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Tropical Pacific cold tongue mode triggered by enhanced warm pool convection due to global warming

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Abstract
A cold tongue mode (CTM) formed in the 1980s as a La Niña-like stepwise response to recent global warming; however, a consensus has not been reached on the mechanism underlying the CTM formation. Here, we attribute the CTM to the enhanced deep convection of the warm pool regions over the western Pacific and south of North America. Increases in the sea surface temperatures in the two Pacific warm pool regions that occurred due to global warming exceeded the threshold of deep convection after the 1980s, which resulted in two opposite anomalous vertical circular circulation patterns and induced the CTM via the intensification, contraction, and westward shift of the Walker circulation and the uplift of the thermocline. Our results provide a novel explanation of the La Niña-like response under recent global warming.

1. Introduction
Changes in the El Niño–Southern Oscillation (ENSO) regime are influenced by the mean state of tropical sea surface temperatures (SSTs) (Fedorov and Philander 2000, Cai et al 2015, Capotondi et al 2015). A cold tongue mode (CTM) of SST anomalies (SSTAs) formed in the tropical Pacific concurrently with recent global warming after the 1980s (Zhang et al 2010, Ashok et al 2012; Solomon and Newman 2012, L’Heureux et al 2013a) and modulated ENSO diversity (Li et al 2017, Jiang and Zhu 2018). However, whether the response of the tropical SST mean state to global warming via radiative heating in a La Niña- or El Niño-like pattern is still under debate (Vecchi et al 2008, Tung and Zhou 2010, Luo et al 2018, Chung et al 2019).

Several competing theories explain the response of the tropical Pacific SST mean state to global warming. From an atmospheric perspective, for example, the observed increase of the specific humidity along-side warming SSTs is not consistent with the increase of precipitation according to the Clausius–Clapeyron relationship (Held and Soden 2006), which requires a slowdown of the Walker circulation and a corresponding relaxation of the equatorial SST gradient (Vecchi and Soden 2007). Although most coupled model simulations produce an El Niño-like SST pattern with a slowdown of the Walker circulation under global warming (Luo et al 2018), a La Niña-like response of tropical SSTAs was observed (Zhang et al 2010, Ashok et al 2012; Solomon and Newman 2012, L’Heureux et al 2013a), and it can usually be attributed to the vigorous upwelling in the eastern Pacific as an ocean dynamic thermostat mechanism under global warming (Clement et al 1996, Canet et al 1997, Seager and Murtugudde 1997, Zhang et al 2010, Li et al 2015b).

The observed La Niña-like response of SSTAs, which was first named the CTM by Zhang et al (2010), has shown a clear long-term trend with an obvious phase transition after the 1980s under recent global warming (Zhang et al 2010; Solomon and Newman 2012, L’Heureux et al 2013a). The CTM occurs with the intensification, contraction, and westward shift of the Walker circulation and the uplift of the thermocline, which can better explain the recent changes in ENSO diversity (Capotondi and Sardeshmukh 2015, Li et al 2017, Jiang and Zhu 2018). The formation of CTM has been mainly attributed to the strong upwelling of the mean state based on the ocean dynamic thermostat hypothesis (e.g. Clement et al 1996, Li et al 2015b). However, some characteristics of CTM, such as the westward
shift of the Walker circulation, the location of the subsurface cooling center, as well as the piecewise temporal variations of the CTM cannot be fully explained by the oceanic upwelling alone. Hence, the relationship between the CTM and past global warming is still controversial. Our results show that due to global warming, an increase of SST in the warm pools over the eastern and western tropical Pacific enhanced the deep convection by exceeding its threshold. And the enhanced deep convection shifted the strengthened Walker circulation westward with the uplift of the thermocline, causing an abrupt phase transition of the CTM during the 1980s, following a piecewise function.

2. Data and methods

The present study uses monthly SSTs from the Hadley Centre Sea Ice and SST data set version 1 (HadISST1) with a 1° × 1° grid (Rayner et al 2003) and the National Oceanic and Atmospheric Administration (NOAA) interpolated outgoing longwave radiation (OLR) dataset (Liebmann and Smith 1996). The OLR data available since 1979 can be used as a proxy for tropical convection.

The monthly sea surface height measurements and wind stress are obtained from the Simple Ocean Data Assimilation product (SODA 2.2.4) with a 0.5° × 0.5° horizontal resolution covering the period of 1871–2008 (Carton and Giese 2008). The atmospheric components are taken from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis products (Kalnay et al 1996), including horizontal and vertical velocity. These variables are available from 1948 to present, with a 2.5° × 2.5° horizontal resolution. The global average surface temperature anomaly (GSTA) are obtained from the Met Office Hadley Centre and Climatic Research Unit Global Land and Sea Surface Temperature Data Set (HadCRUT4.5) (Morice et al 2012).

The monthly anomalies for all the variables are obtained by removal of the mean seasonal cycle from 1961 to 1990. The ensemble empirical mode decomposition (EEMD, Wu et al 2009), as an adaptive time-space analysis method, empirically decomposes all the related variables into nine IMFs (intrinsic mode functions). The resulting IMFs separate the input series based upon their timescales in ascending order. The sum of the last three IMFs (7–9) is defined as the multi-decadal component, and the residual (sum of IMF1–IMF6) is treated as the high-frequency counterpart. Here the EEMD is only used to extract the multi-decadal components, which can be supported by other time-space analysis methods, such as Lanczos low-pass filter (figure S5 (stacks.iop.org/ERL/15/054015/mmedia) in supplementary material).

3. Trends in the tropical SST anomalies in the context of global surface air temperature trend

In this section, we compare the trends in the tropical Pacific SST anomalies with the GSTA trend, and try to reveal the connection between them. In the annual mean climatic state over the tropical Pacific (figure 1), two warm pool regions (SSTs exceeding 28 °C) are observed in the western Pacific and south of North America, namely, the western Pacific warm pool and the Western Hemisphere warm pool (Wang and Enfield 2001), respectively. The western Pacific warm pool is the largest warm pool on Earth and presents a strong atmospheric ascending motion and deep convection (OLR less than 240 W m⁻²). The deep convection is enclosed by the threshold of SST greater than 28 °C with respect to the easterly trade winds into the western Pacific. The Walker circulation is characterized by vertical zonal circulation with atmospheric upward motion over the western Pacific warm pool and returns eastward aloft by descending in the east (figure 1(b)).

As the dominant mode of interannual tropical variability, ENSO can be considered noise in the long-term changes of the tropical Pacific SST, which brings large discrepancies in tropical SST trends, especially in the eastern Pacific. With the ENSO variability removed, the ENSO-residual trend shows a robust La Niña-like pattern in different data sets (Zhang et al 2010; Solomon and Newman 2012, L’Heureux et al 2013a). This La Niña-like pattern, named CTM (Zhang et al 2010), can be obtained as EOF2 by the empirical orthogonal function (EOF) analysis of SSTA in the tropical Pacific (30°S–30°N, 110°E–70°W), representing an out-of-phase relationship of SSTA variability between the Pacific cold tongue region and elsewhere in the tropical Pacific (figure 2(c)), with a significant trend (figure 2(a)).

The corresponding normalized principal component (NPC) of CTM (figure 2(a)) mainly exhibits its strong long-term variability, with a negative phase before the 1980s, and its long-term variability has been speculated to represent a response to recent global warming (Zhang et al 2010; Solomon and Newman 2012, L’Heureux et al 2013b, Li et al 2015b). However, compared to the gradual increase of GSTAs since the 1970s, the timing of the CTM formation, namely, the CTM phase transition, was observed during the 1980s (figure 2(a) vs. (b)), and no clear upward trends of the CTM time series were observed during the periods of 1950–1975 and 1995–2016 (before and after the formation of CTM, respectively, shown as black lines in figure 2(a)) as a piecewise function. Therefore, in addition to the ocean dynamic thermostat hypothesis, there should be other factors affecting the CTM formation.

The GSTA is mainly affected and well reproduced by these factors: longwave radiative forcing.
due to greenhouse gases, atmospheric heating anomalies associated with ENSO and shortwave scattering by stratospheric sulfate aerosols (Hu and Fedorov 2017). Among these factors, the GSTA interannual variation is closely tied to ENSO (Kosaka and Xie 2013). Utilizing EEMD, the GSTA can be decomposed into a multi-decadal component (green line in figure 2(b)) and an interannual counterpart (blue line in figure 2(b)). Then the GSTA-regressed tropical Pacific SSTA (figure 2(d)) are also decomposed into an ENSO-related high-frequency component (figure 2(e)) and a multi-decadal component (figure 2(f)). Figure 2(f) illustrates the correlation between the GSTA multi-decadal component and SSTA, which nearly resembles the linear trend of the tropical Pacific SSTAs (pattern correlation: 0.98; figure 2(f) vs. Figure 2(a)). Although the warming trend of tropical SSTAs shown in figure 3(a) may result from low-frequency internal variability, we speculate that the linearity of the trend and its magnitude are more consistent with the global warming influence.

Least-squares linear regression is utilized to estimate the linear trend (figure 3(a)). The coefficient of determination ($R^2$), as a usual measure of the fit of a regression, is computed as $R^2 = \frac{SSR}{SST}$ (the regression sum of squares/the total sum of squares), which can be interpreted as the proportion of the variation of the linear trend components (figure 3(b)). Considering the pattern of the CTM, two regions of WP (western Pacific; $5^\circ$S–$5^\circ$N, 130$^\circ$E–180$^\circ$E) and CT (cold tongue; $2.5^\circ$S–$2.5^\circ$N, 170$^\circ$W–100$^\circ$W) have been selected based on the distribution of $R^2$ (figure 3(b)).

The significant warming of the SSTA (figure 3(a)) with a high $R^2$ (shading in figure 3(b)) mainly occurs over the western Pacific and south of North America, surrounding the CT region (figure 3(b)). These temporal variation features are also confirmed by the time evolution of equatorial SST anomalies in figure 3(c). SSTAs in the CT region exhibit a significant interannual variation tied to ENSO events (figure 3(c)). Instead, the western Pacific exhibits an obvious warming trend (figures 3(c) and (d)). Therefore, the multi-decadal warming SSTA with obvious linearity of the trend surrounding the CT region (shading in figure 3(b)) is consistent with a global warming influence, which is speculated to be a bridge linking the CTM with global warming (pattern correlation: 0.87; figure 2(c) vs. Figure 3(a)). The multi-decadal component of the GSTA (green line in figure 2(b)) can be presumably treated as external forcing,

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**Figure 1.** Mean states of the atmospheric and oceanic conditions (long term annual means for 1981–2010). (a) Spatial distribution of surface wind (gray vectors), SST (contours; intervals of 1 °C), and OLR (shading; less than 240 W m$^{-2}$). The thin and thick red lines indicate the 28 °C and 29 °C isotherms, respectively. (b) The zonal mass stream function trend (shading; 10$^9$ kg s$^{-1}$) along the equatorial Pacific (5$^\circ$S–5$^\circ$N) and the mean states of the zonal mass stream function (contours; 10$^9$ kg s$^{-1}$), pressure velocity ($\omega \times -50$; Pa s$^{-1}$), and zonal divergent wind (m/s).
Figure 2. CTM and GSTA time series and their related SSTA spatial distributions. (a) The CTM normalized principal component (NPC) is shaded in blue and red. The black lines indicate the linear trends for 1950–1975, 1976–1994 and 1995–2016, and the red dashed line indicates the linear trend for 1950–2016. (b) GSTA time series (shading) and its intrinsic mode function (IMF) components. The green (blue) line indicates the multi-decadal (high frequency) component of GSTA as sum of IMF7–IMF9 (IMF1–IMF6). The black and red lines are the same as in (a) but for the GSTA. (c) CTM SSTA mode (EOF2; shading). (d) GSTA-regressed SSTA spatial distribution. (e) GSTA high-frequency component regressed SSTAs. (f) SSTAs for the difference between (d) and (e) indicate the GSTA trend component related SSTA. Only the regressed values significant beyond the 95% confidence level in (d) and (e) are plotted.

such as the emerging anthropogenic signal (Kosaka and Xie 2013, Hu and Fedorov 2017). Particularly, the warming trend plays a dominant role in the variability of the WP SSTAs (figures 3(c) and (d)) with the expansion of the western Pacific warm pool (purple isotherms in figure 3(d)), as a result of global warming (red line in figure 3(e)). And the tiny differences between the estimation and the observation in figure 3(e) may be attributed to the low-frequency internal variability. The internal variability also seems to favor the WP SST warming during the CTM transition period (1976–1994).

4. Linkage of the CTM with global warming

The debate about the response of the tropical SST mean state to global warming in the observation is mainly focused on the eastern equatorial Pacific (Tung and Zhou 2010; Solomon and Newman 2012, L’Heureux et al 2013a). Considering the strong ENSO signal in the eastern equatorial Pacific, it is difficult to determine the long-term trend of the SSTs in the CT region. Many studies have confirmed SST cooling in the CT region when the ENSO signal has been removed by different methods and data sets (e.g. Solomon and Newman 2012; L’Heureux et al 2013a). However, separating the ENSO variability from the response to external forcing is still challenging, especially because of the La Niña-like SSTA pattern of the CTM.

Corresponding to the CTM, the ascending motions on the western and eastern sides and the sinking motion in the central Pacific (shading in figure 4) accompanied by low-level circulations form two opposite anomalous vertical circular circulations on the west and east edges of the Walker circulation, which acts as Matsuno-Gill response (Gill 1980) forced by the western and eastern warm pool regions. This anomalous atmospheric circulation is different from the atmospheric response to ENSO. The easterly and westerly anomalous trade winds (figure 4) are on the western and eastern sides of the central Pacific (150°W), a situation which induces strong wind stress divergence over the central-eastern equatorial Pacific. Particularly, these wind stress divergence anomalies can uplift the thermocline and cause SSTA cooling in the CT region.

Compared with the much longer timescales of the ocean, the atmospheric field varies so rapidly
that it can be considered to have almost no memory. However, a clear trend or phase transition can be found in the temporal variation of the CT anomalous divergence, even without any processing (figure S5(a)). Corresponding to the divergence, the uplift of the thermocline can be detected when the ENSO signal is linearly removed (figure S5(b)). In the supplementary material, the western edge index of the Walker circulation is applied to describe the shift of the Walker circulation (Ma and Zhou 2016), which indicates the westward shift of Walker circulation clearly without any processing (figure S1(a)). Statistically, about 40.8% of the total variance of the surface divergence and 44.4% of the oceanic upwelling variance can be explained by the changes of the western edge of the Walker circulation (figure S1(d)). And a theoretical model in the supplementary material suggests that, when it is forced by a wind stress divergence similar as the observation (figure S3), the solution of the oceanic upwelling is consistent with that of the observation (figure S4). Therefore, the CTM-related anomalous atmospheric circulation is suggested to be the direct driver of the SSTA cooling in the eastern equatorial Pacific.

Deep convection over the warm sea water acts as an energy source that drives large-scale atmospheric circulation in the tropical Pacific. The warming SSTs around the CT region seem to modulate the Walker
circulation through deep convection. To identify the sensitivity of deep convection to SSTs, we first interpolated the SSTs into the OLR grid and then plotted the OLR against the SST in each grid during 1979–2016 (figure 5(c)). Afterward, we calculated the two-dimensional density function of the OLR against the SSTs over the equator (figure 5(c)). According to Lau et al (1997), this can be inferred as the long-term change of deep convection relative to the SST. The OLR acts as a piecewise function of the SST (e.g. Gadgil et al 1984, Lau et al 1997)) and can be approximately classified into three regimes (figure 4(c)): (1) a nearly constant OLR with increasing SSTs from 25 °C to 28 °C, (2) a steeply decreasing OLR when the SST increases from 28 °C to 29 °C, and (3) a slightly dropping OLR against the SST when it is greater than approximately 29 °C. Deep convection occurs over most grids when the SST is greater than 29 °C.

This means that the warming SSTs in the tropical Pacific can change the large-scale circulation through deep convection when exceeding the threshold (29 °C). Corresponding to the CTM, anomalous surface convergence can be found in the WP region and near the south of North America with a strong ascending motion, probably as a result of deep convection. Additionally, the WP and the south of North America are around the western Pacific warm pool and the Western Hemisphere warm pool, where the SSTs are close to the deep convection threshold.

Suppose that a uniform external heating, which can be regarded as global warming, is imposed on the tropical Pacific. Around the eastern and western warm pool regions, the SSTs will tend to increase, exceeding the deep convection threshold first (figure 3(d)), which can cause two opposite vertical circular circulations with strong divergence over the CT region (figure 5(a)). In the CT region, the strong divergence can uplift the thermocline (figure 5(b)) and cause SST cooling (figure 2(c)), which will increase the SST gradient between the CT and elsewhere in the tropical Pacific, then strengthening the divergence as positive feedback for CTM formation. The SST around the warm pool regions should be increasing gradually under the global warming (figure 3(e)). While considering the nonlinear relationship between the SST and OLR (figure 5(c)), the response of the deep convection in warm pool regions to the increased SST follow a piecewise function, exhibiting a significant expansion of the warm pool during the 1980s (figure 3(d)), which possibly result in the stepwise response of the CTM’s to the global warming (figure 2(a)).

Based on the above assumption, to identify the changes of deep convection relative to the multi-decadal WP SST warming, an index, namely, the deep convection ratio, is defined as the areal proportion of SSTs over 29 °C in the WP region. Though the WP SST increased gradually under global warming (figure 3(e)), the intensity of the deep convection strengthened abruptly (figure 5(d)) during the 1980s alongside the large expansion of the 29 °C isotherms in the western Pacific (thick purple line in figure 3(d)). Against the warming of the SST, the multi-decadal change of deep convection also follows
Figure 5. Temporal variations of anomalies in (a) the wind stress divergence and (b) the sea surface height averaged within the CT region shown in figure 3(b). Shadings in (a) and (b) illustrate the anomalies without the ENSO signal (which has the Niño-3.4 index linearly removed from the original anomalies (gray lines) following the method of L’Heureux et al (2013b)). (c) Scatter diagram of collocated SST and OLR gridpoint values for the WP (red) and CT (blue) regions in figure 3(b). The contours indicate the joint probability distributions for the WP and CT regions. The superimposed thick black line represents the OLR values as a function of every 0.25 °C SST estimated by the probability distribution for a specific SST value. (d) Temporal variations of the deep convection ratio of WP (black and red lines) and the CTM NPC (shading; same as figure 2(a)). The deep convection ratio is defined as the area proportion of SST over 29 °C in WP. The black line in (d) is obtained from observations, and the red line is estimated according to the SSTA computed by the multi-decadal component of the GSTA (green line in figure 2(b)) through linear regression.

a piecewise function (black line in figure 5(d)), which agrees well with the CTM phase transition (shading in figure 5(d)). The significant multi-decadal warming in the WP and some other regions is presumably a result of global warming (figure 3). The deep convection ratio estimated from the SSTA regressed according to the multi-decadal component of the GSTA also shows a stepwise response (red line in figure 5(d)). Johnson and Xie (2010) found that a parallel upward trend of approximately 0.1 °C/decade over the past 30 years in both the convective threshold and tropical mean sea surface temperatures. After examination, our conclusions are not affected by the selection of the convective threshold from 28.7 to 29 °C.

5. Summary and discussion

A CTM in the tropical Pacific that is considered a La Niña-like response was found in recent years (Zhang et al 2010), and it may act as a bridge linking ENSO diversity with recent global warming (Jiang and Zhu 2018). However, the formation of the CTM related to recent global warming is still a controversial issue. Here, we found that the formation of the CTM in the 1980s can be attributed to the enhanced deep convection in warm pool regions in the western and eastern Pacific. The increase of the SST in the warm pool regions under recent global warming exceeded the threshold of the deep convection around the 1980s (figure 4), resulting in two opposite anomalous vertical circular circulations and inducing strong divergence over the eastern equatorial Pacific with the uplift of the thermocline. The cooling in the eastern equatorial Pacific due to the thermocline uplift strengthened the divergence again, forming the CTM as positive feedback in the 1980s.

A number of studies have suggested that the CTM may have been caused by the intense upwelling of
cold water in the eastern equatorial region under recent global warming as the ocean dynamic thermostat hypothesis (Clement et al 1996, Sun and Liu 1996, Cane et al 1997, Seager and Murtugudde 1997, Zhang et al 2010, Li et al 2015). However, certain CTM features, such as the westward shift of the Walker circulation and the location of the subsurface cooling center (Jiang and Zhu 2018), cannot be fully explained by this ocean dynamic process alone. Our results show that the formation of the CTM was triggered by the enhanced warm pool deep convection with increasing SSTs following a piecewise time function, and the upwelling of cold water played an important role in the formation, reinforcement and persistence of the CTM. A La Niña-like response to an increase in the warm pool temperature is also verified by a low-order ENSO model (Kim and An 2011). Our hypothesis is aimed at explaining the CTM formation in the context of global warming by exploring the stepwise physical processes of air-sea interaction within the tropical Pacific basin. Moreover, rapid warming in the tropical Atlantic and Indian Oceans also contributes to the La Niña-like response (Li et al 2015a; Luo et al 2012, McGregor et al 2014; Zhang et al 2019a, 2019b). The ENSO and other natural low-frequency variability signals are treated as noises in our study. However, it is noted that the ENSO variability (e.g. Bayr et al 2014) and the low-frequency variation (e.g. Yeo et al 2017) could also modulate the manifestation of the tropical Pacific for some particular situations. Besides the large-scale Pacific Walker circulation, the regional atmospheric circulation could also control the tropical Pacific precipitation response to global warming (Sohn et al 2019).

Many efforts have been made for reconciling the discrepancies among the model projections and observations (e.g. Solomon and Newman 2012, L’Heureux et al 2013a; Luo et al 2018, Chung et al 2019) with different theoretical arguments. Our results provide an explanation for CTM formation from a convection perspective as a supplement to the others’ arguments, which may have important implications for understanding the tropical response to recent and future global warming.

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Data availability statements

The data that support the findings of this study are openly available. The HadISST1 and HadCRUT4 data sets were obtained from the Met Office Hadley Centre and can be downloaded from http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html and http://www.cru.uea.ac.uk/cru/data/temperature/, respectively. The SODA data set was obtained from NCAR and can be downloaded from http://dssr.atmos.umd.edu/DATA/soda_2.2.4/. NCEP reanalysis data, interpolated OLR data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA can be obtained from their website at https://www.esrl.noaa.gov/psd/.

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