Tropospheric biennial oscillation and south Asian summer monsoon rainfall in a coupled model

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In this study Tropospheric Biennial Oscillation (TBO) and south Asian summer monsoon rainfall are examined in the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFSv2) hindcast. High correlation between the observations and model TBO index suggests that the model is able to capture most of the TBO years. Spatial patterns of rainfall anomalies associated with positive TBO over the south Asian region are better represented in the model as in the observations. However, the model predicted rainfall anomaly patterns associated with negative TBO years are improper and magnitudes are underestimated compared to the observations. It is noted that positive (negative) TBO is associated with La Niña (El Niño) like Sea surface temperature (SST) anomalies in the model. This leads to the fact that model TBO is El Niño-Southern Oscillation (ENSO) driven, while in the observations Indian Ocean Dipole (IOD) also plays a role in the negative TBO phase. Detailed analysis suggests that the negative TBO rainfall anomaly pattern in the model is highly influenced by improper teleconnections allied to IOD. Unlike in the observations, rainfall anomalies over the south Asian region are anti-correlated with IOD index in CFSv2. Further, summer monsoon rainfall over south Asian region is highly correlated with IOD western pole than eastern pole in CFSv2 in contrast to the observations. Altogether, the present study highlights the importance of improving Indian Ocean SST teleconnections to south Asian summer rainfall in the model by enhancing the predictability of TBO. This in turn would improve monsoon rainfall prediction skill of the model.

Keywords. Tropospheric biennial oscillation; monsoon; ENSO; sea surface temperature; coupled models.

1. Introduction

Tropospheric Biennial Oscillation (TBO) is an integral part of the coupled ocean atmosphere system (e.g., Meehl and Arblaster 2001, 2002). The large-scale east–west atmospheric circulation across the Indian and Pacific sectors is a primary element

of the TBO which involves ocean–atmosphere interactions (Meehl and Arblaster 2001). The Asian–Australian monsoon system is a major part of TBO (e.g., Meehl 1987; Yasunari 1990). According to Chang and Li (2000), TBO involves active interactions of anomalous Asian monsoon heating and the planetary-scale east–west circulation.

These TBO signals are not only seen in the monsoon rainfall, but also in the Sea Surface Temperature (SST), upper-ocean heat content and tropospheric circulation (e.g., Yasunari 1991; Ropelewski *et al.* 1992; Lau and Yang 1996; Meehl 1997).

TBO signals in the monsoon rainfall is the tendency of a strong monsoon to be followed by a weaker monsoon and vice versa with the transitions occurring in the season prior to the monsoon (Meehl and Arblaster 2002). The transitions (from relatively strong to weak monsoon) in the TBO occur in spring (March–May) for the south Asian or Indian monsoon region. Transitions from March–May to June–September tend to set the system for the next year, with a transition to the opposite sign in the following year (Meehl *et al.* 2003). Several studies suggested that the Indo–Pacific SST displays strong impact on TBO as compared to the meridional gradient of temperature anomalies over Asia (e.g., Meehl and Arblaster 2002; Meehl *et al.* 2003).

Spatial scale of TBO is much larger which includes the Asian–Australian monsoon sector and the tropical Indian and Pacific Oceans (e.g., Meehl 1994, 1997; Ashok *et al.* 2014). However, El Niño–Southern Oscillation (ENSO) could influence the TBO variations (e.g., Rasmusson *et al.* 1990; Yasunari 1990; Goswami 1995; Meehl and Arblaster 2001). Li *et al.* (2007) suggested the possibility of TBO being linked to ENSO and circulation anomalies over the western north Pacific and southern Tropical Indian Ocean (TIO). However, some studies demonstrated the presence of TBO signal over the TIO without any remote forcing such as ENSO (e.g., Li *et al.* 2001). Meehl *et al.* (2003) reported that the TBO in the Asian–Australian monsoon region would be weakened without the influence of ENSO. It is also documented that TBO movement and formation are different with and without ENSO in the Pacific (Pillai and Mohankumar 2007).

It is demonstrated in the previous studies that anomalous SST variations over the TIO contribute to TBO strength (e.g., Loschnigg *et al.* 2003). The SST anomalies evolution associated with the biennial mode exhibits a strong seasonality in the tropical Pacific and the Indian Oceans (Kim and Kim 2016). The ocean–atmosphere interactions associated with Indian Ocean Dipole (IOD; Saji *et al.* 1999) over the Indo–Pacific sector trigger the biennial phase shift of the ENSO, which in turn could be responsible for the biennial tendency

of the Asian summer monsoon (e.g., Annamalai *et al.* 2005; Izumo *et al.* 2010, 2014; Sakai *et al.* 2010; Tamura *et al.* 2011). Pillai and Mohankumar (2010) pointed out that the TIO variability such as IOD is important local forcing for the biennial monsoon cycle. They also suggested that the local Hadley circulation over the Indian Ocean is found to play an important role in affecting ISM rainfall through TBO cycle. Thus, ISM, ENSO, TIO SST variations and their mutual interactions are involved in the biennial character of the tropical climate over the Indian and Pacific regions (Meehl *et al.* 2003; Wu and Kirtman 2007; Ashok *et al.* 2014).

Coupled General Circulation Models (CGCMs) are essential tools to study long-term climate and so models' successful simulation of teleconnections therefore could justify their prediction of the regional and global climate (Li *et al.* 2007; Goswami *et al.* 2014). Some Coupled Model Inter-comparison Project (CMIP3) models are able to simulate south Asian rainfall related to TBO (e.g., Nanjundiah *et al.* 2005; Rajeevan and Nanjundiah 2009). Using Atmospheric Model Inter-comparison Project (AMIP) type simulations, Liu *et al.* (2015) examined the dominant spatial patterns of summer rainfall on TBO time scales over the East Asian summer monsoon. They showed that the northern China favors dry (wet) conditions during El Niño (La Niña) developing case and vice-versa for southern China region at TBO time scales. Meehl and Arblaster (2011) examined the long-coupled model simulations from Community Climate System Model-4 and showed that internally generated variability associated with the Inter-decadal Pacific Oscillation (IPO) can modulate the TBO. Further, Li *et al.* (2012) noted that many CMIP3 and CMIP5 models have successfully simulated the transition from strong/weak ISM to strong/weak Australian monsoon associated with TBO. Above studies clearly suggest that representing rainfall changes associated with TBO over the ISM region in CGCMs is important. Motivated by the above, in the present study, we have examined the ISM rainfall associated with TBO component over the south Asian monsoon region in the National Centers for Environmental Prediction (NCEP) Climate Forecast System version-2 (CFSv2; Saha *et al.* 2014). This model is successfully implemented by India for seasonal to extended range forecast of ISM (<http://www.tropmet.res.in/monsoon/files/publication.php>) and is being used in other parts of the world (Saha *et al.* 2014).

Therefore, it is essential to evaluate the model performance in simulating/predicting TBO signals associated with ISM and assess the skill in capturing large-scale circulation pattern over tropics related to TBO.

Rest of the paper is organized as follows. Section 2 describes the observational data and model used in this study. Section 3 reports the model performance in representing TBO signals and associated interactions. Out of phase TBO case study is presented in section 4. Summary is presented in section 5.

2. Data and methodology

TBO signals of south Asian summer monsoon rainfall are examined in the NCEP-CFSv2 (Saha *et al.* 2014) hindcast, which is a fully coupled ocean–atmosphere model. NCEP global forecast system (GFS) is the atmospheric component with 64 sigma layers vertically and T126 (~100 km) horizontal resolution. The oceanic component is the Modular Ocean Model version 4 (MOM4P0) (Griffies *et al.* 2004) with horizontal resolution of 0.25° in the 10°S–10°N latitude band and 0.5° resolution elsewhere. Retrospective forecast (hindcast) is prepared for 9 months covering a period of 30 years from 1985–2014 based on CFSv2 at Indian Institute of Tropical Meteorology (IITM). The atmospheric and ocean initial conditions are obtained from the NCEP Reanalysis-R2 and Global Ocean Data Assimilation System (GODAS) data (Saha *et al.* 2010), respectively. Retrospective forecast starts from May with 10 atmospheric initial conditions (10 ensemble members), which are partitioned into two segments. More details of the model run and initial conditions are provided in Srinivas *et al.* (2017). In the present study, we have used the 10 member ensemble mean for detailed analysis. European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim; Dee *et al.* 2011) surface, 850 and 200 hPa level winds, mean sea level pressure (MSLP), air-temperature and Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) are utilized for the entire study period. Observed SST product used in this study is based on Optimum Interpolation Sea Surface temperature (OISST; Reynolds *et al.* 2002). We have used correlation, composite and the Fourier spectrum analysis in the present study. Note that signals more than half (0.5)

standard deviation are only displayed (in figures) and discussed in composite analysis.

TBO is the tendency of a strong monsoon to be followed by a weaker one and vice versa with the transitions occurring in the season prior to the monsoon (Meehl 1997; Meehl and Arblaster 2002). TBO years for south Asian rainfall is selected based on the criteria similar to earlier studies (Chang and Li 2000; Meehl and Arblaster 2001, 2002; Pillai and Mohankumar 2007) and is given below.

If P_i is the value of area averaged rainfall anomalies over the region 5–40°N, 60–100°E for a given year i then a relatively strong monsoon (positive TBO) is defined as:

$$P_{i-1} < P_i > P_{i+1}. \quad (1)$$

And a relatively weak monsoon (negative TBO) is defined as:

$$P_{i-1} > P_i < P_{i+1}. \quad (2)$$

3. TBO variability in CFSv2 hindcast

Figure 1(a) shows the normalized precipitation anomalies (by the standard deviation) over the region (5–40°N, 60–100°E) during JJAS (mean of June, July, August and September) for both the observations and model. Here after this index is referred as TBO index. The model TBO index is well correlated with the observed (0.7), suggesting that model has significant skill in representing/predicting TBO signals over south Asia. Table 1 provides list of positive and negative TBO years selected using the above criteria during the study period for both the observations and model. It is noted that the model is able to represent most of the positive and negative TBO years. To examine the spatial patterns of atmospheric and ocean variables associated with TBO, we have selected the years in which positive (negative) TBO years are common for both the model and observations (table 1). Further to confirm the presence of biennial signals in precipitation anomalies over this region, we have carried out the Fourier spectrum analysis for JJAS ISM rainfall for the observations and model. It is apparent that both the observations and model display clear biennial signals with above 95% confidence level (figure 1b and c). This further supports the importance of present analysis on TBO or biennial variability associated with south Asian monsoon rainfall.

Figure 1. (a) Time series of normalized JJAS precipitation (mm/day) anomalies over TBO (south Asian) region (5–40°N, 60–100°E) of both observations and CFSv2 hindcast (with May initial conditions) for the period 1985–2014. Fourier spectrum analysis of JJAS ISM rainfall for (b) observations and (c) model. Dashed line indicates red noise spectra, above which signals qualify 95% confidence level.

Table 1. List of positive and negative TBO years used for composite analysis.

Positive TBO Years	1988	1998	2003	2005	2007	2010	2013
Negative TBO Years	1997	2004	2006	2009	2012		

Composite of precipitation and 850 hPa wind anomalies for positive and negative TBO years are illustrated in figure 2. During positive TBO years precipitation is positive over most of the south Asian region both in the observations and model (figure 2a and b). Precipitation patterns associated with positive TBO over the maritime continent and equatorial Pacific are also well captured by the model and are comparable to the observations. Convergence associated with strong easterly wind anomalies from central and western Pacific and westerly wind anomalies from Arabian Sea favored positive precipitation anomalies over most of the Indian subcontinent, and is well represented by the model (figure 2a and b).

In the case of negative TBO years, precipitation pattern over the Indian subcontinent displays strong negative anomalies in the model as compared to the observations (figure 2c and d). On the other hand precipitation and wind anomalies over the equatorial Indian Ocean are underestimated by the model. Southwesterly winds over the Indian subcontinent and northwest Pacific are weak in the model unlike in the observations. This analysis suggests that the model is able to capture precipitation patterns associated with the positive TBO years over the south Asian monsoon region but fails to represent during negative TBO years. The factors responsible for differences in the precipitation patterns between model and observations over the

Figure 2. Composite of normalized JJAS precipitation (shaded; mm/day) and 850 hPa wind (vectors; m/s) anomalies during positive TBO years for (a) observations, (b) CFSv2 hindcast with May initial conditions. (c and d) Same as in (a) and (b), but for negative TBO years.

south Asian region during TBO years are further examined.

SST and SLP anomaly patterns associated with positive (negative) TBO years clearly show La Niña (El Niño) type conditions over the Pacific and weak warm anomalies in TIO in both the observations and model (figure 3a and b). This indicates that the model is able to represent SST and precipitation anomaly patterns associated with positive TBO very well. On the other hand negative TBO years show IOD (positive) like patterns with warming over the western equatorial Indian Ocean and cooling over the southeast equatorial Indian Ocean (figure 3c) in observations. However, such kind of SST anomaly patterns in the model is very weak and the same is reflected in the MSLP (figure 3c and d). It is also clear from figure 2 that in the model positive TBO is associated with La Niña like SST and circulation and negative TBO with El Niño like anomalies, suggesting that TBO or monsoon rainfall is mainly driven by ENSO. In the case of the observations, IOD also plays a role in modulating the negative phase of TBO. Further to examine the relation between TIO

SST and south Asian summer monsoon rainfall associated with negative TBO years, we have carried out analysis for IOD years in both observations and model.

Figure 4(a and b) shows the composite of SST and SLP anomalies for negative TBO years associated with IOD (1997, 2006). Observations show strong SST gradient over the equatorial Indian Ocean with negative anomalies in the east and positive anomalies in the west. Associated with this, SLP anomalies are high positive over the eastern Indian Ocean and maritime continent as compared to the western Indian Ocean. In the case of model negative SST anomalies are confined to central equatorial Indian Ocean with the maximum anomalies centered on 12°S and 100°E unlike in the observations, which is also, reflected in the SLP anomalies. Anomalous off equatorial anticyclonic circulation in response to east equatorial Indian Ocean cold SST anomalies are apparent in the observations (figure 4c). This strong anticyclonic circulation in the north of equator strengthens the mean southwesterly winds over Arabian Sea and assisting positive rainfall anomalies over

Figure 3. Composite of normalized JJAS SST (shaded; °C) and MSLP (contour; hPa) anomalies during positive TBO years for (a) observations, (b) CFSv2 hindcast with May initial conditions. (c and d) Same as in (a) and (b), but for negative TBO years.

parts of western India corroborated by strong moisture transport. However, in the model maximum negative SST anomalies are seen south of its normal position and the corresponding atmospheric circulations show strong zonal winds over the equatorial region as compared to the observations (figure 4b and d). Further anomalously strong negative precipitation over central India is evident in the model. It is important to note that rainfall over the west (east) equatorial Indian Ocean is out of phase (in phase) with central Indian monsoon rainfall in the model and vice-versa in the observations. The observed local Hadley circulation (averaged between 80 and 95°E) shows anomalous descent over the east equatorial Indian Ocean, mainly south of the equator and ascending motion over the monsoon trough and head Bay of Bengal (figure 4e). Ascending motion and low level convergence over the monsoon core region are very weak in the model, further supporting the existence of unrealistic IOD-monsoon relation in the mode (figure 4f). This is consistent with [Pillai and Mohankumar \(2008\)](#), who suggested that south Asian summer monsoon TBO signals can be altered by local Hadley circulation from equatorial

Indian Ocean. This clearly suggests that improper distribution of SST anomalies associated with IOD in the model and the atmospheric response mainly effect rainfall patterns over South Asia and hence the strength of the negative TBO.

Large differences in Tropospheric Temperature (TT) and 200 hPa wind anomalies between observations and model are also noted during IOD years over the ISM region (figure 5a and b). Moreover upper level convergence center is located west of its normal position over the equatorial Indian Ocean in the model, which is also identified in the 200 hPa velocity potential anomalies (figure 5c and d). This analysis clearly suggests that relationship between IOD and south Asian monsoon rainfall is under predicted by the model and is mainly responsible for change in the strength of the negative TBO. This is the motivation behind investigating the relationship between IOD and south Asian summer rainfall in the model and observations.

Figure 6 shows the correlation between rainfall over the ISM region and IOD index, SST anomalies of east and west poles of IOD for both the observations and model for the period of 1985–2014. Weak positive correlation is noted over

Figure 4. Composite of normalized JJAS anomalies for IOD (1997 and 2006) year, (a) SST (shaded; $^{\circ}\text{C}$), MSLP (contours; hPa) for observations, (b) is same as (a), but for CFSv2. (c) Precipitation (shaded; mm/day) and 850 hPa winds (vectors; m/s) for observations, (d) is same as (c), but for CFSv2, (e) north–south cross section of meridional wind (m/s) and vertical velocity (10^{-2} Pa/s) averaged over $80\text{--}95^{\circ}\text{E}$ for observations, (f) is same as (e), but for CFSv2.

the monsoon trough region when correlated with IOD index in the observations, whereas the model shows strong negative correlation over the Indian subcontinent (figure 6a and b). Equatorial wind anomalies are much stronger with zonal structure in response to IOD in the model as compared to the observations. It is noted that off equatorial circulation response to IOD is not well represented in the model, which plays an important role in the IOD teleconnections to ISM rainfall. It is known that eastern and western poles of IOD are important in determining the distribution of rainfall around

TIO. It is noted that SST anomalies of eastern pole of IOD is weak negatively correlated with rainfall over the monsoon trough region (figure 6c) in the observations. In case of the model eastern pole of IOD is weak positively correlated with rainfall over parts of Indian subcontinent (figure 6d), which further shows the incorrect teleconnections in the model. Correlation between the SST anomalies of western pole of IOD and ISMR is weak in the observations, whereas in the model strong negative correlation is noted (figure 6f). This analysis indicates that IOD teleconnections to south

Figure 5. Composite of normalized JJAS anomalies during IOD years (1997, 2006). (a) Tropospheric temperature (shaded; $^{\circ}\text{C}$) and 200 hPa winds (vectors; m/s) for observations, (b) is same as (a), but for CFSv2. (c) Velocity potential at 200 hPa (shaded; $10^{-6} \text{ m}^3/\text{s}$), and divergent winds (vectors; m/s) for observations, (d) is same as (c), but for CFSv2.

Asian monsoon rainfall are wrongly represented in the model. Further unrealistic relation between the western pole of IOD and ISMR also affects the strength of TBO in the model unlike in the observations. Most importantly the model eastern (western) IOD pole displays less (high) variance compared to observations during summer and fall seasons (figure 7). Such unrealistic SST variations in the western TIO in the model might strongly influence rainfall anomalies around TIO region and strength of TBO signals. The model JJAS Niño 3.4 is highly correlated with the observations ($r = 0.88$), suggesting that CFSv2 has good skill predicting ENSO (figure 8a). But the model displayed moderate to low skill in predicting IOD ($r = 0.44$) mode (figure 8b). This further supports the fact that Indian Ocean simulation need to be improved in the model to capture the TBO phenomena more accurately. It is noted that many (ENSO) years Niño 3.4 is slightly overestimated in the model as compared to the observations and this indicates that ENSO dependence of TBO rainfall is stronger in the model.

4. Case study: Out of phase TBO signal between observations and model

Above discussions suggest that though most of the model TBO years are in phase with the observations, the magnitude of negative TBO signals are strangely undermined due to improper IOD-monsoon teleconnections. Apart from this some TBO years are found to be out of phase compared to the observations. For example, 1992 is a positive TBO year in the observations, whereas it is negative TBO year in the model (figure 1). The differences in SST, precipitation and large scale circulation anomalies between 1992 and 1991 are analyzed for both observations and model (figure 9). In observations the rainfall difference over most of the north Indian Ocean and parts of Indian subcontinent is positive (figure 9a). In the model on the other hand, the rainfall difference is negative over most of the Indian subcontinent and Bay of Bengal. Large differences in rainfall patterns over the equatorial and south Indian Ocean region with enhanced (reduced) precipitation over

Figure 6. Correlation of precipitation (shaded) and 850 hPa wind (vectors) with IOD index for (a) observations, and (b) CFSv2. (c and d) are same as (a and b), but correlated with eastern IOD pole SST anomalies and (e and f) are same as in (a) and (b), but correlated with western IOD pole SST anomalies for the period 1985–2014.

the south east equatorial Indian Ocean and reduced (enhanced) precipitation over the south west TIO are evident in the observations (model). These rainfall patterns are closely associated with SST anomaly patterns over the TIO. In response to SST anomaly patterns, large scale circulation also displays strong difference between the observations and model. Thus it is clear that Indian Ocean SST patterns are not well predicted by the model during 1991 and 1992 case. Further, previous studies pointed out the model deficiencies in

simulating the south Asian summer monsoon and associated SST patterns (e.g., Wajsowicz 2005; Yang *et al.* 2008; Chaudhari *et al.* 2013; Goswami *et al.* 2014). These differences in SST patterns are primarily responsible for the phase difference in the TBO between model and observations.

5. Summary

Tropospheric Biennial Oscillation (TBO) is described as the tendency of a strong monsoon to be

Figure 7. Standard deviation of JJA, SON SST ($^{\circ}\text{C}$) anomalies of IOD index, western IOD pole, and eastern IOD pole for the observations and CFSv2 (with May initial conditions) for the period 1985–2014.

Figure 8. Time series of normalized JJAS SST ($^{\circ}\text{C}$) anomalies for (a) Niño 3.4 and (b) IOD of observations (black line) and CFSv2 (bars) hindcast (with May initial conditions) for the period 1985–2014.

followed by a weaker monsoon and vice versa (e.g., Meehl 1997; Meehl and Arblaster 2002; Pillai and Mohankumar 2010). Ocean–atmospheric interactions over the tropical Indian and Pacific Ocean regions are known to play key role in determining TBO signals. In this study the ability of NCEP–CFSv2 model to capture the strength of TBO signals is investigated. Previously many studies examined skill of this model in representing the ENSO–monsoon relationship (e.g., Achuthavarier

et al. 2012; George *et al.* 2015; Chowdary *et al.* 2016; Pillai *et al.* 2016; Ramu *et al.* 2016) and Indian monsoon and extra-tropical teleconnections (e.g., Saha *et al.* 2013; Chattopadhyay *et al.* 2016). However, it is poorly known how CFSv2 represents TBO signals associated with the south Asia summer monsoon rainfall.

Analysis suggests that the model is able to capture most of the TBO years and the correlation between the observations and model TBO

Figure 9. Difference (1992 minus 1991) of normalized JJAS precipitation (shaded; mm/day) and 850 hPa wind (vectors; m/s) anomalies for (a) observations, (b) CFSv2. (c and d) is same as in (a and b), but for SST (shaded; °C) and MSLP (contours; hPa).

indices are highly significant. Signals associated with positive TBO phase are well represented over South Asia in the model. But the model predicted rainfall anomalies patterns associated with negative TBO years are uneven and magnitudes are differing as compared to the observations. It is found that model positive (negative) TBO years are strongly associated with La Niña (El Niño) like SST and circulation anomalies. This suggests that the model south Asian monsoon rainfall related to TBO is highly dependent on ENSO, while in the observations IOD also plays a role in modulating the negative phase of TBO. Model results indicate that the negative TBO rainfall anomaly patterns over South Asia are highly tied with incorrect teleconnections associated with IOD. Improper equatorial SST anomaly distribution associated with IOD and an anomalously high zonal pressure gradient forced unrealistic equatorial zonal wind anomalies in the model are reported unlike in the observations. Excessive surface convergence over the western equatorial Indian Ocean reduced the moisture transport toward the Indian subcontinent, which is mainly responsible for the

large negative rainfall anomalies in the model compared to the observations. In addition to that, inappropriate local Hadley circulation related to IOD in the model also contributed for suppressed rainfall over the monsoon region. Previous studies suggested that the TIO SST anomalies could produce a TBO transition for the monsoon (Chang and Li 2000; Li *et al.* 2001). Using a series of CGCM simulations, Yu *et al.* (2003) pointed out that Indian Ocean SST anomalies play important role in the out-of-phase transition of the Australian to Indian summer monsoon as a part of TBO, indicating the importance of representation of TIO SST patterns in impacting TBO signals. High negative (positive) correlation between western (eastern) IOD pole and rainfall over the Indian Subcontinent in CFSv2 relative to observation indicate that the model is missing an important teleconnection process. Present study highlights the importance of improving the Indian Ocean SST teleconnections to south Asian summer monsoon rainfall in the model in order to enhance the predictability of TBO, which in turn would improve monsoon rainfall prediction.

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