Decadal fluctuations in the western Pacific recorded by long precipitation records in Taiwan

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Abstract A 110-year precipitation record in Taiwan, located at the western edge of the subtropical North Pacific, depicts a pronounced quasi-decadal oscillation (QDO). The QDO in Taiwan exhibits a fluctuating relationship with the similar decadal variations of sea surface temperature (SST) anomalies in the central equatorial Pacific, known as the Pacific QDO. A regime change was observed around 1960, such that the decadal variation of Taiwan's precipitation became more synchronized with the Pacific QDO's coupled evolutions of SST and atmospheric circulation than before, while the underlying pattern of the Pacific QDO did not change. Using long-term reanalysis data and CMIP5 single-forcing experiments, the presented analysis suggests that increased SST in the subtropical western Pacific and the strengthened western extension of the North Pacific subtropical anticyclone may have collectively enhanced the relationship between the Taiwan precipitation and the Pacific QDO. This finding provides possible clues to similar regime changes in quasi-decadal variability observed around the western Pacific rim.

Keywords Precipitation · Taiwan · Pacific quasi-decadal oscillation · Subtropical anticyclone

1 Introduction

Interannual variability characterizes the climate of the Asian-Pacific region, making seasonal prediction difficult (Fan et al. 2012; Lu et al. 2013; Zhao and Yang 2014; Sun and Wang 2015). In addition to the interannual variability, the climate in the Asian-Pacific region also fluctuates with a prominent frequency of 10- to 20-years, referred to as quasi-decadal oscillation (QDO) (Hsu and Chen 2011; Wang et al. 2011; Li and Zhou 2014; Li et al. 2015). Located in the northwestern Pacific, near the East Asian continent (Fig. 1a), the climate in Taiwan also exhibits a noticeable QDO influence. Since the early 1960s, the warm season (July–October) rainfall in Taiwan has experienced a marked 10- to 20-year variation (Fig. 1b) (Hsu and Chen 2011). Similar QDO signals were observed in the number of occurrences of tropical cyclones affecting Taiwan (Fig. 1c) (Chan 2008; Chen et al. 2013; Hung 2013) and in the frequency of summer diurnal rainfall events (Fig. 1d) (Huang et al. 2015). Apparently, the QDO is a predominant mode of variability in both the seasonal precipitation and weather systems of Taiwan, even though previous research (Hsu and Chen 2011; Huang et al. 2015) noted that the QDO in the western Pacific only became apparent after the 1960s.

The Pacific QDO describes the coupled evolution of sea surface temperature (SST) and atmospheric circulation at the 10- to 20-year timescale (Li 1998; White and Liu 2008; Wang et al. 2011); its variations in the tropical Western Pacific can serve as precursors of tropical cyclone threats (Wang and Clark 2011). In Taiwan,

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Fig. 1 **a** Location of Taiwan with shaded topography. **b** July to October (JASO) precipitation averaged over Taiwan; **c** October to December (OND) tropical cyclone (TC) frequency in the vicinity of Taiwan (averaged over 115°–125°E, 20°–30°N); **d** June to August (JJA) convective afternoon rainfall (CAR) frequency in Taiwan, adopted from Huang and Chen (2015); **e** Annual rainfall in Taiwan from 5 hundred-year-stations (TP for Taipei, TC for Taichung, TN for Tainan, HC for Hengchun and TT for Taitung), with record from 1901 onwards and site locations given in (a). The original time series are shaded, while the 10- to 20-year band-pass filter is indicated by the thick red lines. The post-1960 period, as used in (b–d), is outlined in (e). **f** Power spectrum of the Taiwan precipitation index overlaid by the 95% confidence interval computed from autoregressive red noise; the quasi-decadal frequency band is highlighted

long-term precipitation records with more than 100 years of data are available from five stations (location given in Fig. 1a), providing useful information for the examination of the influence of the Pacific QDO prior to 1960. A visual examination of the annual precipitation derived from these five stations (defined as the “Taiwan precipitation index”; Fig. 1e) reveals that the QDO signal is persistent throughout the recorded period. Power spectrum analysis of the Taiwan precipitation index (Fig. 1f) reveals a significant peak within the QDO frequency band. For the post-1960 (1901–2009) period, the 10- to 20-year timescale variations explain approximately 29.6% (21.5%) of the total precipitation variability in Taiwan (Fig. 1e), showing a significant spectral power (Fig. 1f).

Intrigued by the prominent quasi-decadal variability in Taiwan, as recorded in the instrumental data and weather events, we decided to examine the Pacific QDO’s teleconnection impact on Taiwan and the associated changes in

the basin-wide SST and atmospheric circulations, using the long-term reanalysis and SST data sets, starting in the twentieth century. To identify the cause of the regime change, we analyzed simulations of the twentieth century under different external forcings. The rest of the paper is arranged as following: Sect. 2 describes the data used for the analyses, Sect. 3 shows the observational analysis, Sect. 4 discusses the modeling results and Sect. 5 provides a conclusion.

2 Data sources

The instrumental precipitation records in Taiwan were provided by the Central Weather Bureau (CWB). For the construction of the long-term Taiwan precipitation index shown in Fig. 1e, we used 5 stations (Taipei, Taichung, Tainan, Hengchun and Taitung) with precipitation

Table 1 CMIP5 model specifics, as used in this study

Acronym	Full model name	Center/Institute, country
BCC-CSM1	Beijing Climate Center, Climate System Model, version 1.1	Beijing Climate Center, Meteorological Administration, China
BNU-ESM	Beijing Normal University—Earth System Model	College of Global Change and Earth System Science (GCES), China
CanESM2	Canadian Earth System Model, version 2	Canadian Center for Climate Modeling and Analysis, Canada
CCSM4	Community Climate System Model, version 4	National Center for Atmospheric Research, USA
CNRM-CM5	Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5	National Centre for Meteorological Research, France
CSIRO-Mk3	Commonwealth Scientific and Industrial Research Organisation Mark, version 3.6.0	Commonwealth Scientific and Industrial Research Organization/ Queensland Climate Change Centre of Excellence, AUS
FGOALS-g2	Flexible Global Ocean-Atmosphere-Land System Model, grid point version 2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, China
GFDL-CM3	Geophysical Fluid Dynamics Laboratory Climate Model version 3	NOAA Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2	Geophysical Fluid Dynamics Laboratory Earth Science Model 2 with Modular Ocean Model (MOM), version 4.1	NOAA Geophysical Fluid Dynamics Laboratory, USA
GISS-E2-H	Goddard Institute for Space Studies Atmospheric Model E, version 2, coupled with the Hybrid Coordinate Ocean Model (HyCOM)	NASA Goddard Institute for Space Studies, USA
GISS-E2-R	Goddard Institute for Space Studies Model E, version 2, coupled with Russell ocean model	NASA Goddard Institute for Space Studies, USA
HadGEM2-ES	Hadley Centre Global Environmental Model 2, Earth System	Met Office Hadley Centre, UK
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5 A, medium resolution	Institute Pierre Simon Laplace, France
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate Earth System Model, chemistry coupled version	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan
MIROC-ESM	Model for Interdisciplinary Research on Climate Earth System Model	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan
MRI-CGCM3	Meteorological Research Institute Coupled General Circulation Model, version 3	Meteorological Research Institute, Japan
NorESM1-M	Norwegian Earth System Model, version 1, intermediate resolution	Norwegian Climate Center, Norway

records starting from 1901. The Joint Typhoon Warning Center (JTWC) typhoon record was used for the data shown in Fig. 1c. For the observed SST, we used the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature (ERSST) V3b dataset, starting in 1854 with a 2° spatial resolution (Smith et al. 2008). Unless otherwise indicated, the analysis used the annual mean for all variables.

Additionally, we used two retrospective reanalysis datasets to depict the global atmospheric circulation and precipitation: the version-2 Twentieth Century Reanalysis (20CR) data (Compo et al. 2006, 2011) and the European Centre for Medium-Range Weather Forecasts (ECMWF) global reanalysis products for the twentieth century (ERA-20C) (Poli et al. 2016). The data of 20CR (ERA-20C) covers 1871–2012 (1900–2010). Based on large ensembles, 20CR (ERA-20C) utilized a coupled Atmosphere/Land-surface/Ocean model to assimilate surface observations of sea level pressure (surface pressure) to produce the atmospheric conditions. In the ERA-20C, the observed surface marine winds were also assimilated. However, due to the lack of upper-level observations prior to 1948 to validate the atmospheric circulation, we analyzed the two reanalysis datasets together in order to examine the consensus of our results. The precipitation output of 20CR and ERA-20C is an ensemble of multiple simulations forced by the observed sea ice, surface temperature, and pressure conditions. The precipitation from 20CR over the tropical landmasses has been shown to outperform the more comprehensive NCEP-DOE Reanalysis 2 (Lee and Biasutti 2014).

For regime-change-attribution purposes, we adopted the ensemble mean of 16 CMIP5 (Coupled Model Intercomparison Project Phase 5) models forced by three different external forcings: (a) Historical (including all transient anthropogenic and natural forcings; hereafter ALL), (b) HistoricalNAT (only including natural forcings; NAT), and (c) HistoricalGHG (only including forcings from long-lived greenhouse gases; GHG). Here, the selection of the 16 CMIP5 models is based on data availability (1850–2005) among all three experiments: Historical, HistoricalNAT and HistoricalGHG; these are listed in Table 1. According to the power spectrum analysis shown in Supplementary Fig. S1, most of the simulations produced interannual to interdecadal variabilities, including a QDO peak for the two target time series (i.e., Taiwan precipitation and Niño4 SST) in the present work. These QDO signals are simulated by different forcings and will be compared to clarify the possible cause of the regime change.

3 Observational analysis

The Pacific QDO resembles the ENSO (El Niño Southern Oscillation) SST anomalies but features a broader warm/cold tongue, with the maximum amplitude occurring in the Niño4 region (White and Tourre 2003; Wu et al. 2003; White and Liu 2008). It is loosely interchangeable with the North Pacific Gyre Oscillation, which has an energetic quasi-decadal frequency (Di Lorenzo et al. 2015). Following Wang et al. (2011), we calculated the Niño4 SST index from the ERSST data within the domain of 160°E–150°W, 5°S–5°N for the depiction of the Pacific QDO. By comparing the Taiwan precipitation index and Niño4 SST anomalies in Fig. 2 (both of which were band-pass-filtered by 10- to 20-years), significant negative correlations between the two appear to be most pronounced after 1960 ($r = -0.75$, significant at $p\text{-value} < 0.1$, with the degree of freedom = 5 after accounting for the band-pass filtering); this suggests increased (reduced) precipitation in Taiwan during the negative (positive) phase of the Pacific QDO. However, such a striking out-of-phase relationship between the Taiwan precipitation index and Niño4 SST did not exist in the pre-1960 period.

3.1 Stationarity issues

To examine the extent to which the changing relationship between Taiwan's precipitation and the Pacific QDO is due to the sampling variability, we tested the significance of the changing relationship using the non-filtered data following the methods of Gershunov et al. (2001); this is shown in Supplementary Figs. S2 and S3. There, we determined the 11-, 15-, 21-, and 31-year running correlations between the Taiwan precipitation index and Niño4 SST,

Fig. 2 The 10- to 20-year bandpass filtered precipitation in Taiwan from 5 hundred-year stations (defined as the Taiwan precipitation index; red solid line) and the annual Niño4 sea surface temperature (SST) anomalies (blue dotted line)

and these running correlations reveal consistent regime changes (from positive correlations to negative correlations) that occurred around the 1960s. The significance test was carried out through the application of a bootstrapping scheme that simulated 500 pairs of correlated white noise time series mimicking the distribution of the Taiwan precipitation index and Niño4 SST. The standard deviations for the 21-year and 31-year windows pass the 95% significance test (using Table 1 of Gershunov et al. 2001), while the 11-year and 15-year windows pass the 90% significance test. We further computed the multitaper method (MTM) of spectral coherence and phase difference, using the unfiltered Taiwan precipitation index and Niño4 index,

for two different periods: 1901–1950 (pre-1960) and 1960–2009 (post-1960). As shown in Supplementary Fig. S4, the decadal bands with significant coherence are present in both periods. However, the phase corresponding to the maximum coherence at the quasi-decadal frequency is different: i.e., there was a more in-phase relationship during 1901–1950 versus an out-of-phase relationship during 1960–2009. These analyses suggest that the observed change in the relationship between the Taiwan precipitation index and Niño4 index (Pacific QDO) is likely not an artifact of stochastic processes. Accordingly, the ensuing analysis uses data filtered for the QDO regime in the 10- to 20-year passband.

Correlation Maps

Fig. 3 One-point correlation maps between the 10- to 20-year band-pass-filtered Taiwan precipitation index and SST anomalies for two time periods: **a** 1901–1950 and **b** 1960–2009. The significant positive (negative) values, at $p < 0.1$, are shaded in pink (blue). The yellow

star marks the location of Taiwan. **c, d** Similar to **a, b** but correlated with the bandpassed Niño4 SST (sign reversed, location outlined). **e–h** Same as **a–d** but for the 850-hPa streamfunction extracted from 20CR. The orange arrow in **f** indicates the southerly wind anomaly

3.2 The diagnoses

The fluctuating correlation between the Taiwan precipitation index and Niño4 index is intriguing, as it suggests a change of the Pacific QDO's influence in the far western region of the Pacific Basin. To substantiate this inference, Fig. 3 shows the correlation map of the bandpass-filtered SST with the Taiwan precipitation index for two periods: 1901–1950 (pre-1960) and 1960–2009 (post-1960). The correlation between the Taiwan precipitation index and the Pacific QDO's SST pattern was positive in the pre-1960 period (Fig. 3a) but was then reversed, showing a distinct negative relationship over the Niño4 region (Fig. 3b). The post-1960 SST pattern bears some resemblance of that delineated by Hsu and Chen (2011) for the 10- to 20-year variability in the northern summer. Next, we constructed similar maps of SST anomalies correlated with the Niño4 index (sign reversed) in Fig. 3c, d. The results portray a consistent cold-tongue-like structure in both periods, suggesting that the underlying dynamics of the Pacific QDO had not changed, at least in the central and eastern Pacific sectors. What has changed is the associated regional SST variation over the western Pacific and northern Indian Ocean, i.e., the SST there was colder (warmer) in the cold (warm) phase of Niño4 before 1960 but has been warmer (colder) in the cold (warm) phase of Niño4 since then.

In correspondence with Fig. 3a–d, the associated change of the low-level atmospheric circulation was examined by computing the correlation maps of the 850-hPa

streamfunction. It appears that the Taiwan precipitation index was strongly connected to an anticyclonic anomaly in the western Pacific after 1960 (Fig. 3f) but was not before 1960 (Fig. 3e). The consequence of this circulation difference is reflected by the low-level southerly flow after 1960 (indicated by the arrows), which increases the moisture supplied to Taiwan. Likewise, Fig. 3g, h depict a post-1960 intensification of the North Pacific subtropical high (associated with the Pacific QDO), whose western extension would enhance the southerly flow near Taiwan. To validate the 20CR analysis (Fig. 3e, f), we also examined ERA20C. The results derived from ERA20C (Fig. 4) are consistent with those from 20CR, suggesting that (1) the Taiwan precipitation index was strongly connected to an anticyclonic anomaly in the western Pacific after 1960 (Fig. 4a, b), and (2) the North Pacific subtropical high associated with the Pacific QDO has intensified since 1960 (Fig. 4c, d). Based on these results (Figs. 3, 4 and Supplementary Figs. S3–4), one could draw a preliminary conclusion that the Pacific QDO's influence on the western Pacific underwent a drastic change in the 1960s, and the resultant local climate impacts were depicted by the annual precipitation in Taiwan.

Further analysis was carried out by computing the sliding correlations of the filtered Niño4 index (sign reversed) with SST (Fig. 5a) and precipitation (Fig. 5b, c), averaged across the latitudinal zone of Taiwan (22°–25°N). As shown in Fig. 5a, the local SST correlation near Taiwan (at approximately 120°E) has changed from being negative in the pre-1960s period to predominantly positive after that.

Correlation Maps

Fig. 4 Similar to Fig. 3e–h, but for ERA-20C

Fig. 5 **a** Sliding correlations between the bandpass-filtered Niño4 SST (sign reversed) and SST within a 30-year window from 1901 (indicating 1872–1901) to 2012 (indicating 1983–2012), averaged across the latitudinal zone of Taiwan (22–25°N). The significant positive (negative) values, at $p < 0.1$, are shaded in pink (blue). **b**, **c** Same as **a** but for the 20CR and ERA20C precipitations, respectively. The global mean surface temperature anomaly (ΔT_s) time series (shaded curve) and its 10-year running mean (purple line) is plotted at the right side of (**a**). The location of Taiwan is indicated by the thick dotted lines at 120°E

The SST shift covers most of the subtropical western North Pacific, which is consistent with Fig. 3c, d. Here, the change of precipitation in relation to Niño4 (sign reversed) was

computed from the precipitation of the 20CR (Fig. 5b) and ERA20C (Fig. 5c) datasets. Both of the results of Fig. 5b, c show that Taiwan's precipitation changes transitioned into a regime with significant negative correlation with Niño4 in the post-1960 period. Together, the results in Fig. 5 imply that the westward expansion of warmer (colder) SSTs in the northwestern Pacific during the negative-phase (positive-phase) Pacific QDO has become more robust, and this has enhanced the link between the Pacific QDO and the QDO in Taiwan. Notably, the two reanalyses did reveal a more consistent QDO signal in Taiwan after 1960, though neither reanalysis dataset captured the pre-1960 precipitation over Taiwan (Supplementary Fig. S5). This does not necessarily negate the quality of the data, however, as this observed feature can also be interpreted as being due to the change of the local responses to the Pacific SST at approximately 1960 affecting the regional precipitation.

3.3 Possible dynamics

Several noteworthy features are revealed in Fig. 5. The Western Pacific warming is known to affect the precipitation in climate model projections (Brown et al. 2015). As inferred from previous studies examining the change of the North Pacific subtropical high under global warming (Li et al. 2012; He and Zhou 2015), it is plausible that the regional SST response to global warming can influence the western extension of the North Pacific subtropical high. To illustrate this point, we overlaid the global surface temperature (GST) anomalies in Fig. 5a to compare it with the sliding correlations. The cooler period, before 1940 (warmer period after 1970), coincides with the predominant negative correlations (positive correlations) between the northwestern Pacific SST and Niño4 SST, while the period of the warming slow-down (between 1940 and 1970) is concurrent with the transition of the correlation regimes. This result echoes the observation of Li et al. (2012) and He and Zhou (2015), who stated that global warming has increased the average northwestern Pacific SST, and this adds to the thermal contrast between the land and ocean, further enhancing the westward extension of the subtropical anticyclone. In other words, precipitation in Taiwan underwent the aforementioned change of the local SST coupled to the Pacific QDO, owing to its proximity to the North Pacific subtropical high extension.

The next question is that of the extent to which the Pacific QDO may have changed during the mid-twentieth century. As an independent measure of Taiwan's

Fig. 6 First mode of the Empirical Orthogonal Function (EOF) analysis of the bandpass-filtered SST for the two periods: **a** 1901–1950 and **b** 1960–2009

precipitation connection, we applied an Empirical Orthogonal Function (EOF) analysis to the bandpass-filtered SST for the two periods: 1901–1950 and 1960–2009; their first mode is shown in Fig. 6. A few changes in the SST pattern are noticeable, and the most relevant one is the increased variation (warming, as in Fig. 6) over the western Pacific. This change echoes the observed increase in the area-averages of the Pacific SSTs over 110°E–150°E, 20°S–40°N, which have shown a linear increase of $\sim 0.8^{\circ}\text{C}$ during 1901–2009 (not shown). Warming in the western Pacific likely increases the sensitivity of air-sea interactions, promoting a more energetic reaction to SST variation (e.g., Wang et al. 2013), and this process can affect the impact of the Pacific QDO. Located near the boundary between the East Asian continent and the Pacific Ocean, the change in SST variations near Taiwan can alter (or shift) the circulation and precipitation distributions, affecting the local weather (e.g., Wang et al. 2016).

4 Regime-shift attribution from CMIP5 simulations

Given that the timing of the regime change coincides with the noticeable anthropogenic warming influence, we

further examined the potential effect of global warming. Figure 7 shows the correlation map based on the filtered Niño4 index (sign reverse) and the eddy Ts (with its zonal mean removed) simulated by the 16 CMIP5 models from the Historical, HistoricalNAT and HistoricalGHG experiments. We used the eddy Ts to highlight the east–west thermal contrast, which is important for the formation of the teleconnection pattern (otherwise, the CMIP5 simulations would show a similar oscillation phase in the QDO for the SST between the western Pacific and eastern Pacific, especially for the post-1960 period; not shown). As revealed in Fig. 7a, the ensemble mean of the historical simulations depicts a regime change towards an enhanced relationship between the negative phase of the Pacific QDO and western North Pacific warming after 1960s. This simulated feature agrees with what was revealed in the observed eddy SST analysis (Supplementary Fig. S6), which shows a regime change similar to that seen in Fig. 3c, d. The details of the capability of the model to simulate SST variability are referred to in Li and Xie (2014), Wang et al. (2014), and Wang et al. (2015).

Next, we compared Fig. 7a with the corresponding correlation maps of the HistoricalNAT (Fig. 7b) and HistoricalGHG (Fig. 7c) simulations. The HistoricalNAT simulations do not reveal any westward shift of the SST

Fig. 7 The correlation map based on the 10- to 20-year bandpass-filtered $\text{Ni}\tilde{\text{no}}4$ index (sign reverse, location outlined) and eddy Ts (with its zonal mean removed) simulated by the 16 CMIP5 models from the **a** Historical, **b** HistoricalNAT and **c** HistoricalGHG experiments for

the two periods: 1901–1950 and 1960–2005. The models including in the ensemble are listed in Table 1. The significant positive (negative) values, at $p < 0.1$, are shaded in pink (blue)

pattern, whereas the HistoricalGHG simulations (Fig. 7c) reproduced the westward shift of the SST pattern that was depicted by Historical simulations. To clarify this finding, we also followed the example of Fig. 5 to compute the 30-year sliding correlations of the filtered $\text{Ni}\tilde{\text{no}}4$ index (sign reversed) with the simulated eddy Ts averaged across the latitudinal zone of Taiwan (22° – 25°N); these are shown in Fig. 8a, b for the HistoricalNAT and HistoricalGHG simulations, respectively. The relationship of the westward expansion of the warmer SST anomalies in the northwestern Pacific with the negative phase of the Pacific QDO becomes increasingly robust in the HistoricalGHG

simulations (Fig. 8b) but does not in the HistoricalNAT simulations (Fig. 8a), suggesting a GHG impact.

Following the example of Fig. 4c, d for the depiction of the teleconnection pattern change, Fig. 9 shows the correlation map between the filtered $\text{Ni}\tilde{\text{no}}4$ index (sign reverse) and the 200-hPa vorticity (ζ , shaded), superimposed with wind circulation (streamline), which were derived from the CMIP5 Historical (Fig. 9a), HistoricalNAT (Fig. 9b) and HistoricalGHG (Fig. 9c) simulations. An apparent westward shift in the Pacific-North American (PNA) teleconnection is revealed in the Historical simulations after 1960 (Fig. 9a). This westward shift in the PNA teleconnection is

Fig. 8 Similar to Fig. 5, but for the 30-year sliding correlations of the filtered Niño4 index (sign reversed) with the simulated eddy Ts averaged across the latitudinal zone of Taiwan (22° – 25°N): **a** HistoricalNAT and **b** HistoricalGHG simulations

only captured by the HistoricalGHG simulations (Fig. 9c) but not by the HistoricalNAT simulations (Fig. 9b). The results of Figs. 7, 8 and 9 lend support to our previous

finding, specifically that the relationship between the negative phase of the Pacific QDO and western Pacific warming after the 1960s is influenced by anthropogenic climate warming by way of the east–west extension of the Pacific QDO teleconnection.

5 Concluding remarks

The 110-year record of Taiwan’s annual precipitation depicts a marked quasi-decadal variation and its fluctuating relationship with the Pacific QDO. The presented analyses indicate that (1) the Taiwan precipitation index exhibits a robust 10- to 20-year oscillation that complements the previous studies of the quasi-decadal variations in precipitation and different types of weather systems affecting Taiwan and (2) the relationship between the Taiwan precipitation index and the Pacific QDO has changed around the 1960s, with an increased and significant negative correlation. It was proposed that the increased SST in the western Pacific, associated with global warming, has modified the regional SST and precipitation signals around Taiwan associated with the western extent of the Pacific QDO teleconnection. This modification is likely caused by the enhancement of the North Pacific subtropical anticyclone, as the strengthened western extension of this system increases the meridional wind anomalies near Taiwan. As a result, the local SST variation around Taiwan (which affects moisture transport and precipitation) has become increasingly “reactive” or sensitive to the Pacific QDO in an out-of-phase manner. The CMIP5 simulations suggest that the GHG-forced SST, precipitation, and circulation anomalies resemble the changes in the Pacific QDO’s relationship with Taiwan’s precipitation, indicating the contribution of global warming.

Given that the strengthened North Pacific subtropical anticyclone is linked to global warming, one might expect the out-of-phase relationship between Taiwan’s precipitation anomalies and the Pacific QDO to continue. If this holds true, then monitoring the Pacific QDO from Niño4’s low-frequency variation could help to anticipate the long-term fluctuations in the precipitation and weather systems of Taiwan. This implication deserves further exploration.

Fig. 9 Similar to Fig. 7, but for the correlation map based on the 10- to 20-year bandpass-filtered Niño4 index (sign reversed, location outlined) and 200-hPa vorticity (ζ , shaded) and related wind circulation (streamline) extracted from the CMIP5 **a** Historical, **b** HistoricalNAT and **c** HistoricalGHG simulations. The significant positive (negative)

values, at $p < 0.1$, are shaded in pink (blue). The symbol “L” represents the cyclonic circulation in the North Pacific that is related to the Pacific–North American teleconnection (linked by dashed line), as discussed in the manuscript

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