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Variabilities of mesospheric tides and equatorial electrojet strength during major stratospheric warming events

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Abstract. The present study demonstrates the relationship between the high latitude northern hemispheric major sudden stratospheric warming (SSW) events and the reversal in the afternoon equatorial electrojet (EEJ), often called the counter-electrojet (CEJ), during the winter months of 1998–1999, 2001–2002, 2003–2004 and 2005–2006. As the EEJ current system is driven by tidal winds, an investigation of tidal variabilities in the MF radar observed zonal winds during the winters of 1998–1999 and 2005–2006 at 88 km over Tirunelveli, a site close to the magnetic equator, shows that there is an enhancement of semi-diurnal tidal amplitude during the days of a major SSW event and a suppression of the same immediately after the event. The significance of the present results lies in demonstrating the latitudinal coupling between the high latitude SSW phenomenon and the equatorial ionospheric current system with clear evidence for major SSW events influencing the day-to-day variability of the CEJ.

Keywords. Ionosphere (Equatorial ionosphere)

1 Introduction

The equatorial electrojet (EEJ) is an intense band of eastward electrical current flowing at an altitude of 105 km during daytime in a narrow latitudinal belt (±3°) around the dip equator. This reflects in the daily variation of the horizontal component (H) of the Earth's magnetic field which shows a positive deviation during the day with a maximum around noon (Onwumecheli, 1997). A negative deviation in H, sometimes, occurs due to the reversal in the direction of the current system from the normal eastward flow to westward which is often called the 'counter electrojet' (CEJ) (Mayaud, 1977). Though the CEJ can occur either in the morning or in the afternoon, the afternoon CEJ events are of special interest to the scientific community, as they are relatively more complex and highly variable.

Though the morphological behaviour of the CEJ is well known (Marriott et al., 1979, for a review), identifying the causative mechanisms for its occurrence still remains an unsolved problem. Height-varying local winds were earlier thought to cause the reversal in the current system. Though such winds can produce altitudinal changes in the vertical polarization field, the desired effects are pronounced not at the magnetic dip equator, but at latitudes ±2° off the equator (Richmond, 1973). Raghavarao and Anandarao (1980) proposed that gravity wave-associated vertical winds can produce this effect at the equator. Besides, global-scale tidal winds with appropriate phase combination were shown to reverse the currents in the afternoon hours (Forbes and Lindzen, 1976; Marriott et al., 1979; Stening, 1989). Singh and Cole (1987) incorporated a three-dimensional numerical model that evaluates the role of tidal modes in causing the observed changes in the magnetic field variations associated with the CEJ. Stening et al. (1996) suggested that there is an association between CEJ events and high latitude stratospheric warming events. The effect of stratospheric warming on tidal propagation has been reported in the past in a few studies. Bhattacharya et al. (2004) noted an increase in the semi-diurnal tidal amplitude over Canada (74.9° N, 94.9° W) during two warming events of 2001. Hoffmann et al. (2007) observed enhanced semi-diurnal tidal amplitudes over a high-latitude station, Andenes (69° N, 16° E), in February 2006, when a major warming event occurred. Goncharenko and Zhang (2008) observed that ion temperatures at a mid-latitude site during the stratospheric warming of January 2008 revealed alternating regions of cooling in a large altitude range (150–300 km) and warming in a narrow altitude band (120–140 km). Earlier, Vineeth et al. (2007a) observed a cooling in the daytime mesopause temperature over

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Trivandrum at the time of CEJ events. They suggested that the gravity wave-tidal interactions in the MLT region along with the changes in chemistry could be a plausible mechanism for the simultaneous occurrence of CEJ and mesopause temperature lowering. Vineeth et al. (2007b) noted a 16-day planetary wave to be associated with the CEJ. Earlier, Sridharan et al. (2002) noted ∼16-day variability in the afternoon CEJ strength. These observations suggest that the variabilities of the electrojet current system are influenced by tidal variabilities, which are partly governed by their interaction with gravity waves and planetary waves.

The present study examines the daily variations of tidal components in the MF radar observed zonal winds over Tirunelveli (8.7° N, 77.8° E) and afternoon EEJ strength over Trivandrum/Tirunelveli during major SSW events.

2 Observations and data analysis

2.1 UKMO data

The UKMO (United Kingdom Meteorological Office) data set is a result of the assimilation of in-situ and remotely sensed data into a numerical forecast model of the stratosphere and troposphere available in the website http://www.badc.rl.ac.uk/data/assim. The description of the original data assimilation system is given by Swinbank and O'Neill (1994). The outputs of the assimilation are global fields of daily temperature, geopotential height, and wind components at pressure levels from the surface up to 0.1 hPa with a global coverage in steps of every 2.5° latitude and 3.75° longitude. The daily zonal mean stratospheric temperature at 10 hPa and 1 hPa and zonal winds at 10 hPa have been used to identify the occurrence of major SSW events (Sathishkumar and Sridharan, 2009).

2.2 Geomagnetic data

The variations in the three components of the geomagnetic field have been recorded by a network of magnetic observatories of Indian Institute of Geomagnetism located from the magnetic equator to the northernmost Indian latitudes. The EEJ strength is derived from the differences between the magnetic field variations in the horizontal field obtained from Trivandrum (TRD) (8.5° N, 76° E, geographic, 0.8° S geomagnetic)/Tirunelveli (TIR) (8.7° N, 77.8° E, geographic, 1° S geomagnetic) and Alibag (ABG) (18.6° N, 72.9° E, geographic, 10° N geomagnetic). Trivandrum and Tirunelveli are stations located close to the center of the EEJ and are also under the influence of Sq current system, whereas Alibag is a station under the influence of Sq current system only (Kane, 1973, Gurubaran, 2002). The observatory at Trivandrum was closed during late 1999 and the one at Tirunelveli has since been functioning as the main equatorial geomagnetic observatory in the Indian sector.

2.3 MF radar winds

The MF radar (1.98 MHz) operating at Tirunelveli (8.7° N, 77.8° E) in the spaced antenna mode has been giving nearly continuous wind information in the upper mesospheric region (78–98 km) since November 1992. The wind measurements, sampled for every ∼2 min, are averaged for each hour and used for further analysis. Though winds are measured every 2 km, the data acceptance rate, which is based on several data rejection criteria (Briggs, 1984), is higher only above 84 km. Radar measurements at higher heights (above 92 km) are constrained by the influence of electric fields and the radar tends to measure the electron drift motion driven by intense electric field rather than the neutral wind (Gurubaran and Rajaram, 2000). The tidal amplitudes are computed using a least squares harmonic fit over a five-day window of hourly wind values, which is successively forwarded every one day. This procedure yields daily variation of tidal amplitudes.

3 Results

The panels of Fig. 1 show (a) the daily diurnal and semidiurnal tidal amplitudes at 88 km, (b) daily variation of A_p index, (c) EEJ strength averaged for 10:00–13:00 IST and 14:00–16:00 IST, (d) zonal mean temperature difference at 10 hPa and 1 hPa between the latitudes 90° N and 60° N and zonal mean zonal wind at 60° N at 10 hPa for a time interval of 1–120 days starting from 1 November 2005. The state of the winter stratosphere is presented using UKMO zonal mean temperatures at 1 hPa and 10 hPa and zonal winds at 10 hPa. The temperature difference between the latitudes 90° N and 60° N shows that there was a series of warming events, which could be inferred from the positive temperature difference at 10 hPa on days 368–370 (3–5 January 2006), 373–384 (8–19 January 2006), and 386–402 (21 January–6 February 2006). The positive temperature difference was noticed at 1 hPa on an earlier date than at 10 hPa, suggesting that warming first occurred at high altitudes and then propagated downward to lower altitudes. However, according to WMO definition (Schoberl, 1978), warming events are identified at 10 hPa and below and they can be classified as major or minor depending on whether there is any wind reversal at latitude 60° N. In the present case, though there were three successive warming events, only the third was the major warming event, as it was accompanied by the reversal of zonal winds from eastward to westward. The westward winds at 60° N persisted during days 386–402. Coinciding with the warming events, the EEJ strength over Tirunelveli decreased and became negative during days 379–384 and 392–398. These days were geomagnetically quiet days with $A_p<12$, while a magnetic disturbance occurred on day 392. The semidiurnal tidal amplitude at upper mesospheric heights over Tirunelveli was larger than diurnal tidal amplitude between

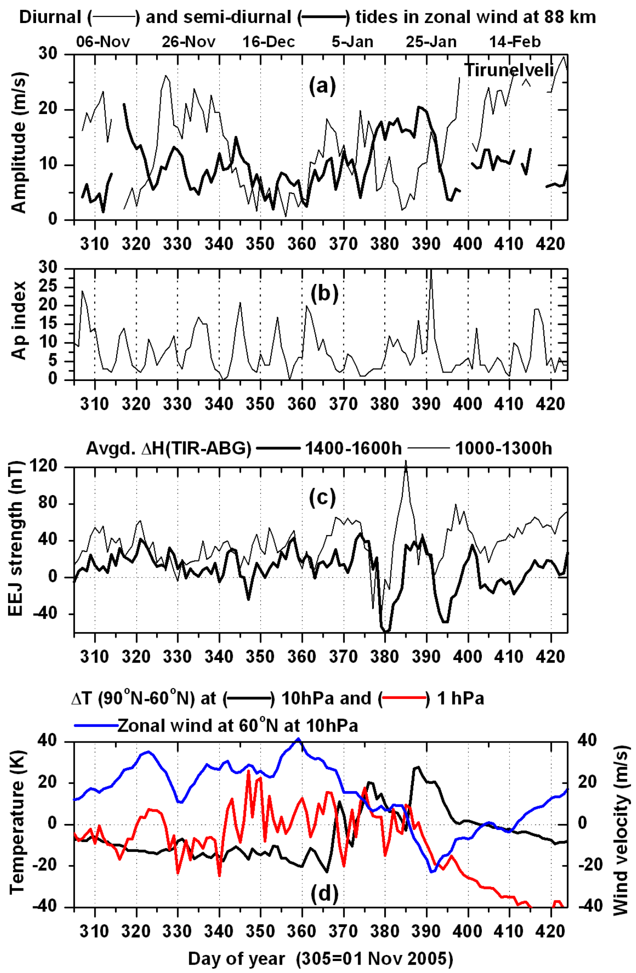

Fig. 1. **(a)** Daily variation of diurnal and semi-diurnal tidal amplitudes at 88 km, **(b)** daily variation of A_p index, **(c)** EEJ strength averaged for 10:00–13:00 IST and 14:00–16:00 IST, **(d)** Zonal mean temperature difference at 10 hPa and 1 hPa between the latitudes 90° N and 60° N and zonal mean zonal wind at 60° N at 10 hPa for a time interval of 1–120 days starting from 1 November 2005.

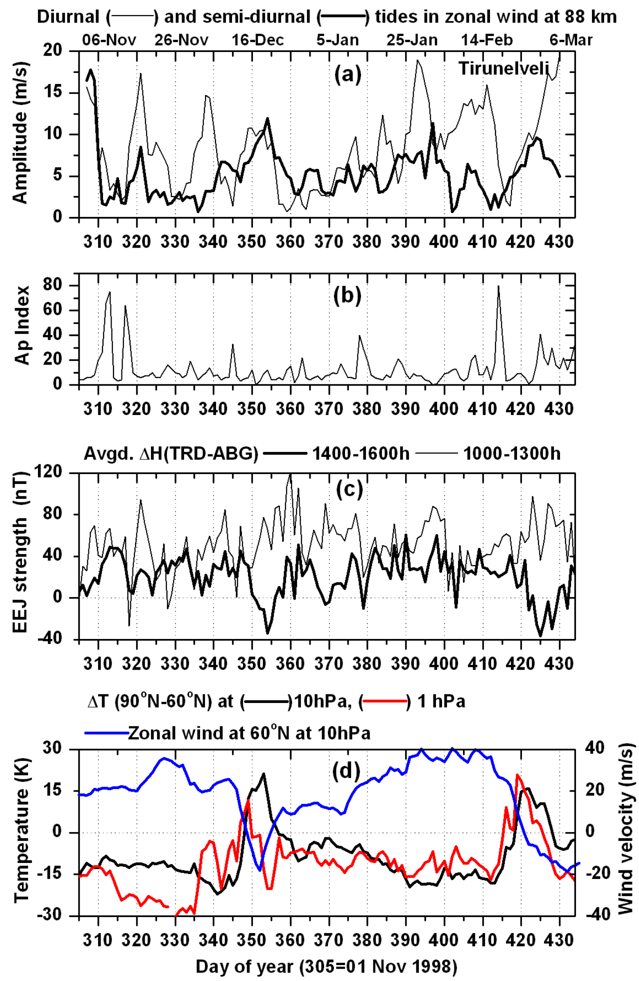

Fig. 2. Same as Fig. 1, but for a time interval 1–130 days starting from 1 November 1998.

days 378–395. The diurnal tidal amplitude decreased from ∼20 m/s on day 377 to 2 m/s on day 400, whereas the semi-diurnal tidal amplitude increased from 2 m/s on day 376 to ∼18 m/s on day 380. An increase in the semi-diurnal tidal amplitude was noticed nearly coinciding with the onset of the minor warming event, which occurred during days 373–384 prior to the major event. Though the event was minor, the maximum poleward temperature difference was ∼20 K (Fig. 1d), which was comparable to that of the major event (∼27 K). During the major warming event, which occurred during days between 386 and 402, the semi-diurnal tidal amplitude (∼16 m/s) became larger than the diurnal tidal amplitude (∼5 m/s). As days progressed, corresponding to the decrease of temperature difference in the high latitude stratosphere, the semi-diurnal tidal amplitude over Tirunelveli decreased slowly, but was still comparable or larger than the diurnal tidal amplitude. Though the latter decreased to ∼8 m/s on day 392, there was a sharp increase to ∼16 m/s on day 394. It may be noted that the day 391 is disturbed (A_p∼30), which makes the comparison of semi-diurnal tidal amplitude and EEJ strength around the day 391 difficult. Hoffmann et al. (2007) noted enhanced semi-diurnal tidal amplitudes during February 2006 over the high-latitude station, Andenes (69° N, 16° E).

Figure 2 is same as Fig. 1, except that the results are for a time interval of 1–130 days starting from 1 November 1998. During this winter, two major warming events occurred and they could be inferred from the positive poleward temperature difference (Fig. 1d) at 10 hPa during days 349–354 (15–21 December 1998) and 419–424 (25 February–4 March 1999) associated with the wind reversal at 60° N. Large negative depressions in the afternoon EEJ strength occurred during days 351–355 and 422–429. The major reversal in the afternoon EEJ strength coincided with major SSW events, though the days 422–429 were geomagnetically

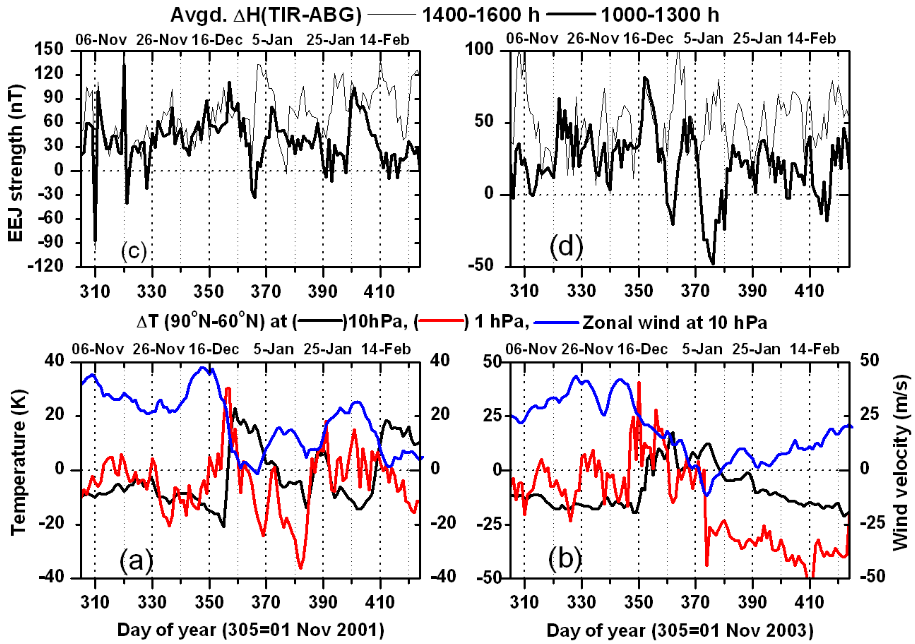

Fig. 3. Daily variation EEJ strength averaged for 10:00–13:00 IST and 14:00–16:00 IST (**c** and **d**) and state of high-latitude winter at 10 hPa (**a** and **b**) for a time interval of 1–120 days starting 1 November 2001 and 1 November 2003.

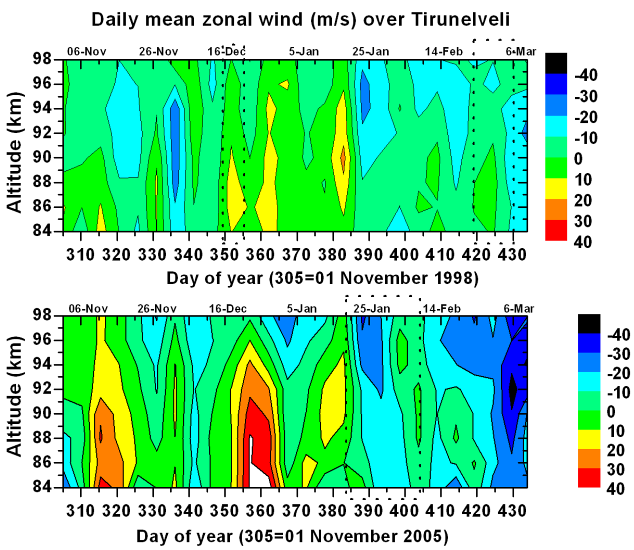

Fig. 4. Daily mean zonal winds for the altitudes 84–98 km over Tirunelveli for 1–130 days starting from 1 November 1998 (top panel) and 1 November 2005 (bottom panel). The dotted boxes show the duration of the CEJ events.

disturbed. In both cases, the semi-diurnal tidal amplitudes were comparable to the diurnal tidal amplitudes. Between the two major warming events, the semi-diurnal tidal amplitude became smaller than diurnal tidal amplitude. Bhattacharya et al. (2004) also noted a decrease in the amplitude of the mesospheric semi-diurnal tide over Canada (74.9° N, 94.9° W) during a cool period between two warming events of 2001. There were reversals in the afternoon EEJ strength around days 369, 379, and 403. However, they lasted only for about two days.

We considered two other major warming events of 2001–2002 and 2003–2004. As the MF radar wind data were not available during these SSW events, the time variation of the EEJ strength was compared with the state of the corresponding high-latitude winters (Fig. 3). In the case of winter 2001–2002, there were three warming events and among these, only the first event, which occurred during days 357–374, was a major event, as it was accompanied by a reversal in the zonal mean wind. It may be noted that the afternoon EEJ strength reversed to −33 nT on days 365–366. The other minor warming events during days 387–392 and 409–428 were also accompanied by negative depression in the afternoon EEJ with maximum depressions of −13 nT and −18 nT on days 393 and 416, respectively. During 2003–2004 winter, the minor and major warming events during days 353–363 and 365–378 were accompanied by depressions in the afternoon EEJ during days 360–362 (A_p<12) and 372–378 (A_p>12) with maximum depression of 20 nT and 48 nT respectively. These observations confirm that the association between the CEJ and high-latitude warming events is consistent. It may also be noted that the reduction in the afternoon EEJ strength persisting during geomagnetically disturbed days (A_p>12) cannot be interpreted only in terms of tidal forcing alone, as auroral electrojet partly influences geomagnetic field variations on these days.

4 Discussion and conclusion

The present study shows that the high latitude Northern Hemispheric major SSW events that occurred during the winters of 1998–1999, 2001–2002, 2003–2004 and 2005–2006 were accompanied by reversals in the equatorial electrojet during afternoon hours, which lasted for several days. Some of the minor warming events of these winters were also associated with the negative depression in the afternoon EEJ strength. As the EEJ current system is mainly driven by tidal winds, an investigation of the tidal variabilities in the zonal wind data available nearly continuously for the winters 1998–1999 and 2005–2006 at 88 km over Tirunelveli was carried out and the results reveal that the semi-diurnal tidal amplitudes at 88 km became comparable to or even larger than the diurnal tidal amplitudes during these days. Stening et al. (1996) first suggested that there is an association between CEJ and high latitude stratospheric warming events. The reduction of diurnal tide amplitude on CEJ days was earlier reported by Somayajulu et al. (1993) and later by using a large number of individual and groups of days by Sridharan et al. (2002). Besides, Sridharan et al. (2002) observed a clear anti-correlation between the semi-diurnal tidal amplitude and afternoon CEJ for the solstice months of June and July 1995.

These observations confirm earlier model simulations that the semi-diurnal tide plays an important role in the generation of the CEJ event. Based on the theoretical calculations, Marriott et al. (1979) found the diurnal tide to be important for the generation of eastward electric field during the equinoxes that will account for a normal EEJ. But, during solstices, the contributions of the semi-diurnal tide, especially the (2, 2) mode, to the equatorial electric field are greater. They suggested that the solar semi-diurnal tides have a tendency to set up a westward electric field in the afternoon hours of the solstice season to cause a CEJ, unless this tendency is opposed by the diurnal tide.

Somayajulu et al. (1993) observed a westward excursion of background wind on CEJ days. They suggested that a combination of global tidal wind fields which tend to weaken the vertical polarization field in combination with local westward winds is necessary to produce the CEJ events. The daily mean zonal winds over Tirunelveli presented in Fig. 4 show that though the winds were not westward during the major SSW event of days 349–354 (1998–1999), they were westward during the major warming events of days 419–429 (1998–1999) and 385–394 (2005–2006). Stening et al. (1996) noted that most winter-time CEJ events at Trivandrum were associated with changes in the mean zonal wind at Saskatoon and stratospheric warming. Stening et al. (1996) further suggested that the wind systems responsible for driving the afternoon CEJ were part of a global system rather than a wind system in the vicinity of the EEJ.

The forcing of the semi-diurnal tide is mainly due to the absorption of ultraviolet radiation by ozone in the stratosphere and mesosphere and absorption of infrared radiation by water vapour in the troposphere. The tidal variabilities during major warming events could be ascribed to the variability of ozone in the stratosphere and/or convective activity associated with latent heat release in the equatorial troposphere during the events. Kodera (2006) examined the role of the SSW events in equatorial convective activity in the troposphere and found the meridional circulation change associated with the warming led to a seesaw of convective activity in the troposphere with an enhancement of convective activity near the equatorial Southern Hemisphere, but a suppression in the tropics of the Northern Hemisphere. Due to major warming events, denitrification, which is the necessary condition for destruction of ozone, is less intense because of high temperature and hence the destruction of ozone is less in the disturbed northern hemispheric winter (Toon et al., 1989). Jacobi et al. (1999) noted that the interannual variability in the semi-diurnal tidal amplitudes was correlated with that of stratospheric polar vortex. Using E-P flux calculations, Yamashita et al. (2002) suggested cross equatorial propagation of semi-diurnal tide, which was excited in the winter hemisphere, up to MLT heights. Goncharenko and Zhang (2008) noted significant afternoon changes in ion temperature in the altitude range of ∼120–140 km and above over Millstone Hill (42.6° N, 71.5° W) prior to the minor SSW event that occurred during January 2008. As the year 2008 corresponds to low solar activity, the authors attributed the increase of ion temperature to be associated with the SSW event and from the temporal and altitudinal variations in the temperature anomaly, they inferred that it might be related to semi-diurnal tide modulation. Recently, Chau et al. (2009) observed an anomalous temporal variation of the vertical $\boldsymbol{E} \times \boldsymbol{B}$ drifts during the minor SSW event, showing a semi-diurnal variation with very large amplitudes lasting for several days. The semi-diurnal variation can also be produced due to interaction of a quasi-stationary wave and migrating tides. Though it is an open question whether planetary waves can propagate to ionospheric heights, it is more likely that semi-diurnal tides are generated in the high latitude stratosphere, propagate cross equatorially to the Southern Hemisphere, as inferred from general circulation model studies (Yamashita et al., 2002).

A major outcome of the present study is the observational evidence for the role that major SSW events play in influencing the day-to-day variability of CEJ events through enhancement of semi-diurnal tides. However, the relationship between SSW and semi-diurnal tide is yet to be firmly established based on solid theoretical understanding, though observations do reveal a linkage between the two.

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