Why Pacific quasi-decadal oscillation has emerged since the mid-20th century

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Abstract

Pacific quasi-decadal oscillation (PQDO) is one component of the multi-time-scale tropical Pacific decadal variability, with a variability center in the equatorial central Pacific (ECP). PQDO has emerged since the 1950s and has a significant impact on decadal climate variability over Asia and North America and Pacific storms. However, why it has intensified since the 1950s remains unknown. Here we test two competing hypotheses, (1) 11-year solar cycle forcing and (2) internal variability arising from El Niño–Southern Oscillation (ENSO) asymmetry, by analyzing simulation results, including one fixed-forcing control (CTRL) experiment and four sensitive experiments with millennial spectral solar irradiance (SSI), obtained from the Community Earth System Model–Last Millennium Ensemble modeling project. The four-member ensemble-averaged SSI experiments suggest that 11-year solar irradiance forcing cannot excite PQDO without stratospheric amplification of solar forcing. By analyzing 144 years of observations and the CTRL experiment, we find that the PQDO is nonstationary, and consecutive La Niña-induced decadal variability can boost PQDO in the ECP. El Niño could induce decadal ENSO signals in the NINO3.4 region but not in PQDO regions. The negative phase of PQDO tends to follow the occurrence of multi-year La Niña. We suggest that the emergence of PQDO since the 1950s is mainly due to the increase in multi-year La Niña events.

1. Introduction

Tropical Pacific decadal variability (TPDV) has attracted a great deal of attention in the climate research community because of its profound impact on weather, agriculture, ecosystems and the economy (Power et al. 2021). TPDV exhibits a variety of forms in terms of their temporal and spatial behaviors. Nevertheless, their complex causes remain uncertain. In terms of time scales, three components have been identified. One is Pacific decadal oscillation, with two preferred periodicities (15–25 years and 50–70 years), most visible in the North Pacific (Mantua et al. 1997). Another is Interdecadal Pacific Oscillation, covering the entire Pacific (Power et al. 1999). The third is Pacific quasi-decadal oscillation (PQDO), which has a variability center over the equatorial central Pacific (ECP) with an 11-year periodicity; its
PQDO in the past 144 years and its link to solar forcing and ENSO. Shown are the time series of the October to February mean ECP index (PQDO) and the Oceanic Nino Index (ONI), and annual mean total solar irradiation (TSI) (W m$^{-2}$) from 1878 to 2021.

Figure 1. PQDO in the past 144 years and its link to solar forcing and ENSO. Shown are the time series of the October to February mean ECP index (PQDO) and the Oceanic Nino Index (ONI), and annual mean total solar irradiation (TSI) (W m$^{-2}$) from 1878 to 2021.

intensity is slightly weaker compared with the first two oscillations (Brassington 1997, Lyu et al 2017). PQDO has a significant impact on tropical cyclone activity, the Asian monsoon and North American continental climate anomalies (Wang et al 2014, Anderson et al 2016, Yue et al 2020).

PQDO is less studied than other components of TPDV. Knowledge about its characteristics and dynamics is still in the development stage. Jin et al (2021) documented the spatial–temporal characteristics of PQDO and found it to be an episodic-like quasi-decadal warm/cold event. It initially develops in a northeast–southwest tilted belt from the Californian coast to the ECP by off-equatorial atmosphere–ocean interaction, and it matures in the ECP. Thus, they represented PQDO by an ECP index defined by the sea surface temperature anomalies (SSTAs) averaged over 10$^\circ$ S–10$^\circ$ N and 160$^\circ$ E–160$^\circ$ W. They showed that ECP warming is amplified primarily due to equatorward heat advection and a deepening thermocline, while zonal advective feedback mainly controls its decay. This ECP development distinguishes it from El Niño–Southern Oscillation (ENSO) dynamics, in which thermocline–upwelling feedback dominates (Bjerkness 1969). However, the origin of PQDO remains controversial.

Some studies attribute PQDO to the response of Pacific sea surface temperature (SST) to the 11-year solar cycle (e.g. White and Liu 2008a, 2008b). To this end, three lines of thinking have been presented. The first postulates that a weak La Niña-like SST is generated during the solar peak year followed by an El Niño-like warming 1 to 2 years later (Van Loon et al 2007, Meehl and Arblaster 2009, Meehl et al 2009). The second proposes the opposite: a weak El Niño-like pattern occurs at the solar cycle maximum (Roy and Haigh 2010, Misios and Schmidt 2012, Misios et al 2019). The third suggests that a weak SST warming pattern in the ECP modulated by the solar cycle leads to neither an La Niña-like nor an El Niño-like SST mode (Tung and Zhou 2010, Huo et al 2021).

In addition, PQDO triggered by the solar cycle may depend on the magnitude and periodicity of the solar irradiance (White et al 1998, Drews et al 2021). How the equatorial Pacific SST responds to the 11-year solar cycle remains obscure.

PQDO could also occur as internal variability. Like other components of TPDV, PQDO shows a spatial structure similar to ENSO (Allan 2000, Tourre et al 2001, Allan et al 2003). Thus, TPDV, including PQDO, was linked to ENSO-like decadal variability generated by the mechanisms that operate through the interannual ENSO cycle (White et al 2003, Vimont 2005) or considered as a residual of ENSO events (Kim and Kug 2020, Power et al 2021). Recent studies have also focused on the interaction between ENSO and interdecadal Pacific variability (e.g. Kim and Kug 2020, Sun and Okumura 2020, Zhao and Di Lorenzo 2020). However, the relationship between ENSO and PQDO has not been fully understood.

Jin et al (2021) found PQDO to be a nonstationary phenomenon: it has emerged since 1950 but was absent between 1878 and 1950. As shown in figure 1, the 11-year solar cycle was also amplified after the 1950s, and PQDO tends to follow it with a 1–2-year phase delay, suggesting that solar forcing might affect PQDO. On the other hand, the properties of ENSO also experienced significant changes (Wang et al 2019). However, the origins of PQDO and why it has intensified since 1950 still need to be addressed.

This study explores the origin of PQDO by testing two competing hypotheses, whether PQDO is a forced response to total solar irradiation (TSI) or a manifestation of internal variability, especially the low-frequency variability associated with ENSO asymmetry. We also explore why PQDO became
strong in the most recent seven decades but not before (1878–1950).

2. Data and method

2.1. Observational data and definition of the indices

The observed monthly mean SST from 1878 to 2021 is merged from two SST datasets, including the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) (Rayner et al. 2003) and the National Oceanic and Atmospheric Administration Extended Reconstructed SST (ERSST) version 5 (Huang et al. 2017), by simply taking their arithmetic means.

PQDO is represented by the ECP index defined by

\[ \text{PQDO} = \frac{\text{SSTA}_\text{ECP} - \text{SSTA}_\text{global}}{\text{SSTA}_\text{global}} \]

with averaged SSTA over the ECP (10° S–10° N, 165° E–165° W) (Jin et al. 2021). ENSO variability is measured by the Oceanic Niño index (ONI); namely, the SSTA averaged over the NINO3.4 region (5° S–5° N, 170° W–120° W). A La Niña year is defined by ONDJF (October–November–December–January–February) with averaged ONI equal to or below –0.5 °C and an El Niño year is defined by ONDJF ONI equal to or above 0.5 °C. Given the increasing trend in the present warming period, all the indices built from the observational data are detrended.

2.2. Validation of the Community Earth System Model’s ENSO

Considering the difficulty in detecting forced signals from limited observations, we analyzed long-term numerical simulation data obtained from the Community Earth System Model–Last Millennium Ensemble (CESM-LME) modeling project (Otto-Bliesner et al. 2016), including one fixed-forcing control (CTRL) experiment and four sensitivity experiments with spectral solar irradiance (SSI) for the period AD 850–2005.

To ensure that the model can reproduce reasonably realistic ENSO variability, we examined some aspects of the model performance, including ENSO phase locking to the annual cycle and El Niño–La Niña asymmetry. The asymmetry here means that El Niño has a larger amplitude than La Niña, but La Niña lasts longer than El Niño (An and Jin 2004, Okumura and Deser 2010).

The observed maximum standard deviation (SD) of the ONI occurs in December (figure S1), confirming ENSO mature phase locking to the end of the calendar year (Rasmussen and Carpenter 1982). Variability of the ONI reaches a minimum from May to June. The CESM-LME CTRL experiment generally captures the observed phase-locking of ENSO, although the simulation slightly overestimates the variance (figure S1, dotted line). CESM can reasonably reproduce the asymmetry in the amplitudes of El Niño and La Niña. The simulated maximum magnitudes for El Niño and La Niña events are 1.81 °C and –1.25 °C, which qualitatively match the observed 1.30 °C and –1.14 °C, respectively.

It has been demonstrated that the first and second empirical orthogonal function (EOF) patterns of ENSO resemble the linear signal (SD) and nonlinear signal (skewness), respectively (Monahan and Dai 2004). The observed EOF1 features a typical mature ENSO-like pattern with the center located over the eastern-central Pacific and explains 70% of the total variance; EOF2 displays an east–west dipole pattern that characterizes the asymmetric aspect of ENSO variability (figure S2). The spatial patterns of EOF1 and EOF2 in the CTRL run are generally consistent with the observed patterns, although the eastern-central Pacific SSTAs in EOF1 extend westward by 20°–30° of longitude, which results from the cold tongue bias commonly seen in many models (Li et al. 2016, Ying et al. 2019). Despite the discrepancies, the model generally captures the observed ENSO asymmetry.

3. Results

3.1. PQDO response to 11-year solar irradiance forcing

There are four solar-forcing (SSI) experiments in which the model was driven by only time-varying solar irradiance forcing with an 11-year solar cycle (Vieira et al. 2011), with all other external forcings being fixed at the AD 850 conditions. The TSI used in the SSI experiment is reconstructed by direct sunspot counts back to 1610 and an indirect record of solar activity from ice cores and tree rings for the longer TSI. Four SSI experiments allow for an ensemble mean that better represents a forced response by substantially reducing the internal variability. We examined the ensemble mean of four SSI experiments to investigate the responses of Pacific SST to different intensities (mean value) and variabilities (SD) of TSI forcing.

Based on the wavelet analysis of the TSI used in the SSI experiments (figure S3), we selected four equal-length (70 year) epochs with the strong 11-year solar cycle and four epochs with weak 11-year solar cycles, respectively (figure 2(a)). The averaged mean value and SD of the TSI during the four strong 11-year epochs are 1360.92 W m⁻² and 0.29 W m⁻², respectively. These are larger than their counterparts during the four weak 11-year solar cycle epochs with a mean (SD) value of 1360.15 (0.09) W m⁻².

The power spectra of the annual ECP index measure the significance and intensity of PQDO. We analyzed the averaged spectra of the four strong (weak) 70-year epochs to detect the forced response to a strong (weak) 11-year solar cycle. The averaged power
Figure 2. Response of PQDO to solar forcing. (a) Time series of the TSI (W m\(^{-2}\)) used in the solar-only experiments. The light pink shading is used to highlight the epochs with a strong 11-year solar cycle (AD 910–980, AD 1090–1160, AD 1560–1630 and AD 1935–2005), the light blue shading denotes the epochs with a weak 11-year solar cycle (AD 1280–1350, AD 1400–1470, AD 1471–1541 and AD 1650–1720). Red (blue) lines are the mean value of the TSI during each selected strong (weak) epoch. (b), (c) Averaged power spectra of the annual ECP index for the four strong 11-year solar epochs and four weak 11-year solar epochs derived from the four-member ensemble SSI experiments. The blue (red) curve represents the upper bound of the Markov red noise spectrum at the 90% (95%) confidence level.

Spectra show similar spectral peaks for the strong and weak 11-year solar cycle epochs (figures 2(b) and (c)); both have significant peaks on a 4–7-year time scale. Notably, no significant forced decadal signals exist, suggesting that 11-year solar irradiance cycles could not excite PQDO in the model. The 4–7-year peak manifests residual ENSO variability in the central Pacific because the four-member ensemble mean could not completely remove ENSO signals. But the average substantially reduced the internally generated interannual variance by one order of magnitude compared with the peaks in the control run (figure 4(b)). The power spectra of the ONDJF ECP index derived from the SSI experiment present similar results. Results here provide evidence that the 11-year solar irradiance forcing cannot directly excite the ECP quasi-decadal oscillation, regardless of the strong 11-year solar cycle or the strong solar intensity and variability.

A cautious note is that this conclusion is derived from a single model, namely CESM. Previous studies have speculated on the role of the top-down stratospheric amplification of the solar forcing in impacting Pacific SST variation acting together with a bottom-up coupled ocean–atmosphere response (Meehl et al 2009). However, the model used in the CESM-LME simulation does not have sufficient vertical resolution to resolve the stratospheric processes. Therefore, further studies with more sophisticated models are deemed necessary to assess the potential impacts of 11-year solar forcing on PQDO.

3.2. The links between PQDO and ENSO
3.2.1. Temporal structures of PQDO and ENSO low-frequency variation

We start to explore the observed linkage between PQDO and ENSO by focusing on boreal winter (ONDJF), because both ENSO and PQDO mature during ONDJF. Given the ENSO phase asymmetry, our power spectra analysis of ONI is applied to La Niña-only (or El Niño-only) years. Therefore, we
define two new indices (figure 3(a)). One is the ONI-El Niño, in which the ONI time series includes only El Niño years, and the neutral and La Niña years are replaced by zero. Another is ONI-La Niña, a time series that sets neutral and El Niño years to zero. Figure 3(a) shows the time series of ONI-El Niño and ONI-La Niña. The motivation was to identify the contributions of El Niño and La Niña to PQDO. Note that if we set all negative (positive) values of the ONI as ONI-La Niña (ONI-El Niño), the obtained
power spectra are highly similar (figure not shown for brevity).

Let us examine what happened between 1950 and 2021 first. Interestingly, the ECP index and ONI-La Niña have nearly the same spectral peaks (figures 3(b) and (c)), and both have a significant 12-year peak \( (p < 0.05) \). These results suggest that La Niña events have a prominent decadal signal beyond the interannual time scale that could contribute to PQDO. Additionally, the time series of ONI-La Niña is highly positively correlated with the ECP index with a correlation coefficient \( r = 0.76 \), an effective degree of freedom (EDF) of 23 and \( p < 0.01 \). In contrast, ONI-El Niño is insignificantly correlated with the ECP index with \( r = -0.22 \) (EDF = 18), suggesting that La Niña makes a critical contribution to PQDO but El Niño does not. In calculating the correlation coefficient, we did not account for the neutral years, and the significance test used the EDF following Bretherton et al (1999).

The intimate linkage between PQDO and ONI-La Niña arises because La Niña’s minimum SSTAs is nearly collocated with PQDO in the ECP. Conversely, the El Niño events have maximum SSTAs in the NINO3.4 region, coinciding with the maximum ONI. Thus, one might expect ONI to be linked to ONI-El Niño. It turns out that ONI and ONI-El Niño have almost the same spectral peaks on an interannual time scale but not on a decadal time scale (figures 3(d) and (e)). The quasi-12-year peak in the ONI is marginally significant \( (p = 0.1) \), while the decadal signal is absent in ONI-El Niño. Hence, the ONI decadal peak is also related to a La Niña-generated decadal component.

How about the power spectra in observations before 1950? As shown in figure S4, the power spectra of the ECP index, ONI-La Niña, ONI and ONI-El Niño differ considerably from the results shown for 1950–2021. Between 1878 and 1949, the ECP index and ONI-La Niña have similar spectral peaks, except that ONI-La Niña has a significant 8-year peak, and ONI-El Niño shows a sharp 4-year peak that dominates the interannual variability of the ONI.

To test the findings obtained from observations, we analyze the CTRL experiment. In the CTRL experiment, the external forcing is fixed at \( AD \) 850 so that the climate variations of the models are produced by internal feedback processes within the coupled climate system. We selected a continuous 500-year sample from the CTRL experiment to study the temporal behaviors of ENSO and PQDO using the ONI and ECP indices. A wavelet analysis of the ECP index confirms that the model-simulated PQDO is nonstationary: it tends to be stronger in the first 250 years and weaker in the last 250 years. The ECP index and ONI share a similar power distribution on the interannual (2–7-year) time scale. However, the ECP index has significant interdecadal (>16 years) variability which is absent in the ONI. The two equal-length (250 years) epochs provide a testbed for investigating the relationship between PQDO and ENSO.

During the first 250 years, the magnitude of the positive ONI is much stronger than the negative ONI, reflecting the skewness of the ENSO cycle or ENSO phase asymmetry (figure 4(a)). Conversely, the ECP index is primarily symmetric between the magnitudes of the positive and negative anomalies. Thus, the negative ECP index generally coincides with negative ONI, but the positive ECP values are usually much lower than the positive ONI values. This feature corroborates the observed features, especially for 1950–2021 (figure 1). The power spectra of the ECP index, ONI-La Niña, ONI and ONI-El Niño derived from CTRL experiment during the first 250 years are generally consistent with the results shown for the strong PQDO epoch (1950–2021). The simulated ECP spectrum coincides with ONI-La Niña on the interannual and decadal time scales, with a significant 11-year periodicity. The ONI spectrum resembles ONI-El Niño, although the spectral amplitude of the ONI is much stronger than that for ONI-El Niño. Besides, the time series of ONI-La Niña is well positively correlated with that of the ECP \( (r = 0.86, EDF = 69, p < 0.01) \). In contrast, the ONI-El Niño time series is negatively related to the ECP index with \( r = -0.41 \) \( (EDF = 61) \).

An important point we want to make is that the low-frequency (decadal) ENSO produced by irregular occurrence of El Niño and La Niña is highly nonstationary in both periodicity and amplitude (Wittenberg 2009). This assertion is exemplified by what happened in the weak PQDO epoch (years 251–500) (figure S6). During that epoch, the ECP index and ONI-La Niña had very similar spectral peaks, but the decadal signal was absent, suggesting that the absence of the La Niña decadal signal leads to an inactive PQDO. On the other hand, ONI-El Niño shows a sharp 11-year peak that dominates the decadal variability of the ONI.

In sum, both La Niña and El Niño could produce a significant decadal component beyond the interannual. However, the two phases of ENSO, i.e. El Niño and La Niña, have different SST variability centers. Therefore, El Niño’s decadal component can affect low-frequency ONI but not PQDO. In contrast, La Niña’s decadal component mainly affects PQDO. ENSO phase asymmetry in SST variability centers plays a critical role in generating PQDO.

3.2.2. Evolution of the spatial structures of PQDO and ENSO low-frequency variation

To investigate evolution of the spatial structures of the SSTAs associated with PQDO and the low-frequency ENSO, we used 3-year running ONDJF
Figure 4. CESM simulated contribution of El Niño and La Niña to PQDO. (a) Time series of the ONDJF mean ECP index and ONI derived from the CTRL experiment. (b)–(e) As figures 3(b)–(e), except that they are derived from the CTRL experiment during the strong decadal signal epoch (years 1–250).

SSTA to construct the lead–lag correlation maps with reference to the ECP index, ONI-La Niña and ONI-El Niño decadal variability from year −2 to year +2 derived from observation and the model's CTRL experiment (figures 5 and S7, S8). From 1951–2021 when PQDO was significant, ONI-La Niña SST evolution differs significantly from El Niño–only evolution (figures 5(a) and (b)). ONI-La Niña has a longer life cycle, whereas ONI-El Niño is more like a short and smooth single event. The evolution of ONI-La Niña shows an expanded PDO-like pattern, while ONI-El Niño features a more equatorially
Figure 5. Evolutions of the spatial structures of PQDO and ENSO low-frequency variation. Evolution of (a) ONI-La Niña (decadal variation associated with La Niña), (b) ONI-El Niño (decadal variation associated with El Niño) and (c) PQDO from 1950 to 2021 derived from observations. Shown are the lead–lag correlation maps of the ONDJF mean SSTA with reference to ONI-La Niña (a), ONI-El Niño (b) and the ECP index (c) from year $-2$ to year $+2$. The dotted areas denote significance at the 90% confidence level, conducted by a two-tailed $t$-test.

The simulated evolution of PQDO resembles the observations, suggesting that the model can simulate PQDO.

3.2.3. Why the PQDO emerged after 1950 but was absent from 1878 to 1949

We have shown that the La Niña–induced decadal signal makes a significant contribution to PQDO in the ECP. A more profound question remains about what causes La Niña’s significant decadal variability, and why is it nonstationary? From 1950 to 2021, the negative phase of PQDO tends to follow the frequent occurrence of multi-year La Niña (figure 5), suggesting that multi-year La Niña events are conducive to reinforcing PQDO.

It is conceivable that the frequent occurrence of multi-year La Niña might be responsible for the emerging PQDO since 1950. The frequency of multi-year La Niña has increased, while the frequency of single-year La Niña events has decreased over the past 144 years. Ten multi-year and five single-year La Niña events occurred between 1950 and 2021. In contrast, there were only three multi-year but 11 single-year events from 1878 to 1949. This change is statistically significant at a 95% confidence level by
the contingency table test (table 1), suggesting that intensification of PQDO since the 1950s is probably due to the change in properties of La Niña.

### 4. Conclusion and discussion

It has been a great challenge to determine the cause of PQDO in the ECP due to the mixture of heterogeneous internal variability and forced responses in the observations. Our analyses of the 144-year observations and the millennial simulation results from the CESM-LME project shed light on the nonstationary nature and origin of PQDO. Our significant findings are summarized as follows:

- Analysis of the four solar-forcing-only simulation results suggests that 11-year solar irradiance cannot excite PQDO without stratospheric amplification of the solar cycle (figure 2).
- Analysis of the results of both observations and fixed-forcing experiments indicate that PQDO is a nonstationary phenomenon, and internal variability in the coupled climate system could generate PQDO from time to time (figures 3 and 4).
- The internally generated PQDO is primarily shaped by the La Niña-induced decadal variability (figures 3 and 4). The negative phase of PQDO tends to follow the frequent occurrence of multi-year La Niña (figure 1), suggesting that multi-year La Niña events are conducive to generating PQDO.
- Both La Niña and El Niño could induce a significant decadal component. However, La Niña and El Niño possess different SST variability patterns and evolutions (figure 5). The action center forced by La Niña's decadal variability is in the ECP, but the maximum SSTA caused by El Niño's decadal variation is located over the eastern Pacific NINO3.4 region. Therefore, only La Niña's decadal component can reinforce PQDO.
- The intensification of PQDO since 1950s might be primarily due to the increased multi-year La Niña events (table 1). The nonstationarity of PQDO may be rooted in the secular change in the properties of La Niña.

Our findings have ramifications for understanding future changes in PQDO. This work has attributed the emergence of PQDO since the 1950s to the frequent occurrence of multi-year La Niña on a decadal time scale. As shown in figure 3(a), negative PQDO coincides with La Niña events, and the previous consecutive 2-year or 3-year La Niña events correspond to the minima of PQDO. The ongoing (2020–2022) La Niña events (Fang et al 2022, Mukhopadhyay et al 2022) will probably contribute to a new minimum of PQDO. The observed global warming since the 1950s might have contributed to the increasing trend in multi-year La Niña. However, what makes multi-year La Niña events occur on a decadal time scale remains unknown. These issues deserve further investigation.

Additionally, ENSO and TPDV might be interactive: ENSO could induce low-frequency TPDV, but the ENSO-like TPDV could also impact the Pacific mean-state, changing the relative frequency of the El Niño and La Niña events (Sun and Okumura 2020). There are other unresolved issues. For instance, if PQDO arises from the decadal variation of La Niña, it means an equatorial origin. However, PQDO seems to start from the subtropical northeast Pacific (figure 5(c)). The hypotheses proposed in this work are based on the results from a single-model simulation. More comprehensive multi-model studies are needed to verify the model results.

### Data availability statement

The HadISST data are available from www.metoffice.gov.uk/hadobs/hadisst/. The ERSST data can be accessed from https://climatedataguide.ucar.edu/climate-data/sst-data-noaa-extended-reconstruction-sstsv5. The numerical simulation data are obtained from CESM-LME (Otto-Bliesner et al 2016) and retrieved from www.cesm.ucar.edu/projects/community-projects/LME/data-sets.html; the solar forcing used in the CESM-LME is reconstructed by Vieira et al (2011) and can be downloaded by the link www.geosci-model-dev.net/4/4/2011/gmd-4-4-2011-supplement.zip. Figures were made with NCAR Command Language Version 6.6.2, available at www.ncl.ucar.edu/Download/.

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions
C J initialized and wrote the manuscript. B W and J L provided valuable comments and revisions of the manuscript.

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