer than that of P1. For NOS, on the other hand, the two maximum peaks in P2 broaden and shift eastwards to ~100° W with the maxima SST anomalies reduced by ~0.2 K (figure 2(i)). In both the SON and NOS simulations, the eastward-propagating feature has been intensified during P3.

Despite of the large differences in composite life cycles during each of the three periods between SON and NOS discussed above, the differences in SST between P3 and P1 for SON (figure 2(e)) and NOS (figure 2(j)) suggest that the warming prolongs the life cycle of CP-El Niño and strengthens the eastward-propagating feature from P1 to P3, particularly apparent in SON.

Moreover, the differences between NOS and SON vary greatly between the three periods, showing dipoles with colder SSTs before the peak and warmer SSTs in the decaying stage (figures 2(f)–(n)) for NOS compared to SON. Interestingly, the differences between NOS and SON for \( P_{\text{all}} \) are relatively smaller (figure 2(k)) but resemble P3, which supports the detrending length taken in each period adopted in this study.

The CP-El Niño activity is commonly treated as surface wind-driven phenomenon, which allows one to use anomalous surface wind stress (figure 3) to interpret the anomalous SST evolution (figure 2). The Hovmöller diagrams of anomalous surface wind stress for SON show that, in P1 (figure 3(b)), the anomalous surface westerly wind stress takes place during the onset of CP-El Niño starting from the 12th month (lag −12), and weakens sharply after the peak (lag 0), associated with the weakened and more-westward tilting CP-El Niño SST anomalies (figure 2(b)). In P2, the stronger westerly surface wind stress anomalies occur 2 months later than P1 and cease around 3 months after mature peak (figure 3(c)), which is consistent with the prolonged evolution of SST life cycle (figure 2(c)). In P3, such westerly surface wind stress anomalies greatly intensify in magnitude and cease at lag +11 months (figure 3(d)), which seems to be responsible for the eastward-propagation component in the SST evolution (figure 2(d)).

In contrast to SON, in P1, NOS shows stronger westerly surface wind stress anomalies than in SON after the mature peaks. In P2, the westerly surface wind stress sustains from the initial stage without an obvious cease and becomes stronger in the decaying stage than SON (figure 3(h)), which explains the double-peak evolution of the SST anomalies (figure 2(h)). In P3, the westerly surface wind stress remains strong and propagates even eastward compared to that in P2, which corresponds well with the intensified eastward-propagation component in the SST evolution with broader regions of higher anomaly values (figure 2(i)).

The differences between P3 and P1 in NOS demonstrate that the strengthened westerly wind stress anomalies (figure 3(j)) sustaining until the decaying stage make CP-El Niño stronger, associated with the prolonging SST life cycle in NOS simulation. The differences between SON and NOS for the whole life cycle are most evident for P1 (figure 3(l)) then become minor for P2 and P3 mainly due to the prolonged life cycle in SON (figures 3(m) and (n)).

4.2. Differences in the strength and variability of CP-El Niño in the ten selected CMIP5 models

Figure 4 shows the Hovmöller diagrams of the composite CP-El Niño life cycle from CMIP5 MMM for SST (figures 4(a)–(e)) and surface wind stress anomalies (figures 4(f)–(j)) averaged over 5° S–5° N, respectively. Similar to Li et al (2018), the SST and wind stress magnitudes in the CMIP5-MMM are weaker compared to the CESM1-CAM5 SON and NOS simulations, partly as models place their CP-El Niño peaks at different longitudinal locations (see supplementary information (available online at stacks.iop.org/ERL/16/124062/mmedia)), and so their surface wind vectors tend to be canceled out across CMIP5 models producing smooth ensemble-mean spatial signal. In general, the maximum SST anomalies at the mature phase are ~0.8 K. There is a small component of SST anomalies that clearly propagates eastward following the peak, in addition to the westward propagation from the initial to the mature stages with sustained westerly anomalies, particularly apparent in P3. The eastward-propagating features in NOS are also present in the CMIP5-MMM. The eastward-propagating component around 120° W–100° W (the 0.4° C contour) in the SST anomalous evolution shrinks from P1 to P2 and becomes much apparent in P3. In P3, the maxima SST anomalies slightly intensify, accompanied by the strengthening and prolonged westerly wind stress anomalies (figures 4(f)–(j)).
Figure 3. Same as figure 2 but for the life cycle composite of the zonal component of wind stress anomalies (N m$^{-2}$) associated with CP El Niño averaged over the equator (5°S–5°N).

In summary, the above findings are consistent with the results found in Li et al (2018) and with the hypothesis that anomalous SSTs are driven by anomalous surface wind stress. That is, in NOS, model simulates weaker surface wind stress, reducing upper-ocean vertical mixing as well as cold water advection in the oceanic mixed layer (Li et al 2016), which in turn results in warmer SSTs to the east, allowing longer-lasting CP-El Niño events. The warm SST anomalies of longer-lasting CP-El Niño events are able to propagate eastwards, at least in CESM1-NOS and CMIP5-MMM.

5. Discussion

We presented evidence on the weakening surface wind stress and the associated warmer SSTs during CP-El Niño life cycle in CESM1-CAM5 simulation without FIREs (NOS), compared to that with FIREs (SON), the same version contributed in CMIP5, under progressive global warming following CMIP5 1pctCO2 scenario. We found that NOS produces weaker surface wind stress, causing warmer SSTs and reducing zonal gradients of SSTs in the south-central Pacific in both the mean state (not shown) and CP-El Niño cycle during the mature to decaying phases over three 40 year (P1, P2 and P3) periods. The NOS anomalous SST and wind stress patterns are found similar to those in CMIP5 models that exclude FIREs, hinting that the commonly found warming-driven changes over the Pacific might be partially contributed by the exclusion of FIREs for CP-El Niño evolution.

We further found that when CP-El Niño occurs, both NOS and CMIP5-MMM simulations exhibit flatter east–west SST gradients and weaker easterlies (associated to the Walker circulation) heading into the central-south Pacific region, leading to SST warming to the peak and an eastward propagation of warm SSTs with westerly anomalies. In NOS, the weaker easterlies cannot contain the CP-El Niño related warmer SSTs, and there is an unrealistic eastward propagation of warm SST anomalies following the peak in CP-El Niño events. This is consistent with some past studies mentioned in the introduction using CMIP3 and CMIP5 model outputs, which showed that the weakened Walker circulation associated with global warming favors a flatter oceanic thermocline and thus more frequent occurrences and weaker variability of CP-El Niño events. In contrast, the stronger easterly winds in SON keep the SSTs colder over the Pacific Ocean compared to NOS in the
simulated 140 years mean surface wind stress and SST over the Pacific for annual and CP-El Niño cycle mean states for P1.

The SON simulation during P1 shows an initial propagation of the warm water from the east to near the central Pacific and then a decrease in the magnitude of SST anomalies after the peak phase, whereas NOS shows the warm SSTs persistently propagate eastward following the peak. In P2, the apparent differences between SON and NOS remain, but the SON exhibits a prolonged life cycle and tends to propagate eastwards slightly during the decaying phase, while NOS evolves into double peak with a CP behavior at the mature phase followed by an EP-like behavior at the decaying phase. In P3, the features found in P2 appear to intensify. Although the amplitude is weaker, the CMIP5-MMM exhibits a similar variation as CESM-NOS from P1 to P3 (figure 4).

The model-specific variability is also shown for most of the ten selected CMIP5 outputs (figure S1) except for MIROC5 with relatively strong CP-El Niño variations. Most models show similar evolution as in CESM-NOS from P1 to P3. From the ten selected CMIP5 models, seven models (ACCESS1-0, CCSM4, CESM1-BGC, CNRM-CM5-2, MIROC5, NorESM1-M, NorESM1-ME) are found to have a NOS-like performance, while two models (bcc-csm1, IPSL-CM5A-L) show a slightly SON-like performance even without FIREs. The westerly surface wind stress anomalies and warmer SST anomalies continuously propagate to the eastern Pacific after the peak phase in most of the models, except for these two. Compared to the CESM1-CAM5 SON simulation which truly includes the FIREs, these two models have a slightly different development for SST and wind stress over the 140 years period. Their life cycles of CP-El Niño firstly show a NOS-like pattern during P1 but start to shrink and perform like SON from P2 and P3, which is opposite to the evolution of CP-El Niño in the CESM1-CAM5 SON simulation. A more detailed analysis is needed to find the potential reason in the future. Noting that the magnitudes of wind stress and SST anomalies in the CMIP5-MMM are smaller and vary less spatially, partly as models placed their CP-El Niño peaks at different locations (figure S1), and so their surface wind vectors tend to be largely canceled out across models to produce a smoother composite pattern (figure 4).

Through the variability from P1 to P2 in both the SON and NOS simulations, it is indicated that the SST
detrending approach over the 140 years integration is a reasonable step to take because the mean climates over the model integration period can vary greatly. Moreover, it is important to explore when exactly this abrupt warming behavior in the warm SST anomalies associated with westerly wind stress anomalies happens between P1 and P2. Figure 5 shows the Hovmöller diagrams of the composite CP-El Niño life cycle for SST anomalies (detrended and averaged) over 40 years (a), (f); 50 years (b), (g); 60 years (c), (h); 70 years (d), (i); and 80 years (e), (j) for SON and NOS simulations, respectively.

As seen from figure 5, the strength of CP-El Niño SST anomalies in SON continuously amplifies as the averaging period lengthens. The CP-El Niño life cycle prolongs and the negative SST anomaly signal at the dissipating stage has weakened during 21–80 years period compared to P1. The warm SST anomalies take over during the late stage for 21–90 averages and the CP-El Niño life cycle is 6 month longer than P1. From this stage, an eastward-propagation component occurs around 100° W and slightly strengthens during 21–100 years.

For NOS, the double-peak El Niño evolution occurs during 21–80 years with a CP behavior at the mature phase followed by an EP-like behavior at the decaying phase. This pattern gets even stronger afterwards. The warm SST anomalies continuously amplify and propagate eastwards starting from the 21–80 years period, but slightly weaken for the maxima SST anomalies during 21–100 years period. The differences between SON and NOS simulations are large until 80th year but become smaller from 90th till the end of the integration. It is indicated that the change of CP-El Niño is most likely to initiate in the 70th ∼ 90th years over the 140 years integration found in NOS, SON and CMIP5 models.
6. Conclusions

Building upon the earlier CP-El Niño studies of Li et al (2018) and Chen et al (2018), we have examined the differences between experiments with FIREs (SON) and without FIREs (NOS and CMIP5) to explore the influence of FIREs on the simulated tropical CP-El Niño in a warming world. Moreover, the 140 year integration was divided into three periods: P1 (21–60 years), P2 (61–100 years), and P3 (101–140 years) to demonstrate the CP-El Niño evolution. We have also compared with the behavior of CP-El Niño in the CMIP5 models that do not include FIREs.

The mechanism presented in this study can be summarized as follows. The NOS simulation tends to have persistently stronger westerly surface wind stress anomalies and warmer SST anomalies relative to SON, particularly during the mature to decaying phases of CP-El Niño life cycle. This, in turn, results in warm SSTs sustained to the east associated with westerly wind anomalies resulting in longer-lasting CP-El Niño events in which the warm anomalies continue to propagate eastward driven by the persistent easterly anomalies found in NOS and CMIP5 models. Distinct CP-El Niño evolution were examined in the NOS and SON simulations. We found that in the first period (P1) of the warming scenario, the SON and NOS show distinct patterns which is consistent with their present-day counterpart. In P2 and P3, SON exhibits a prolonged CP-El Niño life cycle, while NOS develops into a double-peak El Niño evolution at the mature and decaying phases.

We acknowledge that the manifestation of the impacts from the FIRE reported might not be the only factor and may be model-dependent. The eastward propagation of SST and surface wind anomalies may depend on the strength of the mean state trade winds, which could be affected by other physical and dynamical processes. From our previous studies (Gettelman et al 2010, Li et al 2014a, 2014b), even CAM5 (CESM1) with FIREs does not mitigate biases over the tropical Pacific when compared to the case in NOS (Li et al 2014a, 2014b). However, CESM1-CAM5 reported from prior studies mentioned in the introduction exhibited dramatically reduced biases compared to the models without considering FIREs in CMIP3 and CMIP5.

We conclude that the NOS and CMIP5-MMM projected changes of CP-El Niño in SST and surface wind stress anomalies are partially influenced by the lack of the FIREs relative to SON. The common features relative to SON is that the CMIP5 models tended to have warmer SSTs and weaker surface easterlies for the annual mean and annual cycle. The most robust feature is that the evolution of CP-El Niño without FIREs is characterized by more frequent occurrences and a longer life cycle with sustained eastward propagation of SST anomalies after the peak of the event, which are associated with the prolonged surface wind stress anomalies. This feature is consistent with many previous studies in CMIP3 and CMIP5 models. El Niño diversity and the changes in the future are one of the most frequently discussed questions. One potential key explanation could be the lack of the FIREs in most CMIP5 models. Our proposed FIRE mechanism partially alleviated the common shortcomings of CMIP5 models in simulating the CP-El Niño variability, although further controlled FIRE experiments with other GCMs would be required to provide a robust estimate of its likely magnitude. Thus, it will be helpful if other GCMs begin to include them as well to confirm the influence of FIREs presented in this study.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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The 1pctCO2 CMIP5 data is obtained from https://esgf-node.llnl.gov/search/cmip5/. The model output of sensitivity experiment using CESM1-CAM5 without FIREs is available through Chen et al (2018).

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References

Ashok K, Behera SK, Rao SA, Weng H and Yamagata T 2007 El Niño Modoki and its possible teleconnection J. Geophys. Res. 112 C11007

Cai W, Borlace S, Lengaigne M, van Rensch P, Collins M, Vecchi G, Timmermann A, Santosco M, McPhaden M and Wu L 2014 Increasing frequency of extreme El Niño events due to greenhouse warming Nat. Clim. Change 4 111–6

Cai W, Wang G, Santosco M, McPhaden M, Wu L, Jin F-F, Timmermann A, Collins M, Vecchi G and Lengaigne M 2015 Increased frequency of extreme La Niña events under greenhouse warming Nat. Clim. Change 5 132–7

Capotondi A, Wittenberg AT, Newman M, de Lorenzo E, Yu J-Y, Braccionto P, Cole J, Dewitte B, Giese B and Guiard Y 2015 Understanding ENSO diversity Bull. Am. Meteorol. Soc. 96 921–38

Chen CA, Li J, Richardson M, Lee WL, Fetzer E, Stephens G, Hsu H, Wang Y H and Yu J Y 2018 Falling snow radiative effects enhance the global warming response of the tropical Pacific atmosphere J. Geophys. Res. 123 10,109–10,124

Collins M, An S-I, Cai W, Ganachaud A, Guihard E, Jin F-F, Jochum M, Lengaigne M, Power S and Timmermann A 2010 The impact of global warming on the tropical Pacific Ocean and El Niño Nat. Geosci. 3 391–2

Fedorov AV and Philander SG 2000 Is El Niño changing? Science 288 1997–2002

Feng J, Lian T, Ying J, Li J and Li G 2020 Do CMIP5 models show El Niño diversity? J. Clim. 33 1619–41

Freund MB, Brown JR, Henley B J, Karyol D J and Brown J N 2020 Warming patterns affect El Niño diversity in CMIP5 and CMIP6 models J. Clim. 33 8237–60

Gettelman A, Liu X, Ghan S J, Morrison H, Park S, Conley A, Klein SA, Boyle J, Mitchell D and Li J 2010 Global simulations of ice nucleation and ice supersaturation with an improved cloud scheme in the community atmosphere model J. Geophys. Res. 115 D18216

Gettelman A, Morrison H and Ghan S J 2008 A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part II: single-column and global results J. Clim. 21 3660–79

Guihard E, Wittenberg A, Fedorov A, Collins M, Wang C, Capotondi A, van Oldenborgh G J and Stockdale T 2009 Understanding El Niño in ocean–atmosphere general circulation models: progress and challenges Bull. Am. Meteorol. Soc. 90 325–40

Ham Y-G and Kug J-S 2012 How well do current climate models simulate two types of El Niño? Clim. Dyn. 39 383–98

Ham Y-G, Kug J-S, Kim D, Kim Y-H and Kim D-H 2013 What controls phase-locking of ENSO to boreal winter in coupled GCMs? J. Clim. 383640–45

Kohyama T, Hartmann D L and Battisti D S 2017 La Niña–like mean-state response to global warming and potential oceanic roles J. Clim. 30 4207–25

Kug J-S, Jin F F and An S-I 2009 Two types of El Niño events: cold tongue El Niño and warm pool El Niño J. Clim. 22 1499–315

Larkin NK and Harrison D 2005 On the definition of El Niño and associated seasonal average US weather anomalies Geophys. Res. Lett. 32 L11705

Lee T and McPhaden M J 2010 Increasing intensity of El Niño in the central-equatorial Pacific Geophys. Res. Lett. 37 L14603

Li J, F et al 2012 An observationally based evaluation of cloud ice water in CMIP3 and CMIP5 GCMs and contemporary reanalyses using contemporary satellite data J. Geophys. Res. 117 D16105

Li J, Lee W L, Waliser D, Neelin J, Stachnik J P and Lee T 2014a Cloud–precipitation–radiation–dynamics interactions in global climate models: a snow and radiation interaction sensitivity experiment J. Geophys. Res. 119 3809–24

Li J, Lee W L, Waliser D, Stachnik J P, Fetzer E, Wong S and Yoo Q 2014b Characterizing tropical Pacific water vapor and radiation bias in CMIP5 GCMs: observation-based analyses and a snow and radiation interaction sensitivity experiment J. Geophys. Res. 119 10,981–10,955

Li J, Suhas E, Richardson M, Lee W L, Wang Y H, Yu J Y, Lee T, Fetzer E, Stephens G and Shen M H 2018 The impacts of bias in cloud–radiation–dynamics interactions on central Pacific seasonal and El Niño simulations in contemporary GCMs Earth Space Sci. 5 50–60

Li J, Wang Y H, Lee T, Waliser D, Lee W L, Yu J Y, Chen Y C, Fetzer E and Hasson A 2016 The impacts of precipitating cloud radiative effects on ocean surface evaporation, precipitation, and ocean salinity in coupled GCM simulations J. Geophys. Res. 121 9474–91

Li J, Xu K M, Jiang J, Lee W L, Wang L C, Yu J Y, Stephens G, Fetzer E and Wang Y H 2020 An overview of CMIP5 and CMIP6 simulated cloud ice, radiation fields, surface wind stress, sea surface temperatures, and precipitation over tropical and subtropical oceans J. Geophys. Res. 125 2020JD033248

Lindvall J, Svensson G and Hannay C 2013 Evaluation of near-surface parameters in the two versions of the atmospheric model in CESM1 using flux station observations J. Clim. 26 26–44

McPhaden M J, Zebiak S E and Glantz M H 2006 ENSO as an integrating concept in earth science science 314 1740–5

Meeth G A and Ting H 2007 Multi-model changes in El Niño teleconnections over North America in a future warmer climate Clim. Dyn. 29 779–90

Michibata T, Suzuki K, Sekiguchi M and Takemura T 2019 Prognostic precipitation in the MIROC6-SPRINTARS GCM: description and evaluation against satellite observations J. Adv. Model. Earth Syst. 11 839–60

Morrison H and Gettelman A 2008 A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part I: description and numerical tests J. Clim. 21 3642–59

Neale RB, Chen C-C, Gettelman A, Lauritzen P H, Park S, Williamson DL, Conley AJ, Garcia R, Kinnison D and Lamarque J-F 2010 Description of the NCAR community atmosphere model (CAM 5.0) NCAR Tech. Note NCAR/TN-486-I STR vol 1 pp. 1–12

Power S, Delam F, Chung C, Kociuba G and Keay K 2013 Robust twenty-first-century projections of El Niño and related precipitation variability Nature 502 541–5

Ren H L and Jin F F 2011 Niño indices for two types of ENSO Geophys. Res. Lett. 38 L04704

Taschetto AS, Gupta AS, Jourdain NC, Santosco M, Umehnohner C C and England M H 2014 Cold tongue and El Niño Modoki and its possible teleconnection J. Clim. 27 8631–89

Taylor KE, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98

Wang G and Hendon HH 2007 Sensitivity of Australian rainfall to inter-El Niño variations J. Clim. 20 4211–26

Yeh S-W, Kug J-S and An S-I 2014 Recent progress on two types of El Niño: observations, dynamics, and future changes Asia-Pac. J. Atmos. Sci. 50 69–81

Yeh S-W, Kug J-S, Dewitte B, Kwon M-H, Kirtman B P and Jin F F 2013 El Niño in a changing climate Nature 502 511–4

Yu J Y and Kim S T 2010 Identification of Central-Pacific and Eastern-Pacific types of ENSO in CMIP3 models Geophys. Res. Lett. 37 L11507

11

L-C. Wang et al