Historical change of El Niño properties sheds light on future changes of extreme El Niño

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El Niño’s intensity change under anthropogenic warming is of great importance to society, yet current climate models’ projections remain largely uncertain. El Niño events have been classified as eastern Pacific (EP) and central Pacific (CP) El Niños based on the location of the maximum warming (3–10). This classification, however, does not distinguish strong El Niño from moderate ones, although strong El Niño usually exhibits an EP pattern (11), making it difficult to project future change of El Niño intensity. Objective delineation of El Niño-Southern Oscillation (ENSO) diversity on a firm physical basis and using long records is required to distinguish the strong and moderate events and to understand the physics governing changing ENSO properties.

Three Types of Dynamically Distinguished El Niño Events

Different from past classification schemes, we delineate El Niño events based on their evolution from the preonset to mature phases, including initiation, development, propagation, and intensity. A nonlinear K-means cluster analysis (12) (SI Appendix, Method) is applied to the evolution of equatorial sea-surface temperature anomalies (SSTAs) in 33 El Niño years during the period of 1901 through 2017 when reanalysis data are more reliable (SI Appendix, Method). The analysis uncovers 4 physically meaningful clusters. Fig. 1 shows the composite spatial–temporal structures of their SSTAs. The 4 composite patterns generally represent well the individual events within respective composite groups, although the strong basin-wide (SBW) group is less homogeneous before the onset (SI Appendix, Fig. S1).

Clusters 1–3 (Fig. 1 A–C) depict the first-year El Niño events and they are, respectively, SBW, “moderate eastern Pacific” (MEP), and “moderate central Pacific” (MCP) events. Cluster 4 depicts 2 consecutive El Niño years (Fig. 1D) and so is named a “successive” El Niño. Table 1 summarizes characteristics of the SBW, MCP, and MEP El Niños shown in Figs. 1 and 2.

Significance

How the magnitude of El Niño will change is of great societal concern, yet it remains largely unknown. Here we show analysis of how changing El Niño properties, due to 20th century climate change, can shed light on changes to the intensity of El Niño in the future. Since the 1970s, El Niño has changed its origination from the eastern Pacific to the western Pacific, along with increased strong El Niño events due to a background warming in the western Pacific warm pool. This suggests the controlling factors that may lead to increased extreme El Niño events in the future. If the observed background changes continue under future anthropogenic forcing, more frequent extreme El Niño events will induce profound socioeconomic consequences.

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Data deposition: All data generated in this analysis are available on figshare (https://figshare.com/articles/Data_deposition_for_El_Niño_diversity/8922760) and are available upon request.

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positive thermocline and SST anomalies in the far EP by about 2 to 3 mo (Fig. S2), suggesting that the anomalous westerlies trigger EP warming by exciting eastward-propagating downwelling Kelvin waves (13–15). As a result, the strong events are characterized by a ubiquitous basin-wide warming.

The MEP El Niños (12 events) are notably preceded by La Niña events (Fig. 1B). The warming originates from the far EP, and then propagates westward and reaches a maximum intensity around 130°W in December (Fig. 1B). The onset occurs around July in the Niño 3 region, coupled with convective anomalies in the CP and westerly anomalies in the western Pacific (SI Appendix, Fig. S2B). An exclusive feature of the MEP Niño is the dramatic reversal of easterly anomalies from February to June over the central-western Pacific, which is accompanied by a sudden relaxation of thermocline slope and thermocline deepening in the EP (Fig. 2B), triggering a rapid EP warming (Fig. 2B, 7–9). The warming propagates westward because an SST- induced positive wind-stress anomaly promotes warming to its west by suppressing upwelling, deepening the thermocline, and reducing evaporative cooling.

In contrast, the MCP El Niños (8 events) begin with a prolonged mild warming in the western Pacific (~165°E), move and expand eastward, reaching a maximum in the CP (Fig. 1C). The onset occurs around July with maximum warming at the dateline, which is tightly coupled with convective and westerly anomalies located slightly to the west of the dateline (SI Appendix, Fig. S2C). Compared with SBW events, the westerly anomaly is much weaker and occurs later after April (Fig. 2C). The MCP El Niño develops near the dateline where the climatological SST gradient is large. The anomalous westerlies associated with the MCP events are strong over the central-western Pacific (Fig. 2C), favoring a strong zonal advective feedback (5–9).

The 3 types of El Niño onset identified by the cluster analysis involve distinctive dynamical processes. This assertion is supported by an ocean mixed-layer heat budget analysis (Method). As shown in Table 2, during June, July, and August, the zonal advective feedback is much stronger in the MCP event (0.15 °C month⁻¹) than in the MEP event (0.06 °C month⁻¹); on the other hand, the thermocline feedback is stronger in the MEP event (0.08 °C month⁻¹) than in the MCP event (0.05 °C month⁻¹). Interestingly, the zonal advective (0.35 °C month⁻¹), thermocline (0.23 °C month⁻¹), and upwelling (0.26 °C month⁻¹) feedbacks are all strong in the SBW events, leading to their distinctive large amplitude. In addition, over the CP, the zonal advective feedback is stronger in all 3 cases, whereas over the EP, the thermocline feedback is stronger than the zonal advective feedback in the MEP and SBW events. The mixed-layer heat budget results may change somewhat when another ocean reanalysis dataset is used (16), but the qualitative conclusions are unlikely to be changed.

Comparing with the existing classification of El Niño events, the present categorization distinguishes between the strong and moderate El Niño events and also between the first-year and successive El Niño. The strong events originate from the western Pacific (similar to the MCP-El Niño) but mature in the EP (similar to the MEP-El Niño) and they involve both the zonal advective feedbacks in the CP (as in the MCP-El Niño) and the thermocline feedback in the EP (as in the MEP-El Niño). Classification based

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**Table 1. Comparison of the characteristics of the MCP, SBW, and MEP events**

<table>
<thead>
<tr>
<th>Phase</th>
<th>MCP</th>
<th>SBW</th>
<th>MEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preonset</td>
<td>Prolonged weak warming in WP</td>
<td>Initial warming and strong WWBs in WP</td>
<td>La Niña conditions</td>
</tr>
<tr>
<td>Onset</td>
<td>Summer at CP</td>
<td>Spring, basin-wide</td>
<td>Summer at EP</td>
</tr>
<tr>
<td>Development processes</td>
<td>Zonal advective feedback</td>
<td>Zonal advective and thermocline/upwelling feedbacks</td>
<td>Thermocline feedback</td>
</tr>
<tr>
<td>SSTA propagation</td>
<td>Eastward</td>
<td>Eastward at onset</td>
<td>Westward</td>
</tr>
<tr>
<td>Mature</td>
<td>~160°W (1.0 to 2.5 K)</td>
<td>~120°W (&gt;2.5 K)</td>
<td>~140°W (1.0–2.5 K)</td>
</tr>
</tbody>
</table>
only on the locations of the maximum warming in the mature phase would mix the SBW events with the MEP events. The present analysis finds that SBW and MCP events share a common western Pacific origin and 3 super SBW events occur in the period that MEP events prevail. On the other hand, SBW events are distinguished from the MEP events by the prominent westerly anomalies in the western CP occurring from January to April (Fig. 2). During the EI Niño developing summer, the SSTAs associated with 3 types of EI Niño onset show distinct differences in both the locations and intensities of maximum SSTAs; thus, their impacts on global land precipitation are expected to be distinctive.

**Change of the EI Niño Onset under the 20th Century’s Climate Change**

The change of EI Niño properties under the 20th century’s climate change remains a gap in our knowledge. The classification reveals that all of MEP events occurred before the late 1970s, while all of MEP events occurred after the late 1970s (Fig. 3). Three out of 5 SBW events, namely the 3 extreme EI Niño events (1982 to 1983, 1997 to 1998, and 2015 to 2016) all occurred after the late 1970s. Note that the 3 extreme events occurred in the years adjacent to MEP EI Niños, not MEP EI Niños. Thus, since the late 1960s, the EI Niño onset changes from an EP origin to a western Pacific origin with intermittent SBW events having occurred more frequently in coincidence with MEP events. This is likely a consequence of sharing their common origin in the western Pacific. Similar to MEP events, the recent extreme EI Niño events have all originated from the western Pacific and initially propagated eastward. The change of the EI Niño onset and propagation patterns since the late 1970s was documented in the 1990s (17) and has continued to date (Fig. 3).

The change of EI Niño onset regime around the late 1970s is statistically significant. Table 3 shows a 2-way table for testing the statistical significance of the changes of the frequency of occurrence of the 3 types of EI Niño before and after the late 1970s. The \( \chi^2 \) test indicates that the regime shift around 1978 is significant at the 99.9% confidence level.

What has caused the observed change of EI Niño regimes? It has been recognized that decadal variations of the background state may have profound impacts on ENSO behavior (17–19). Fig. 4 shows the equatorial background-state changes. The equatorial western Pacific has experienced a significant warming trend coincident with global warming (Fig. 44) but the central-EP has not. As such, the equatorial zonal SST gradient around the dateline, defined by SST (5°S–5°N, 135°E–165°E) minus SST (5°S–5°N, 165°W–135°W), has been enhanced since 1980. Consistent with the increased westward SST gradient, the easterly trade winds near the dateline (150°E–150°W) have also strengthened and the thermocline has shallowed in the past 4 decades with the largest shoaling occurring in the NINO3.4 (120°W–170°W) region (Fig. 48), which results from the enhanced easterlies in the CP and the basin-wide wind anomalies (20). This thermocline shoaling together with surface layer warming has substantially increased the vertical temperature gradients (upper-ocean stratification) across the equatorial Pacific.

These changes in the background conditions over the past 4 decades are arguably favorable for the occurrence of MEP and SBW EI Niño events. First, the warming in the western Pacific increases the zonal SST gradients across the dateline, and thus enhances the zonal advective feedback process, which is conducive to EI Niño being initiated in the NINO4 (160°E–150°W) region. This explains why MCP and SBW events tend to occur coincidently and predominantly after the late 1970s. To support this argument, we show, in Fig. 5, that the observed NINO4 SSTAs
Changes in the equatorial ocean temperature (the upper 300 m) climate during the El Niño onset phase (April through August) indeed increases with the increasing mean-state zonal SSTA gradient measured by SSTA (5°S–5°N, 135°E–165°E) minus SSTA (5°S–5°N, 15°E–150°W) with a significant correlation coefficient $r = 0.85$ ($P < 0.01$). To a large extent, the explanation here is also consistent with the results obtained from coupled climate model experiments (21), in which an initial warming in the western Pacific is associated with strong zonal gradients of mean SST and trade winds in the equatorial CP. Second, the western Pacific warming provides favorable conditions for the Madden-Julian Oscillation (22) events to move into the western Pacific more frequently (23), increasing the frequency of WWBs and thereby the probability of occurrence of SBW events. In addition, the increased vertical temperature gradients strengthen the thermocline feedback, favoring occurrence of SBW events.

Implication for the Future Change of El Niño Properties

The aforementioned observational analysis reveals the controlling factors that would lead to increased large-amplitude El Niño events in the future. We hypothesized that more frequent occurrences of SBW and MCP events require an enhanced zonal SSTA gradient in the CP. We have tested this hypothesis using 8 CMIP5 (Coupled Model Intercomparison Project phase 5) models’ historical runs and future projection results (Methods). We find that the model results are consistent with the hypothesis derived from the observations. Under anthropogenic forcing-induced warming, the 8 CMIP5 models project different changes in the mean-state zonal equatorial SSTA gradients measured by the western Pacific (WP) SST (5°S–5°N, 150°–180°E) minus EP SST (5°S–5°N, 120°–150°W) (Fig. 6). As shown in Fig. 6, when the zonal mean SSTA gradient increases under the anthropogenic forcing, both the frequency of occurrence and the intensity of the SBW El Niño events increase significantly. This implies that if anthropogenic forcing enhances the SSTA gradients in the CP as we have observed over the past century, the extreme El Niño events will occur more frequently.

Conclusion and Discussion

In the present work, consideration of the onset and evolution of El Niño events (Figs. 1 and 2) has led to the innovative classification of El Niño diversity, and uncovered an El Niño onset regime change from an EP origin to a western Pacific origin in the late 1970s (Fig. 3). The onset changes and more frequent occurrence of the extreme events in the past 4 decades arise from a background warming in the equatorial WP and the associated enhanced zonal SSTA gradients in the equatorial CP (Fig. 4). This reveals that a controlling factor that could lead to increased extreme El Niño events in the future is the enhanced mean-state zonal SSTA gradient in the CP. Observation suggests that increased zonal SSTA gradients in the CP favor the development of warming in the NINO 4 region (Fig. 5). The CMIP5 models’ historical simulations and future projections also indicate that both the frequency and intensity of the strong El Niño events increase significantly with increased mean-state CP zonal SSTA gradients (Fig. 6).

While the observed background-state changes in the Pacific Ocean are responsible for the changing El Niño properties, the root causes of the observed background changes in the later part of the 20th century remain elusive and the background SST changes also remain uncertain due to differences among SST datasets (24). It could be linked to natural internal variability (25, 26) because, even in the absence of external radiative forcing, coupled general circulation models can generate multi-decadal variations of the mean state and ENSO diversity (27). However, the change of El Niño in the late 1970s coincides with a rapid warming in the Indo-Pacific warm pool, suggesting that the recent rapid global warming may have had an impact on the observed El Niño changes. Note that this recent global warming need not have been due solely to anthropogenic forcing. The forced component of recent tropical SST trends, as given by the ensemble mean of climate model simulations, is much weaker and more spatially homogeneous than the observed SST trend (28). Natural variability may have added significant contributions to the recent warming. While we attribute the El Niño onset...
regime change to the mean SST gradient change, there is an alternative possibility that the mean-state change is affected by the rectification effect of the randomly changing El Niño and La Niña due to their nonlinear asymmetry (25, 29).

The future change of ENSO amplitude is an extremely important issue. Fig. 3 indicates that El Niño amplitude change is primarily determined by the frequency of SBW El Niño events; in addition, SBW events tend to concur with MCP events. More frequent occurrences of SBW and MCP events require enhanced SST gradients in the western-CP which can enhance zonal advective feedback and increase the probability of WWB occurrence in the WP. In addition, increased upper-ocean vertical temperature gradients in the central-EP may favor SBW events by enhancing the thermoline and upwelling feedbacks. If anthropogenic warming produces a mean-state change similar to the recent change, more frequent MCP and strong El Niño events will occur; however, an El Niño-like mean-state change will favor prevailing MEP events, reducing the frequency of extreme El Niño events.

The current generation of models has great difficulty in capturing the El Niño diversity and the projected Pacific mean-state changes are highly uncertain due to models’ biases in simulating mean states and ENSO (30, 31). The impact of climate change on the mean east–west gradient of SST in the tropical Pacific has been an issue of some debate. The “weak Walker circulation” theory (32, 33) proposes that the Walker circulation must slow down because the greenhouse-gas-induced warming increases atmospheric static stability. The weakened Walker circulation, in turn, reduces the east–west SST gradient by a mechanism known as “the Bjerknes feedback.” On the other hand, the “ocean dynamical thermostat” theory (34, 35) argues that increased heating at the surface warms SSTs in the west more because the heating in the east is offset by cold upwelling. The increase in SST gradient induces an enhanced pressure gradient and hence a stronger Walker circulation, which in turn enhances the SST gradient. The present work indicates that the uncertainty in the projected equatorial zonal SST gradients currently prohibits faithful prediction of the future change in El Niño. The cluster analysis for delineating ENSO diversity provides a metric for validation and improvement of the capacity of climate models to reproduce the observed ENSO complexity, which is critical for improved ENSO prediction and reduced uncertainties in future projection of ENSO changes.

Methods

Definition of El Niño Years (1901 through 2017). The SST anomaly averaged in the NINO 3.4 region (5°N–5°S, 120°–170°W), known as Oceanic Niño Index (ONI), is averaged for October-November-December-January-February (ONDJF) to identify El Niño years, because ONI has largest variances during ONDJF (SI Appendix, Fig. S5B). An El Niño year is defined as ONDJF ONI is greater than or equals to 0.6 °C. Using the linearly detrended data, 33 El Niño years are identified.

Cluster Analysis. The K-means cluster analysis (12) uses squared Euclidean distance to measure the “similarity” between each cluster member and the corresponding cluster centroid. The silhouette clustering evaluation criterion was used to evaluate the performance of cluster analysis (SI Appendix, Fig. S5). The silhouette value for each member is a measure of the similarity between that member and other members in its own cluster, which ranges from −1 to +1. A high silhouette value indicates that the member is well-matched to its own cluster and poorly matched to its neighboring clusters (36). We used K = 4 clusters as the exemplars of different evolutionary patterns mainly based on physical meanings and its stability.

Ocean Mixed-Layer Heat Budget Equation. The ocean mixed-layer heat budget equation is

\[
\frac{\partial T}{\partial t} = \left( -V \cdot \nabla T + \frac{\partial}{\partial y} V + \frac{\partial}{\partial z} T \right) + \frac{\partial}{\partial x} \left( \frac{\partial T}{\partial x} + \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\partial T}{\partial y} + \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} + \frac{\partial T}{\partial z} \right) + \frac{Q_{\text{net}}}{C_{H}} + R_{*}
\]

where \( T \) denotes the mixed-layer temperature; \( V = (u, v, w) \) represents the zonal and meridional currents and upwelling velocities, respectively; The mixed-layer depth \( H \) is taken as a constant 50 m (29, 37), which is not sensitive to the different mixed-layer thickness in this study, such as \( H = 30 \) or \( 70 \) m.

For detailed introduction of data and method please refer to SI Appendix.

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