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El Niño–Southern Oscillation and its impact in the changing climate

Song Yang[1,2,3], Zhenning Li[1], Jin-Yi Yu[4], Xiaoming Hu[1,2,*], Wenjie Dong[1,2,3] and Shan He[1]

ABSTRACT

Extensive research has improved our understanding and forecast of the occurrence, evolution and global impacts of the El Niño–Southern Oscillation (ENSO). However, ENSO changes as the global climate warms up and it exhibits different characteristics and climate impacts in the twenty-first century from the twentieth century. Climate models project that ENSO will also change in the warming future and have not reached an agreement about the flavor, as to the intensity and the frequency, of future ENSO conditions. This article presents the conventional view of ENSO properties, dynamics and teleconnections, and reviews the emerging understanding of the diversity and associated climate impacts of ENSO. It also reviews the results from investigations into the possible changes in ENSO under the future global-warming scenarios.

Keywords: El Niño–Southern Oscillation (ENSO), diversity, teleconnections, climate impacts, ENSO projection

[1]School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou 510275, China; [2]Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Guangzhou 519082, China; [3]Institute of Earth Climate and Environment System, Guangzhou 510275, China and [4]Department of Earth System Science, University of California, Irvine, CA, USA

*Corresponding author. E-mail: huxm6@mail.sysu.edu.cn

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INTRODUCTION

El Niño–Southern Oscillation (ENSO) is a powerful climate phenomenon that exerts profound impacts on the global climate and accounts for the major skill source of seasonal-to-inter-annual climate prediction. Since the coupled nature of oceanic El Niño and atmospheric Southern Oscillation was recognized [1–3], substantial effort has been devoted into understanding and later predicting the occurrence, development or evolution, physical properties, links to other climate systems and climate impacts of ENSO [4–12]. Compared with other climate phenomena, ENSO is perhaps the one whose occurrence, dynamics and influences have been relatively well understood and predicted [13]. Nevertheless, the Earth climate is changing and ENSO, including its responses to the changing global climate and feedback/influences on the worldwide climate, is also undergoing significant changes [10,11,14–18]. ENSO has tended to occur with the warmest sea-surface temperature (SST) anomalies in the tropical central Pacific, instead of eastern Pacific, in past decades [19]. This change requires us to reconsider the mechanisms responsible for ENSO occurrence and development, the links of ENSO to other climate systems and atmospheric-oceanic fields including temperature and precipitation, and the basis and methods for climate prediction.

While the long-term changes in the properties and climate impacts of ENSO in past decades have not been fully understood, we face another challenging question: how will ENSO change in the future climate? Numerous studies have been conducted using climate models to project the ENSO conditions under different scenarios of global warming due to increases in carbon dioxide. These investigations provide relatively consistent results about the flavor or type of ENSO, but also present large uncertainties in the intensity and frequency of ENSO. Therefore, only limited information about future ENSO conditions can be provided by climate models based on their future climate projections.

In the next section of this article, we review the fundamental features of ENSO and the theories of ENSO occurrence and development. The third section discusses the ENSO-related teleconnection

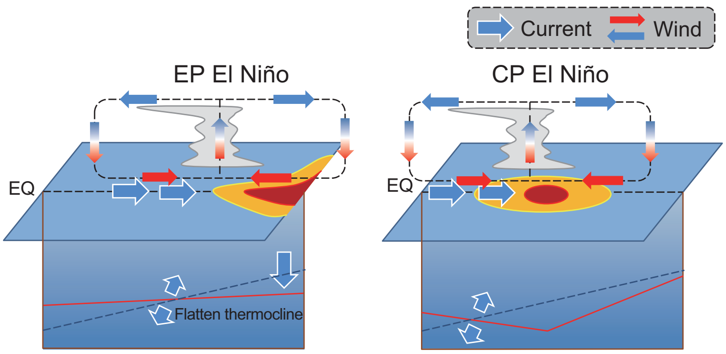

Figure 1. Conceptual diagram for the spatial patterns of EP El Niño events (left figure) and CP El Niño events (right figure). Arrows with (without) white borderlines represent anomalous oceanic (atmospheric) circulations, respectively. Shadings at the sea surface denote the spatial location of the SST anomaly. Dashed blue lines and solid red lines represent the climatological and El Niño-conditioned equatorial thermocline, respectively (adapted from fig. 3 in Yeh *et al.* [54]).

patterns and the involved physical mechanisms, emphasizing the tropical thermally driven forcing, wave trains and the interaction between atmospheric eddies and jet streams. The climate impacts of ENSO and its changes are discussed in the fourth section and the ENSO conditions projected for the future warming climate are reviewed in the fifth section. The main features associated with different types of ENSO are also discussed correspondingly in the various sections of this article. A summary is provided in the final section.

FUNDAMENTALS OF ENSO

ENSO characteristics

ENSO and its variations are usually measured by the dominant modes of the equatorial Pacific SST [3,20–23]. In the twentieth century, the warm phase of ENSO (El Niño) is basically characterized by large SST anomalies in the eastern Pacific, while a new type of ENSO with large SST anomalies over the central Pacific was recognized several decades ago [14,24] (Fig. 1), referred to as the central Pacific (CP) El Niño [11,25], dateline El Niño [26], El Niño Modoki [10] and Warm Pool El Niño [27]. This new type of El Niño also displays different seasonal evolution and teleconnection patterns compared with the canonical El Niño [28–31]. Phase-reversal features cannot be clearly identified in CP El Niño events [25,29]. The emerging ENSO diversity challenges inter-annual climate prediction [17,32] and the skills of forecasting ENSO and its changes with greenhouse warming depend on our understanding of the underlying physics, which has also evolved over the past several decades.

Conventional views of ENSO dynamics

Conventional views explain the occurrence of ENSO as either a stochastic and damped event triggered by stochastic forcing including westerly wind bursts [33,34], the Madden-Julian Oscillation [35], tropical instability waves [36], monsoon activity [37–39] and forcing from the subtropical South Pacific [40,41], or a self-sustained and naturally oscillated air–sea coupled system. From either perspective, the Bjerknes feedback [2], describing a typical unstable air–sea interaction, is the essential positive feedback process in the growing stage of ENSO. Initial positive (negative) SST anomalies in the equatorial eastern Pacific associated with westerly (easterly) anomaly and weakened (strengthened) Walker Circulation are amplified via the Bjerknes feedback, leading to the mature phase of an El Niño (La Niña) event. In the self-sustained framework, ENSO involves at least four negative feedback processes to terminate warm/cold episodes and complete the transition to an opposite phase: the delayed oscillator [7], the discharge/recharge oscillator [9,42], the western Pacific oscillator [43,44] and the advective/reflective oscillator [45].

The delayed oscillator

The idealized delayed oscillator theory, proposed by Schopf and Suares [46] and Battisti and Hirst [7] and shown in a conceptual delayed oscillator model by Suarez and Schopf [5] based on the coupled ocean–atmosphere model of Zebiak and Cane [6], considers the effect of equatorially trapped oceanic wave propagation. An initial sea-surface height anomaly is displaced into eastward-propagating Kelvin waves and westward-propagating Rossby waves. The Rossby waves that propagate westward are reflected at the western ocean boundary and return as equatorial Kelvin waves. The reflected eastward-propagating equatorial Kelvin waves have westward currents, referred to as the delayed negative feedback flow. The traditional version of the delayed oscillator theory involved the equatorial eastern Pacific SST anomalies, while Clarke *et al.* [47] presented the theory for zonal equatorial displacements of the equatorial eastern edge of the western Pacific warm pool.

The discharge/recharge oscillator

The discharge/recharge oscillator theory emphasizes the major role of equatorial heat storage and the wind stress curl anomalies related to the equatorial eastern Pacific SST anomalies. Jin [9,42] formulated the discharge/recharge oscillator based on the intermediate anomaly coupled model of Cane and Zebiak [48]. Since the work of Wyrtki [49,50], the buildup of warm water in the tropical Pacific has been considered as an essential precondition for the development of El Niño events. During El Niño, positive SST anomalies in the equatorial eastern Pacific and the associated westerly wind anomalies cause a meridional poleward Sverdrup transport of equatorial warm water, resulting in a basin-wide raised thermocline. SST anomalies in the equatorial eastern Pacific are more sensitive to the change in mean thermocline than those in the equatorial western Pacific, leading to a larger SST decrease in the eastern Pacific and easterly wind anomalies. The transition from El Niño to La Niña is completed and the recharge process restarts. On average, the El Niño-related discharge process is stronger than the La Niña-related recharge process, which may contribute to the asymmetric evolution of El Niño and La Niña [51].

The western Pacific oscillator

The western Pacific oscillator theory by Wang *et al.* [44] and Wang [52] begins with condensation heating in the western-central Pacific, which induces twin off-equatorial cyclones and westerly wind anomalies at the equator. The anomalous wind stress deepens the thermocline and increases the SST in the eastern Pacific. Positive feedback between wind stress and SST leads to growth of the anomaly. Meanwhile, the pair of cyclones raises the thermocline, so that SST decreases and SLP increases off the equator in the western Pacific. Anomalous high pressure induces easterly wind anomalies that cause upwelling and cooling. The cooling spreads eastwards and provides negative feedback, thereby creating an oscillating coupled ocean–atmospheric system. Unlike the delayed oscillator theory, this theory does not require wave reflection for the coupled ocean–atmosphere system to oscillate.

The advective/reflective oscillator

Picaut *et al.* [45] pointed out two notable modifications of the delayed oscillator theory and proposed the advective/reflective oscillator theory. First, the major region of air–sea interaction is over the central Pacific rather than the eastern Pacific. Second, the contributions of equatorial Kelvin wave reflection from the eastern Pacific boundary, zonal advection of SST and zonal current convergence are the integral parts of the ENSO cycle, which were ignored in the delayed oscillator framework.

As discussed above, these four ENSO oscillator paradigms have different emphases but are also interconnected [53]. The delayed oscillator theory was proposed from the perspective of tropical wave propagation and reflection. The discharge/recharge oscillator theory introduced the extra-tropical thermocline variation into the ENSO mechanism and explained how it leads to a self-sustaining oscillation. The western Pacific oscillator paradigm emphasized the local air–sea interaction over the off-equatorial western Pacific but ignored the wave reflection at the west boundary of the western Pacific. The advective/reflective oscillator conceptual model pointed out the crucial role of zonal current in the ENSO mechanism.

View on ENSO diversity

Displacement of the thermocline dynamics

While both CP ENSO and the conventional eastern Pacific (EP) ENSO emphasize the fluctuations of depth of the equatorial Pacific thermocline on the production of ENSO, Ashok *et al.* [10] argued that the flattening of the equatorial Pacific thermocline from 1958 to 2004 might have displaced the upwelling zone of the thermocline from the tropical eastern Pacific to the tropical central Pacific, resulting in more El Niño and La Niña in the central Pacific. In this view, the emergence of CP ENSO does not really represent a change in ENSO dynamics, but rather a displacement of the action center of ENSO.

Zonal advective feedback (favoring CP-type) vs thermocline feedback (favoring EP type)

Kug *et al.* [27] offered a different view to explain the production of CP ENSO. While others emphasized the role of the background difference in the tropical Pacific in the generation of two types of ENSO, the authors considered that thermocline variations are important for affecting the SSTs in the cold tongue but not in the western Pacific warm pool, where ocean advection terms and surface heat flux forcing are important for determining SST variations.

Kug *et al.* [27] indicated that zonal advection feedback was a crucial factor in modulating the SST anomaly of CP ENSO. In particular, the east–west SST gradient is relatively strong in the transition zone from warm pool to cold tongue over the central Pacific. Thus, SST anomalies can be effectively induced by the zonal advection of mean SST by El Niño-related anomalous zonal current. The enhanced SST anomalies in turn lead to surface wind anomalies, and then amplify the zonal current anomalies [27,54]. Specifically, during the ENSO onset season June–July–August (year 0, JJA(0)), both an off-equatorial eastward current over the central Pacific and an equatorial eastward current related to the negative sea

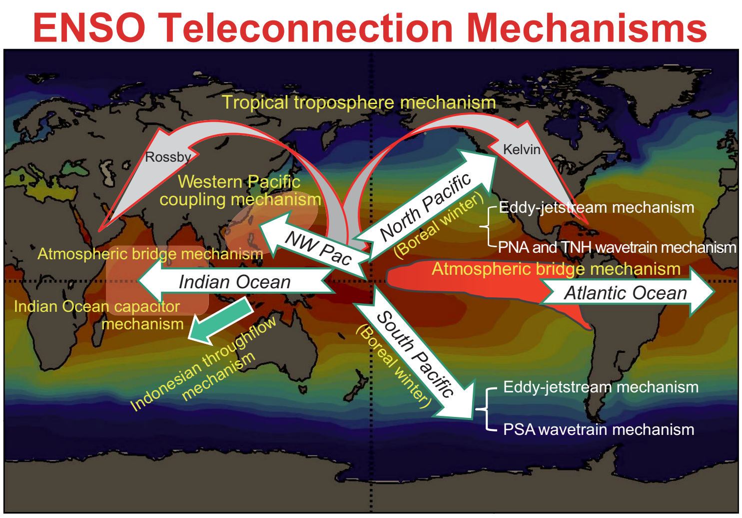

Figure 2. A schematic illustrating the major teleconnection mechanisms through which ENSO affects the global climate.

level anomaly in the western North Pacific contribute to warm advection by the mean temperature gradient. In August–September–October (year 0, ASO(0)), the anomalous eastward current develops, enhancing the SST anomaly. In the peak season (December(0)-January-February(1), D(0)JF(1)), however, a weak westward current anomaly related to the westward gradient of the equatorial sea level and reflected upwelling Kelvin wave from the western boundary, decaying warm SST by cold advection, appears in the central Pacific [55]. After the peak of CP El Niño, the westward current is further developed and appears in the whole equatorial region during February–March–April (FMA(1)), indicating termination of CP El Niño. The other important mechanism for CP ENSO is the latent heat feedback. Compared to the eastern Pacific where latent heat flux plays a damping role in the SST anomalies, there is a positive latent heat flux feedback to the SST warming in the equatorial central Pacific, which reinforces the surface warming [27,56,57].

Subtropical forcing mechanism

The view by Kao and Yu [25] and a series of follow-up studies [29,58] also considered that the CP and EP types of ENSO were produced by distinct mechanisms. Differing from Kug *et al.* [27], the authors proposed that the forcing from the subtropical Pacific Ocean and atmosphere was particularly important in triggering CP ENSO. The initial SST anomaly off the coast of Baja California is considered as a trigger of CP ENSO by a southwestward propagation [30,59], which is induced by atmospheric disturbance, particularly the North Pacific Oscillation [60]. As soon as the SST anomalies are established in the equatorial Pacific, local air–sea interaction including the ocean advection term emphasized by Kug *et al.* [27] quickly intensifies the SST anomalies into a full-blown CP ENSO event. Therefore, this view of CP ENSO dynamics involves three key processes: (i) the initial SST anomalies produced off the Baja California coast, (ii) the southwestward spread of the subtropical Pacific SST anomalies into the equatorial Pacific [29,61] and (iii) the equatorial Pacific coupling that intensifies the arriving SST anomalies into CP ENSO. The first and second processes invoke subtropical atmospheric forcing and subtropical Pacific coupling and are also known as the footprinting mechanism [62,63]. This view of the CP ENSO dynamics emphasizes the processes outside the tropical Pacific for the generation of CP ENSO, which is in contrast to EP ENSO dynamics that reside completely within the tropical Pacific. The recent study by Su *et al.* [64] demonstrated that forcing from the subtropical South Pacific can also affect CP El Niño, while Ding *et al.* [65] argued that more Northern Hemisphere extra-tropical processes triggered El Niño events that existed after 2000, which might be related to the frequent occurrence of CP El Niño.

THE ENSO TELECONNECTION MECHANISMS

ENSO affects the climate in different regions of the world via different teleconnection patterns. Figure 2 provides a schematic that illustrates the major teleconnection mechanisms enabling ENSO to affect the global climate, which are discussed as follows.

ENSO teleconnections within the tropics

Atmospheric bridge and tropical tropospheric mechanisms

Within the tropics, there are two major mechanisms that enable ENSO to affect the tropical Indian and Atlantic Oceans. The first major mechanism is the tropical tropospheric warming/cooling mechanism [66], which explains the spread of ENSO signals to the other two ocean basins via the propagation of Kelvin and Rossby waves in the tropical troposphere. In this mechanism, El Niño (La Niña) first causes warming (cooling) of the troposphere over the tropical central-eastern Pacific [67]. These temperature anomalies then excite Kelvin and Rossby waves that propagate eastward and westward, respectively, to spread the SST anomalies throughout the global tropics. These tropical tropospheric temperature anomalies then affect temperature and humidity in the atmospheric planetary boundary layer, resulting in SST anomalies in the tropical Indian and Atlantic Oceans through surface fluxes.

The second major mechanism is the atmospheric bridge mechanism [68–70] associated with the Walker circulations that span the tropical Pacific, Indian and Atlantic Oceans. During El Niño, the eastward displacement of convective activity weakens the Pacific branch of the Walker Circulation, resulting in anomalous descending motions over the tropical eastern Indian Ocean, which then induce an Indian Ocean warming via solar radiative and latent heat fluxes. This displacement also disturbs the Atlantic branch of the Walker Circulation, resulting in anomalous descending motions over the tropical Atlantic, which weaken the surface trade winds to produce Atlantic warming via surface latent heat fluxes.

Additional mechanisms for the tropical Atlantic Ocean

Wang [71] suggested that the El Niño-induced anomalous descending motions over the equatorial Atlantic can induce anomalous ascending motions over the Atlantic subtropical high region through the regional Hadley Circulation. The weakened subtropical high decreases northeast trade winds, resulting in warming in the tropical North Atlantic (TNA) region. Another popular mechanism to explain the TNA response to ENSO invokes a wave train response in the mid-latitudes. This mechanism suggests that the Pacific North American (PNA) pattern excited by El Niño (La Niña) events has an anomaly center over the southeastern US, which extends into the Atlantic and weakens (strengthens) the subtropical high, resulting in TNA warming (cooling). The ENSO-induced SST anomalies in the TNA region typically peak during March–April–May (MAM) after ENSO peaks but can linger through June–July–August (JJA) and beyond.

Additional oceanic mechanisms for the tropical Indian Ocean

Additional mechanisms are also needed to explain the more complex Indian Ocean response to ENSO, which includes the Indian Ocean basin warming and cooling [68–70,72] and the Indian Ocean dipole (IOD) [73,74]. Both the atmospheric bridge and tropical tropospheric mechanisms have been used to explain how the Indian Ocean basin warming (cooling) is induced by El Niño (La Niña). The mechanisms that enable ENSO to force the IOD are even more complicated.

The dynamics of the IOD has not been fully understood, although it has been linked to ENSO forcing [75,76] and non-ENSO-related processes in the Pacific and Indian Oceans [77–79]. Positive IOD events usually co-occur with El Niño events and are characterized by warmer SST in the tropical western Indian Ocean than in the tropical eastern Indian Ocean (vice versa for negative IOD events). The El Niño-induced anomalous descending motions over the southeastern Indian Ocean during its developing summer can intensify the climatological southeasterlies off Java and Sumatra to produce cold anomalies in the southeastern equatorial Indian Ocean [75]. These cold anomalies become the cold pole of the positive phase of IOD. Since the climatological trade winds reverse directions in boreal winter, the ENSO-induced anomalous cooling weakens and switches to a warming after October, answering why the intensity of ENSO-induced IOD typically peaks in the boreal fall [80]. The ENSO-induced anticyclonic wind stress anomalies in the southeastern equatorial Indian Ocean also excite a downwelling Rossby wave that propagates into the western Indian Ocean, where the climatological thermocline is shallow. The arrival of the Rossby wave deepens the local thermocline ridge and warms the regional SSTs [75,81], which becomes the warming pole of the positive IOD. The SST gradient across the equatorial Indian Ocean also triggers positive Bjerknes feedback to further facilitate the growth of IOD. Therefore, ocean dynamical processes are involved in establishing the ENSO–IOD teleconnection.

In addition, the Indonesian Through Flow has been also suggested to play a role in transmitting ENSO influence into the Indian Ocean. Pacific anomalies may leak via the through flow to first arrive at the Northwest Australia coast and then radiate into the Indian Ocean interior [82]. However, due to limited observations, the magnitude of this throughflow leakage and its importance for the ENSO teleconnections in the Indian Ocean are still a matter of debate.

The recent change in ENSO from the EP type to the CP type may have changed the ENSO impact on the Indian Ocean. The more westward-located positive SST anomalies of CP ENSO may induce weaker SST anomalies in the Indian Ocean than EP ENSO [83], possibly changing the ENSO–IOD relationship [84].

Downstream ENSO teleconnections to the Northern and Southern Hemispheres

Two major teleconnection mechanisms have been proposed for the impacts of ENSO on the middle-high-latitude climate downstream of ENSO: a wave train mechanism and an eddy–jet stream mechanism. The wave train mechanism emphasizes that ENSO heating or cooling in the tropical Pacific can excite stationary wave trains emanating from the tropics into the middle and high latitudes of the Northern and Southern Hemispheres, remotely influencing regions such as North and South Americas, the North Atlantic Ocean, the Antarctic, etc. The eddy–jet stream mechanism considers the ENSO influences on the strengths and locations of zonal-mean flows in the mid-latitude troposphere, which include the thermally driven subtropical jet stream and the eddy-driven polar jet stream.

The PNA and Tropical Northern Hemisphere (TNH) wave train mechanisms in the Northern Hemisphere

These two wave train patterns lead the variability modes of mid-latitude atmospheric circulations. They differ from each other in their spatial structures and their relationships to the two types of ENSO. As a result of these differences, the two patterns enable the two types of ENSO to produce different downstream impacts on the North American climate [30,85].

The PNA pattern [86] is a wave train pattern that has been often emphasized for producing remote impacts in the Northern Hemisphere. It is characterized by geopotential height anomalies that spread eastward and poleward from the tropical Pacific to Alaska and Canada and then equatorward through the US. The anomaly centers over the US tend to cause above-normal winter temperatures over the northern US and below-normal over the southern US during El Niño events and vice versa during La Niña events [30,87]. This pattern also causes an enhanced winter Pacific jet stream that extends farther east than normal toward the southern US during El Niño events. Since the jet stream determines the paths of winter storms, the PNA pattern enables ENSO to affect winter rainfall patterns in the US.

The TNH [88] pattern is another wave train pattern that has been invoked to establish a downstream teleconnection to the Northern Hemisphere. The associated geopotential height anomalies display centers over the tropical central Pacific and off the Pacific coast of North America and show a zonally elongated dipole crossing the North Atlantic Ocean [89]. Since the atmospheric wave train response to ENSO is sensitive to the exact location of maximum SST anomalies of ENSO [69,90–92], it is believed that EP ENSO excites primarily the TNH pattern while CP ENSO excites the PNA pattern [30,85]. Thus, due to the differences between these two patterns, the impacts of ENSO on North America are different between the two types of ENSO.

The Pacific South American (PSA) wave train mechanism to the Southern Hemisphere

For the Southern Hemisphere, the PSA [93]) pattern is the key pattern through which ENSO exerts its impacts on the South American and Antarctic climate via the downstream wave train mechanism [90,94]. The PSA pattern is characterized by a stationary Rossby wave train emanating from the tropical central Pacific with major anomaly centers to the east of New Zealand, over the Amundsen–Bellingshausen Seas and near the southern tip of South America, and its negative (positive) phase is related to El Niño (La Niña) [95]. Specifically, through this wave train pattern, ENSO affects Southern Ocean SSTs [96–98], Antarctic sea-ice concentrations [99–101] and Antarctic surface air temperatures [102,103].

The two types of ENSO affect the Southern Hemisphere climate differently through the combined effects of this wave train mechanism and the eddy–jet stream mechanism that modifies the response of the Southern Annular Mode (SAM) to ENSO. The CP ENSO tends to influence the Southern Hemisphere more strongly. The increasing occurrence of CP ENSO is associated with a PSA pattern that is more in phase with the SAM, giving rise to a stronger ENSO impact on the Southern Hemisphere climate [83,104], probably explaining the recent substantial warming in the West Antarctic via an enhanced ENSO-induced anticyclone over the Amundsen Sea [103].

Jet stream displacement mechanisms

The tropospheric jet streams serve as a transmitter to broadcast ENSO influence into the middle and high latitudes. During an El Niño event, the warming of the tropical troposphere strengthens and contracts the Hadley Circulation to move the subtropical jet stream equatorward and the displaced jet stream affects the central location of baroclinic eddies, which drives anomalous ascending motions in the mid-latitudes. The eddy forcing then induces anomalous adiabatic cooling in the mid-latitudes to displace the location of the polar jet stream, which is driven by north–south thermal gradient and the resultant baroclinic eddy forcing [105]. This series of eddy–jet stream responses enables ENSO to cause a latitudinal displacement of the zonal-mean flows in the middle-high latitudes via the Arctic Oscillation [106] in the Northern Hemisphere and the Antarctic Oscillation in the Southern Hemisphere.

Nevertheless, statistically significant correlations are observed only between ENSO and the SAM during austral summer but not between ENSO and the NAM [107], likely because the atmospheric circulation is more zonally symmetrical in the Southern Hemisphere than in the Northern Hemisphere. This feature allows the eddy–jet stream mechanism to be more effective in establishing the ENSO–jet stream relationship. The SAM tends to be in its positive phase during La Niña and negative phase during El Niño. The ENSO–SAM relationship during austral spring is stronger for the CP type of ENSO [83]. As a result, the CP ENSO exerts stronger impacts on the Southern Hemisphere climate by exciting a stronger SAM response than the EP ENSO.

Upstream ENSO teleconnections to the western Pacific and East Asia

Significant responses to ENSO have been observed in the northwestern Pacific and East Asia, which are located upstream of ENSO. To explain such upstream responses, a Gill-type response mechanism [108] has been used. This mechanism suggests that a pair of Rossby waves can be excited to the west of anomalous tropical heating or cooling. However, the Rossby wave response alone cannot fully explain the ENSO impacts that are observed in the northwestern Pacific and East Asia, located further west (i.e. more upstream) from ENSO, and usually peak in the boreal summer after ENSO decays. Two mechanisms have been proposed to explain these important features of the upstream ENSO teleconnections. One is the local air–sea coupling mechanism proposed by Wang *et al.* [109], who argued that the Gill-type response to an El Niño warming in the tropical central Pacific first excited a cyclonic wind anomaly pattern to the west of the warming, enhancing the mean trade winds and thus evaporation from the oceans. As a result, a cold SST anomaly center is induced to the west of the warm SST anomalies associated with El Niño. The induced cold anomaly then excites a second Gill-type response and an antic-cyclonic anomaly farther to the west [110]. Through this series of two Gill-type responses, El Niño is able to produce an anomalous anticyclone over the northwestern Pacific. The anticyclonic anomaly then reinforces the cold SSTs by enhancing the mean northeastern trade winds to strengthen surface wind speeds and surface evaporations. Through this wind–SST-evaporation feedback [111], the anomalous anticyclone and cold SSTs are maintained through the summer even after El Niño has ended. This upstream and delayed ENSO teleconnection can affect the strength of the western Pacific subtropical high (WPSH), profoundly influencing the East Asian weather and climate [112,113], in particular the monsoons and typhoon activity [114,115].

The Indian Ocean capacitor mechanism [116] is another mechanism that has been proposed to explain how the observed upstream and delayed ENSO teleconnection is produced. As mentioned, El Niño can induce warming in the Indian Ocean during the mature phase of El Niño. Through local air–sea interactions in the Indian Ocean, this warming can be maintained through the summer after El Niño decays. The Indian Ocean warming then excites a warm Kelvin wave response in the atmosphere that propagates eastward into the western Pacific. Surface friction then induces subtropical divergence on the northern flank of the Kelvin wave, which suppresses convection and forms a surface anticyclone over the northwestern Pacific. Besides producing a strengthened WPSH, the suppressed convection can also excite a wave train propagating northward toward Japan to form another important ENSO teleconnection in East Asia: the Pacific-Japan pattern [117].

The key to the Indian Ocean capacitor effect is the ability of ENSO to induce basin-wide warming or cooling in the Indian Ocean during its developing and maturing phases. If it is proven that the CP ENSO is less capable of inducing the Indian Ocean SST response than the EP ENSO, as argued by Yu *et al.* [83], the importance of the Indian Ocean capacitor effect may decrease when CP ENSO becomes more dominant. Additionally, El Niño can also contribute to the maintenance of the WPSH via the SST anomalies over the tropical Atlantic Ocean in the decaying summer [118].

Besides these two mechanisms, a combination mode mechanism [119] has recently been suggested to explain how ENSO can produce upstream impacts on the western Pacific and East Asia. The mechanism emphasizes that the non-linear interactions between ENSO and the annual cycle of the western Pacific can give rise to a near-annual mode of variability that is termed the combination mode [120]. This mode can modulate the inter-hemispheric structures of the atmosphere and ocean to affect the phase transition of ENSO and, at the same time, affect the WPSH intensity after ENSO decays.

THE CHANGING ENSO AND ITS CLIMATE IMPACT

Long-term changes in ENSO

Both paleo-climatic proxy record and instrumental record have shown that ENSO presents long-term changes in amplitude, frequency and other features [121–123]. In the past century, ENSO demonstrates significant characteristic changes on a decadal time scale, featured by larger amplitudes and longer persistence after the late 1970s [11,124,125]. The reasons for the amplification of ENSO strength in the last century are still uncertain. Without imposing anthropogenic forcing, simulations by various coupled general circulation models (GCMs) show that ENSO amplitude modulation, even on a century-long time scale, may be a result of natural variability [126,127]. However, several studies argued that the intensified ENSO amplitude could be partially contributed to by anthropogenic forcing, and there exists evidence that the atmospheric CO_2 concentration could exert an influence on tropical Pacific variability [128,129]. For example, forced by historically increased concentration of greenhouse gases, models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) demonstrate a 10–15% enhancement of ENSO amplitude since the pre-industrial era [130]. However, the feature may be model-dependent and different from the recent observed evidence. For example, in CCSM3, ENSO variability decreases in the global-warming scenario [131]. And, in the observations, ENSO variability has been suppressed since 1999/2000 [132]

Accompanied by the observed change in ENSO intensity, the recently emerging CP ENSO indicates the change in the dominant El Niño flavor in the last several decades. The mechanism for the higher CP ENSO frequency in recent decades is still not fully understood. There exists evidence that the frequent occurrence of CP ENSO may be related to anthropogenic forcing. For example, Yeh *et al.* [133] analysed the model simulations of the Climate Model Intercomparison Project's Phase 3 (CMIP3) and suggested that anthropogenic forcing contributed to an increased frequency of CP ENSO compared to EP ENSO. The flavor change is related to a flattening of the thermocline in the equatorial Pacific, which is favorable for amplifying the zonal advection feedback—the major dynamical feedback process in exciting CP El Niño. The internal positive feedback process between the climate mean state and the frequency of CP ENSO may also serve as a factor for increasing CP ENSO frequency. Choi *et al.* [134] analysed a GCM output and found that the frequent occurrence of CP El Niño increased the zonal contrast of tropical Pacific SST, which in turn resulted in more frequent CP El Niño events by enhancing the crucial zonal advection feedback.

The changing impact of ENSO

By modulating the *in situ* atmospheric deep convection, the spatial distribution of tropical SST anomalies can influence the atmospheric circulation dramatically [90,91,135]. As mentioned above, the atmosphere tends to be most sensitive to the changes in SST anomalies or SST gradient in the western Pacific warm pool and less responsive to the SST change over the eastern Pacific, where the climatological SST is below the convective threshold. However, as the variations in SST anomalies amplify from the western Pacific to the eastern Pacific, the climatological SST over the central equatorial Pacific is higher than that in the eastern Pacific and the amplitude of SST anomalies is higher than that in the western Pacific [136,137]. Therefore, the emerging occurrence of CP ENSO with sea-surface warming confined to the dateline region can exert significant changing impacts on the variations in precipitation and surface air temperature.

The changing impacts on tropical oceans

The IOD plays an important role in affecting the Indo-Pacific climate, the Asian monsoon and others. While ENSO and the IOD varied relatively independently in the 1950s [138], the relationship between the two has become closer since the mid-1970s due to the deep thermocline of the eastern equatorial Indian Ocean [80]. On intra-seasonal variations, Hsu and Xiao [139] suggested that, accompanied by more unstable atmospheric stratification induced by the enhanced moisture in the boundary layer related to CP El Niño, strengthened convection was found in the initiation and eastward-propagation phases. EP El Niño causes significant warming of the TNA via the atmospheric bridge mechanism in boreal spring [68], while the TNA does not display a robust response to CP El Niño events [140]. In addition, both EP and CP El Niño events can influence the South Atlantic Ocean via the Pacific South America pattern, although the feature is less robust than the response seen in the TNA [140,141].

The changing impacts on the North American climate

The EP El Niño impact on the North American climate has been documented by Ropelewski and Halpert [87] and Halpert and Ropelewski [142], among others. The response in winter temperature is traditionally characterized by a north–south dipole pattern, in which anomalously warm temperatures are over the northern US and southern Canada, and cold temperatures over the southern US [87,143]. However, Yu *et al.* [30] demonstrated that the temperature over northwestern and southeastern US was most sensitive to CP El Niño (see Fig. 3), resulting from different atmospheric wave train patterns in response to the SST anomalies in

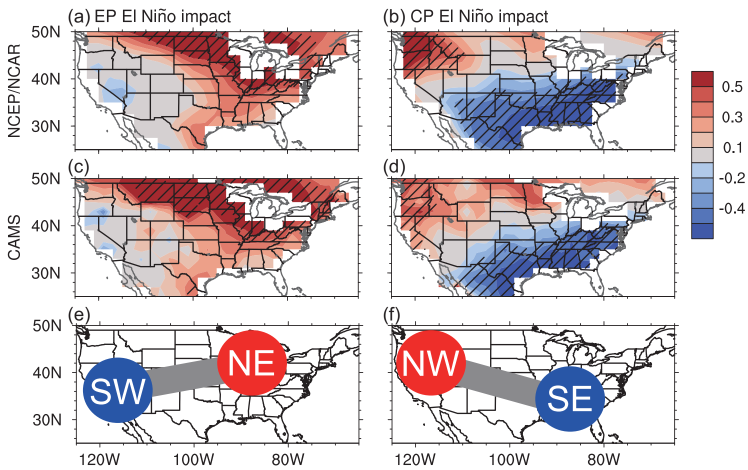

Figure 3. US winter (JFM) surface air temperature anomalies regressed onto EP El Niño (left panels) and CP El Niño (right panels) indices based on (a) and (b) the NCEP-NCAR reanalysis and (c) and (d) the CAMS air temperature data set. Regression coefficients significant at the 90% confidence level are shaded. (e) and (f) Conceptual diagrams of the impacts of EP El Niño and CP El Niño on US winter surface air temperature (from fig. 1 in Yu *et al.* [30]).

the two types of ENSO, as discussed in the third section of this article. Moreover, the recent increasing frequency of CP ENSO has led to more exposure to the El Niño influence over the northwestern and southeastern US. In addition to the robust change in wintertime temperature, Weng *et al.* [144] suggested that the dry-north and wet-south pattern in the western US more likely occurred during CP El Niño, while much of the western US was wet during EP El Niño.

The changing impacts on Asian and Australian monsoons

EP El Niño events are associated with reduced precipitation over the Indian and Australian monsoon regions [4,87,145]. However, a case analysis shows that, while moderate CP El Niño events (e.g. 2002, 2004) have resulted in severe droughts in India [146], the super El Niño in 1997/98 exerted a very limited influence on the Indian summer rainfall. Similar results can also be found in the Australian monsoon region [147,148]. In highly populated East Asia, the interaction between ENSO and monsoons is linked by a low-level anticyclone over the Philippine Sea [109,149]. The anticyclone forms in fall and persists to the ensuing summer. It strengthens the WPSH and causes enhanced precipitation in southeastern China [32,112,150]. During CP El Niño, however, the anticyclone is weaker and is confined to the west of the Philippines [151] (see Fig. 4). Yuan and Yang [16] then showed that an anomalous –/+/– rainfall anomalous pattern appeared during CP El Niño in East Asia in summer. The dry condition over southeastern China and the northwestern Pacific during CP Niño results likely from the anomalous anticyclone [151]. Chen *et al.* [152] also pointed out that CP El Niño played a crucial role in forming the triple precipitation anomaly pattern over East Asia, which was less clear and shifted southeastward during EP Niño. Nevertheless, although statistically significant, the limited sampling may restrict the robustness of the conclusions. For example, through observational diagnosis and model simulations, Hu *et al.* [153] argued that the surface air temperature anomalies over the Eurasian continent are not significantly affected by the type of El Niño. Also, the changes in the mean state, especially the mean SST over the western Pacific warm pool, contribute to the changing ENSO-related impact on the Asian summer monsoon [154]. Meanwhile, due to the shift in the ENSO-driven Walker cell anomalies and the warming over Eurasia, the relationship between ENSO and the Asian monsoon also changes [155]. Although the results from four models (the Geophysical Fluid Dynamics Laboratory Climate Model versions 2.0 and 2.1 (GFDL_CM_2.0 and GFDL_CM_2.1), the Meteorological Research Institute (MRI) model and the Max Planck Institute ECHAM5 (MPI_ECHAM5)) with a robust ENSO–monsoon connection suggest that the relationship between ENSO and the South Asian summer monsoon will not weaken with global warming [156], the relationship is projected to become weaker by the majority of models [157].

The changing impacts on tropical cyclones

Cyclone activity is often weakened during El Niño but activated during La Niña. However, an increased frequency of Atlantic hurricanes is associated with the warming over the central Pacific and the likelihood of landfall along the Gulf of Mexico and Central America is higher [158]. Over the western North Pacific, TC frequency is significantly higher during CP El Niño compared to the case of EP Niño [159]. Due to the favorable boundary layer condition for cyclogenesis in the central Pacific during CP El Niño, the occurrence of strong typhoons over the western North Pacific is significantly higher in autumn compared to EP El Niño [160]. Over the South China Sea, the displacement of WPSH during the EP El Niño is favorable for typhoons to make landfall in China [115,161]. However, the recent work by Han *et al.* [162] pointed out that the GCMs struggled in capturing the differences in TC activity between EP El Niño and CP El Niño, as shown in observations, possibly due to the bias of the models

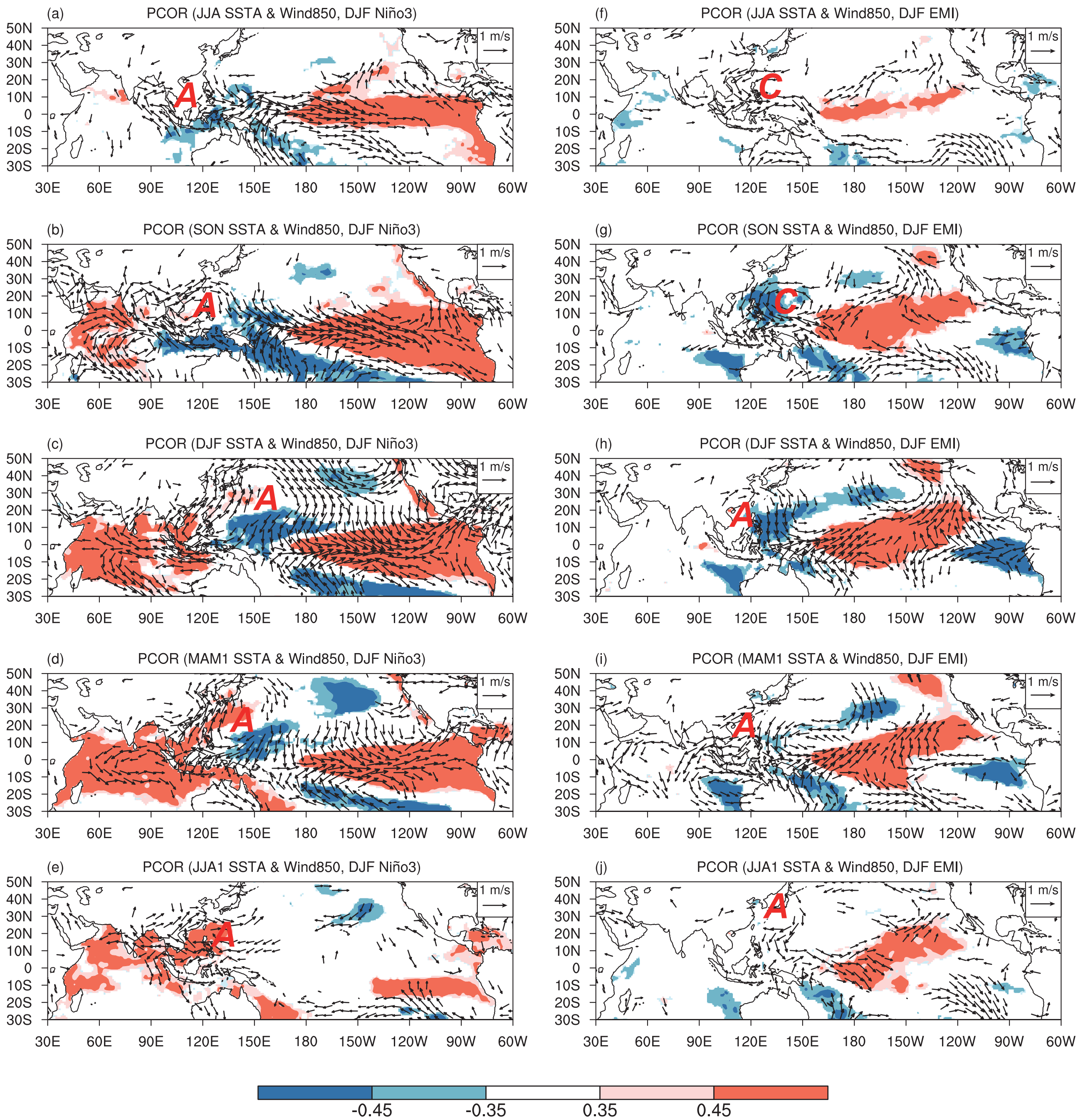

Figure 4. (a)–(e) Partial correlations of seasonal SST (shadings) and 850-hPa winds (vectors) with normalized DJF Niño-3 indices and (f)–(j) DJF EMI (El Niño Modoki indices). Shadings indicate correlations above the 95% and 99% confidence levels; only the vectors significantly above the 95% confidence level are shown. 'C' ('A') denotes anomalous cyclone (anticyclone) (from fig. 1 in Yuan *et al.* [151]).

in response to the shift of tropical heating associated with CP El Niño.

The changing impacts on mid-latitude and polar climates

As pointed out by Ashok *et al.* [10], CP El Niño exerts a significant influence on the wintertime storm-track activity in the Southern Hemisphere. It was further shown that CP events led to more blocking conditions over Australia associated with warming in the subtropics and a southward-shifted subtropical jet stream in the eastern Pacific [163]. Recently, Wilson *et al.* [164] used the National Center for Atmospheric Research (NCAR) Community Atmosphere Model to reveal that both EP and CP El Niño conditions supported the observed feature that there were stronger equatorward momentum fluxes on the equatorward side of the eddy-driven jet stream, shifting the jet equatorward.

Moreover, the changing ENSO affects the polar climate by altering the planetary wave patterns. Hegyi and Deng [165] revealed that the increasing CP El Niño drove a stationary Rossby wave train that interfered with the zonal wave number 1 component of the extra-tropical wave. The interference suppressed upward propagation of wave energy into the stratosphere, causing a stronger stratospheric polar vortex and a tendency to forming a positive phase of the Arctic Oscillation. Thus, a poleward shift of the NH storm tracks could be found, particularly in the North Atlantic. Hu *et al.* [166] demonstrated that the emerging CP El Niño events deepened the tropospheric polar vortex and strengthened the circumpolar westerly wind in the Arctic, thereby inhibiting summer Arctic warming and sea-ice melting. Atmospheric model experiments confirmed the observed responses of Arctic circulation and the surface temperature to CP El Niño forcing. For the Southern Hemisphere, Yu *et al.* [83] discovered a change in the early 1990s in the relationships between ENSO and two leading modes (SAM and PSA) of the Southern Hemisphere atmospheric variability. While the PSA maintained a close correlation with ENSO in 1940–2014 during austral spring, the SAM–ENSO correlation became strong after the early 1990s. In addition, while both EP ENSO and CP ENSO can excite the PSA, only CP ENSO exerts a significant impact on the SAM through the tropospheric and stratospheric pathway mechanisms.

ENSO IN THE FUTURE

Changes in the properties (e.g. amplitude, spatial pattern, temporal scales, etc.) of ENSO during the recent decades are likely linked to global warming [25,27,133]. These changes in ENSO variability exert feedback on the global climate change in turn. Climate models have been widely used for studying the projections of ENSO in the future climate [167–169]. These projections have been focused on three key questions: how ENSO intensity may change in the future [170,171], how the location of maximum ENSO variability may be shifted in the future [58,172–174] and how ENSO teleconnection may be affected by the changing mean states in the atmosphere and oceans [175–177]. The prevailing views on these three questions are summarized in this section.

Changes in intensity and frequency

Model consensus

Given the significant impact of ENSO on global climate, how ENSO intensity and frequency will change in the future is of great concern. Compared to the projections by CMIP3 climate models, the ENSO response to global warming in CMIP5 models showed robust projected changes in certain aspects such as the increase in extreme El Niño and La Niña events [178–180] and the reduction in the asymmetry of ENSO amplitude due to global warming [181]. Cai *et al.* [178,182] used the ENSO-related rainfall anomalies to describe ENSO strength and pointed out that there would be increasing extreme El Niño and La Niña events in a warmer future climate. The frequency of extreme El Niño events may continue to increase for one century after the greenhouse gases have or the global mean surface temperature has stabilized [180]. However, the ensemble means of multi-model SST anomalies do not exhibit the similar signal as clear as rainfall anomalies, due possibly to the non-linear relationship between SST and precipitation [181,183,184]. CMIP5 simulations also exhibit a reduction in Nino3 skewness in the future climate state compared to that in the historical simulations [181], which may partially result from a larger increase in extreme La Niña events than extreme El Niño events [185].

Diversity in ENSO intensity and frequency

Compared to CMIP3, the ability of CMIP5 in simulating ENSO has been significantly improved in terms of either individual model or ensemble mean. However, there is still no consensus about how ENSO intensity and frequency will change in a warmer climate [170,171].

For ENSO intensity, as measured by SST standard deviation, about half of the models show no significant response to increasing greenhouse gases, while the rest indicate either strengthening or weakening [169,186–188]. Furthermore, Zelle and Dukstra [189] examined 62-member ensemble simulations by employing the NCAR Community Climate System Model (CCSM, version 1.4) and found no obvious change in ENSO amplitude under warmer scenarios.

Substantial effort has been devoted to understanding the fundamental processes that control the ENSO amplitude change under global warming. When most of the energy is consumed by the seasonal cycle, little is left for inter-annual signals. In this case, El Niño amplitude tends to be an inverse function of the relative strength of the annual cycle and the mean climate state [190]. Subsurface thermocline properties are thought to be the key for El

Niño amplitude change, as in the thermocline and zonal advective feedback [34]. Atmospheric feedback is also considered as a main source of inter-model diversity of ENSO amplitude under global warming [191]. To a large extent, these uncertainties in ENSO-related feedback processes are further attributed to the diversities of changes in climate mean state, such as the changes in mean zonal thermocline slope and mean zonal SST contrast [187,192], climatologic mean Pacific subtropical cell [34,193], mean meridional overturning circulation in the equatorial Pacific Ocean [34] and atmospheric mean state related to tropical precipitation [194]. It should be noted that CMIP5 models ensure a high level of consistency in basin-wide warming in the tropic Pacific: a stronger warming in the equatorial eastern Pacific and a weakened Walker Circulation in a warmer climate [130,195–197]. ENSO fluctuation shows different characteristics under the similar basic climate changes because ENSO is sensitive to the mean state among the different models [191,198].

For frequency, it is hard to reach an agreement about how ENSO will change in the future climate [170,199,200] and results are largely model-dependent. Timmermann *et al.* [199] applied a global atmosphere–ocean GCM model [201] and found that more frequent El-Niño-like conditions and stronger cold events would occur under global warming. Using the HadCM2 and HadCM3 models, Collins [202] found an increase in the frequency of ENSO at 4 × CO_2 in the HadCM2, but no significant change at 4 × CO_2 in the HadCM3. Zelle *et al.* [189] found no apparent change in ENSO frequency in a warmer climate based on the CCSM1.4. To obtain a reliable projection, models should reproduce ENSO realistically in the present era [203], such as its seasonal phase locking feature [170]. Multi-model ensemble (MME) results from both CMIP3 and CMIP5 show comparable seasonal phase locking, whereas individual models show that ENSO can peak at any season. Given the apparent model bias in historical ENSO frequency, it is challenging to project ENSO frequency in the future climate. Additionally, the discrepancy in observational data sets may be another factor causing the diversity in ENSO intensity and frequency.

Change in the type of ENSO

ENSO diversity is another featured issue in the framework of ENSO dynamics. Several studies have referred to the more frequent occurrence of CP-type ENSO as a climate response to global warming [133], while others have suggested it as a part of the natural variation [204,205]. The science community has strived to answer how the EP and CP types of ENSO will change in a warmer climate. Compared to the CMIP3, the CMIP5 models perform better in simulating the two types of ENSO [58,173,174] with a clearer CP type of ENSO and smaller inter-model spread. Based on the experiments by the CMIP5 models that can simulate EP and CP ENSO events as observed, Kim and Yu [173] found responses of strengthened and more frequent CP events but uncertain EP events under the RCP4.5 scenario. However, Taschetto *et al.* [206] suggested that there was no notable enhancement of the ratio of CP/EP ENSO under the RCP8.5 scenario. Xu *et al.* [207] examined the ENSO response under the RCP8.5 scenario and found that EP events would be weaker but no robust change occurred to CP events. According to the discussion above, there is controversy about the relative frequency from CP to EP El Niño events in a warmer climate, as well as their relative intensity. It should be noted that the inconsistent responses of CP-type events to a warmer climate suggested by Taschetto *et al.* [206] and Xu *et al.* [207] are based on the output from 34 models, some of which cannot simulate EP and CP ENSO events realistically.

Changes in ENSO impacts

The potential change in ENSO under global warming may distinctly affect the global climate. Here, we focus on the changes in ENSO teleconnection and climate impact forced by increased greenhouse gases reflected by MME results, in spite of the inter-model diversity.

ENSO-related climate impacts can be robust due to the highly consistent basic state climate evolution such as the El Niño-like ocean warming pattern in the tropic Pacific. A larger climatological mean of water vapor content over the equatorial Pacific forced by increasing greenhouse gases results in an intensified ENSO-related rainfall anomaly [177–179,207], although the rainfall anomaly may be partly offset by the simultaneously weakened atmospheric circulation [208]. The intensified ENSO-related rainfall anomaly in turn maintains a stronger western North Pacific anticyclone during the decaying phase of El Niño [188]. The El Niño-like warming pattern in the tropic Pacific may also cause an eastward shift in the main convection centers, resulting in a systematic eastward shift of the ENSO-related teleconnection pattern [27,209]. Correspondingly, the ENSO-induced PNA teleconnection pattern associated with an eastward and northward-shifted anomalous low is expected to intensify the rainfall anomalies over the west coast of North America and cause temperature to increase (decrease) throughout northern (southern) North America [209]. Generally, broader impacts of ENSO over land can be found from the CMIP5 projection [210]. The warming in the tropical mid- and upper troposphere forced by the greenhouse effect tends to increase atmospheric stability, which may suppress the circumglobal teleconnection and weaken the relationship between the Indian summer monsoon and ENSO [175,176] but significantly enhance the relationship between the Asian–Australian monsoons [211].

Thus, although there are large uncertainties in the responses of ENSO properties and related climate impacts to increasing greenhouse gases, part of the ENSO-related climate impacts is closely linked to the robust changes in the mean climate state under the future emission scenario. However, there is still a large gap between observation and model simulations. For instance, under the influence of increasing GHG concentrations, models projected El Niño-like warming in the tropical Pacific with weakened easterly trade winds and Walker Circulation [186,212], while observations show significant La Niña-like SST anomaly patterns in the tropical Pacific in the last three decades [213,214]. Although the long-term changes in observed and simulated SST are different, both indicate that the CP-type ENSO occurs more frequently. This may be because the long-term change in SST from observations includes other features such as decadal variations and is thus more complicated than that from model simulations. Given the various model biases for the historical simulation, however, there is a large uncertainty in whether the projected changes for ENSO and related behaviors would actually take place.

SUMMARY AND DISCUSSIONS

This article reviews ENSO and its climate impacts including the mechanisms for ENSO occurrence, the characteristics of ENSO, the ENSO-related teleconnections patterns, the impacts of ENSO on global climate and the long-term changes in ENSO and related climate features observed and projected for future climate. The major mechanisms that explain the occurrence of ENSO include the theories of the delayed oscillator, the discharge/recharge oscillator, the western Pacific oscillator and the advective/reflective oscillator, most of which are within the Bjerknes feedback framework. As a powerful phenomenon that explains much of the skill source of seasonal-to-inter-annual climate prediction, the occurrence of ENSO is always accompanied by significant atmospheric teleconnection patterns and climate anomalies over many places of the world. ENSO-related teleconnection patterns occur over not only the tropical Pacific, Indian and Atlantic Oceans, but also the middle- and high-latitude regions both downstream of ENSO (North and South America, the North Atlantic Ocean, the Antarctic, etc.) and upstream of ENSO (e.g. the northwestern Pacific and East Asia). These patterns, associated with changes in the mean flow, wave trains and the eddy–jet stream interaction, cause significant temperature and precipitation anomalies over those regions via different mechanisms.

However, ENSO has experienced apparent changes, especially those in its flavor from the traditional eastern Pacific type to the central Pacific type, and many features associated with ENSO including its climate impacts have changed. These changes occur not only in temperature and precipitation, affecting the daily life of human beings, but also in disaster weather and climate events, often causing enormous loss in economy and lives. The changes in ENSO also lead to alterations in the relationships between ENSO and other climate systems such as the monsoons. In addition, the changing ENSO is a challenge to the sector of operational climate prediction.

The future changes in ENSO, which can only be understood using climate models, are still unclear at present. Large uncertainties remain in the projections of ENSO properties such as ENSO intensity, frequency and even flavor by climate models. Even the state-of-the-art models cannot reach agreement about whether more or fewer El Niños will occur, whether El Niños will become stronger or weaker and whether El Niños will occur more or less frequently. Correspondingly, many features about ENSO teleconnections and climate impacts revealed by model projections need to be explained and applied with cautions. Nevertheless, climate models tend to agree that, in the warming climate, the anomalies of tropical Pacific SST are more El-Niño-like. They also agree that there will be more CP types, instead of EP types, of El Niño in the warming future. This information, plus our knowledge of the current ENSO properties and climate impacts, may be helpful for understanding and predicting the variations of future climate.

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