Relationship between the tropical tropopause and tropical easterly jet streams over Indian monsoon region

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Abstract

This paper presents the first quantitative relationship between the cold point tropopause (CPT) and tropical easterly jet (TEJ) using radiosonde observations over Gadanki (13.450N, 79.20E) during the Indian summer monsoon season 2006–2014. CPT and TEJ peak altitudes (H_CPT and H_TEJ) show amalgams of two categories of variability on day to day scale. In category1 H_TEJ occurs close to H_CPT and they show in phase variation. While in category2 H_TEJ occurs far apart from H_CPT and they do not show any relationship. For category1 H_CPT and H_TEJ are strongly correlated (0.70) as well as H_CPT and T_CPT (CPT temperature) are moderately anticorrelated (-0.55) significant at 95% confidence level indicating the dominance of adiabatic processes. Whereas in category2 H_CPT and T_CPT are not significantly anticorrelated. Thus, when TEJ and CPT are close to each other it may serve as an indicator for the prevalence of synoptic-scale effect.

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8	Key Points:							
9 10	• Using radiosonde observations, we report the plausible relationship between tropical tropopause and tropical easterly jet (TEJ) streams.							
11 12	• Cold point tropopause altitude and temperature are driven by adiabatic processes when TEJ core lies in the vicinity of tropical tropopause.							
13 14	• It indicates that the TEJ plays an important role in the tropical tropopause variability which needs to be taken into account.							
15 16								

17 Abstract

This paper presents the first quantitative relationship between the cold point tropopause 18 (CPT) and tropical easterly jet (TEJ) using radiosonde observations over Gadanki (13.45°N, 19 79.2°E) during the Indian summer monsoon season 2006–2014. CPT and TEJ peak altitudes 20 $(H_{CPT} \text{ and } H_{TEJ})$ show amalgams of two categories of variability on day to day scale. In category 1 21 H_{TEJ} occurs close to H_{CPT} and they show in phase variation. While in category 2 H_{TEJ} occurs far 22 apart from H_{CPT} and they do not show any relationship. For category 1 H_{CPT} and H_{TEJ} are strongly 23 correlated (0.70) as well as H_{CPT} and T_{CPT} (CPT temperature) are moderately anticorrelated (-24 0.55) significant at 95% confidence level indicating the dominance of adiabatic processes. 25 Whereas in category $2 H_{CPT}$ and T_{CPT} are not significantly anticorrelated. Thus, when TEJ and CPT 26 are close to each other it may serve as an indicator for the prevalence of synoptic-scale effect. 27

28 Plain Language Summary

During Indian summer monsoon (ISM) season tropical easterly jet (TEJ) streams develop 29 in the upper troposphere. Several times TEJ core reaches the altitude very close to the cold point 30 tropopause (CPT) and sometimes even penetrates the lower stratosphere. When CPT and TEJ are 31 close to each other they vary in phase for several days continuously and are strongly correlated. It 32 is well known that adiabatic processes dominate during the ISM season, which controls the day to 33 34 day variability of the CPT altitude and temperature. In this study, we report that when TEJ is closer to CPT, adiabatic processes prevail. Thus, it indicates the relevance of the TEJ in the variability of 35 the tropical tropopause which needs to be taken into account. 36

38 **1 Introduction**

Indian summer monsoon (ISM) is one of the dominant climatological features of the global 39 circulation and it originates from the differential heating of the land and sea during summer season 40 (Koteswaram, 1960). ISM brings several changes in the meteorological and dynamical features 41 42 from the surface to the upper troposphere (UT). A noticeable feature in the UT is the development of the tropical easterly jet (TEJ) streams with speeds often exceeding 30 m/s. TEJ spans around 43 the equator to 20°N latitude and 50–90°E latitude (Krishnamurti & Bhalme, 1976; Roja Raman et 44 al., 2009). TEJ is a thermal wind maintained by the meridional temperature gradient between land 45 and ocean (Hastenrath, 1995; Koteswaram, 1958). Other dominant features of the ISM are the shift 46 of the intertropical convergence zone poleward, development of the low-level jet streams (Joseph 47 & Sijikumar, 2004), increase in cloudiness and rainfall (Sikka & Gadgil, 1980) which leads to the 48 enhancement in tropospheric humidity (Fasullo & Webster, 2003), and the increase in the 49 frequency of deep convection which generally couples with the transport of the pollutants from 50 the surface to the UT and lower stratosphere (LS; UTLS) (Garny & Randel, 2016). ISM can affect 51 the UTLS thermal structure either directly due to diabatic heating associated with the convection 52 53 or indirectly due to convectively generated phenomena such as propagation of atmospheric waves (Krishna Murthy et al., 2002; Tsuda et al., 1994), the occurrence of the cirrus clouds (Tseng & Fu, 54 2017) and transport of surface pollutants (Pan et al., 2016). 55

The tropical tropopause here is defined as the level of the coldest point in the UTLS called the cold point tropopause (CPT). CPT plays an important role in entry of the water vapor into the LS and hence regulates the climate variability (Gettelman et al., 2009; Holton et al., 1995). CPT shows connections with various tropospheric and stratospheric phenomena on different time scales. It has been linked with Madden Julian Oscillation (Zeng et al., 2012) and Brewer-Dobson

circulations (Birner, 2010) on a seasonal and annual scale, respectively. On the interannual scale,
CPT shows connections with El Nino Southern Oscillation (Zhou et al., 2001) and quasi-biennial
oscillations (Baldwin et al., 2001; Reid & Gage, 1985). On longer-term scale, an increase in the
tropopause height was associated predominantly due to the increase in the well-mixed greenhouse
gases (Santer et al., 2003).

Over the Indian monsoon region, 60% of the day to day variability of CPT (i.e. out of phase 66 variation of the CPT height (H_{CPT}) and temperature (T_{CPT})) is driven by adiabatic process (Mehta 67 68 et al., 2010; Jain et al., 2011; Mehta et al., 2011) indicating a strong connection with ISM. The adiabatic process is due to hydrostatic adjustment to convective heating or cooling (Holloway & 69 Neelin, 2007; Kim et al., 2018). While the in-phase variation of H_{CPT} and T_{CPT} is governed by the 70 71 diabatic processes such as radiative heating/cooling from cirrus clouds (Hartmann et al., 2001; Boehm & Verlinde, 2000), turbulent mixing of the overshooting air with the environment 72 (Sherwood et al., 2003, a large-scale westward propagating Rossby wave and eastward 73 74 propagating Kelvin wave response (Highwood and Hoskins, 1998; Randel et al., 2003) or a combination of these. Recently, a link between the onset of ISM and tropical tropopause are 75 observed (RavindraBabu et al., 2019). Kulkarni and Verma (1993) observed that the tropopause is 76 at a higher altitude during active monsoon when compared to weak monsoon years (Varikoden & 77 Preethi, 2013). TEJ core has been found in between the peaks of the frequency distribution of the 78 tropopause altitudes obtained over a few stations in the ISM region (Ramanadham et al., 1969). 79 Jain et al. (2011) observed that the occurrence of the extreme CPT was due to the westward 80 propagating wave associated with TEJ. Fujiwara et al. (2003) observed a persistent temperature 81

inversion layer in the UT which they attributed to TEJ. Ratnam et al. (2011) noticed that sometimes
TEJ penetrates to the LS which may lead to the transport of ozone into the UT.

Thus, TEJ has been associated with various studies such as occurrence of cirrus clouds 84 (Das et al., 2011), gravity wave generation (Ramkumar et al., 2010; Sasi et al., 2000) and 85 horizontal transport of the constituents (Orbe et al., 2015; Ploeger et al., 2017) which in turn may 86 modify the CPT. However, to the best of our knowledge, no systematic study has been reported 87 on the relationship between TEJ and CPT. Hence, here we make an attempt to understand the 88 89 relationship between the day to day variability of the CPT and TEJ. The main objectives of the present study are to (i) investigate the plausible connection between H_{CPT} and H_{TEI} , and, (ii) 90 delineate the effect of the TEJ on the relationship between H_{CPT} and T_{CPT} . 91

92 **2 Database**

High-resolution radiosonde (Väisälä RS-80, Väisälä RS-92, and Meisei RS-06G) 93 temperature and zonal wind profiles observed at around 1730 IST (IST = UT + 0530 h) over 94 Gadanki (13.5°N, 79.2°E) during June-July-August (JJA) 2006-2014 are used in this study 95 (www.narl.gov.in). These profiles are originally observed at height resolution ~ 25-30 m (sampled 96 97 at 5 s intervals) which are uniformly gridded to 100 m. The uncertainties in temperature and wind speed given by the manufacturer are 0.2/0.3 K (below/above 100 hPa) and 0.15 m/s in Väisälä 98 radiosonde (Vömel et ., 2007) and ± 0.5 K and ± 0.2 m/s in Meisei radiosonde, respectively (Kizu 99 et al., 2018). We have only considered those soundings which have reached at least 50 hPa (Mehta 100 101 et al., 2011) in order to obtain the altitude of CPT and TEJ. Globally merged infrared brightness temperature (IRBT) data obtained from national weather service Climate Prediction Centre, 102 NOAA also used in the present study to examine the role of the convection of the relationship 103 between TEJ and CPT. For our purpose, we have averaged the IRBT data into $0.5^{\circ} \times 0.5^{\circ}$ (latitude 104

- longitude) centered to Gadanki and within half-hour of 1730 IST. More details about IRBT data
can be found in Mehta et al., (2017).

- 107 **3 Results and Discussion**
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3.1 Typical observations- relationship between H_{CPT} and H_{TEI}

After examining several hundred profiles it is found that H_{CPT} and H_{TEJ} occur very close 109 to each other frequently and sometimes match. We have observed that both the temperature and 110 111 zonal wind show similar structures just below and above the CPT in many of the profiles. Typical examples of comparison between H_{CPT} and H_{TEI} are shown in Figures 1a – 1f for three different 112 types of temperature profiles indicating the sharp, broad, and multiple tropopause cases, 113 respectively. It is interesting to observe that the zonal wind profiles also show sharp, broad and 114 115 multiple TEJ peaks similar to the temperature profiles. Figures 1a-b show the temperature and zonal wind profiles for the sharp case in which H_{CPT} and H_{TEI} occur at the same altitude ~ 17.3 116 km observed on 02 July 2006. The T_{CPT} is found to be 194.5 K and TEJ core speed is -49.4 m/s. 117

Similarly, the temperature and zonal wind profiles are shown in Figures 1c-d depict the 118 broad case in which the observed H_{CPT} and H_{TEI} also occur at the same altitude ~ 17.2 km on 10 119 August 2008. The temperature remains almost constant (~ 190 K) between 16.5 -17.5 km 120 characterizing a broad tropopause and the zonal wind is found to vary a little (~ -37.8 to -38.7121 m/s) between altitude 16.8–17.7 km characterizing a broad TEJ. The typical case presented here 122 123 shows that the broader tropopause is colder (by ~ 5 K) when compared to the sharp tropopause in contrast to the generally known fact that the tropopause is warmer and lower when compared to 124 the sharper tropopause (Seidel et al. 2001; Schmidt et al. 2004; Kim and Son, 2012) which needs 125 126 a detailed investigation; however, it is out of the scope of the present study.

An example of the double tropopauses and double peaks in the zonal wind is observed on 09 July 2010 as shown in Figures 1e – 1f. The temperature profile shows H_{CPT} at ~ 17.9 km and 128 the Lower Tropopause (Mehta et al., 2011) at ~ 16.5 km. The zonal wind profile shows H_{TEI} at ~ 129 17.6 km with a lower peak at altitude ~16.4 km similar to the temperature profile. These typical 130 examples indicate that the zonal wind and temperature profiles around the tropopause behaves in 131 a similar fashion which further indicates the possibility of a direct relationship between H_{CPT} and 132 H_{TEI} (Supplementary Fig. S1). 133

134 Observed similar structures in the temperature and zonal wind around the tropopause region (Figure 1) are expected due to thermal wind balance. The thermal wind equation, which 135 describes the relationship between the vertical gradient of zonal wind speed and the meridional 136 gradient of temperature under hydrostatic equilibrium, is 137

138
$$\frac{\partial u}{\partial z} = -\frac{g}{fT}\frac{\partial T}{\partial y} \tag{1}$$

Where u is the zonal wind, g is the acceleration due to gravity, f is Coriolis parameter and y is 139 the northward distance (Andrews, 2010). It is observed that tropopause temperature gradient is 140 greater (i.e. sharp tropopause) in the presence of relatively stronger zonal wind shear (Figures 1a-141 b) when compared to the cases when broad and multiple tropopauses are observed (Figures 1c-f). 142 Also, the tropopause with broad and multiple structures are colder than the sharp tropopause. It is 143 144 important to mention here that the warm (cold) air advection is associated with the wind which turns clockwise (counterclockwise) with height (Holton, 2004). The relatively warmer (colder) 145 tropopause in the case of the sharper (broader and multiple) tropopause could be related to warm 146 (cold) air advection due to the TEJ streams. The thermal wind balance due to TEJ streams is 147 described in Supplementary Figure S2. 148

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3.2 Temporal variation of H_{CPT} and H_{TEI} and an approach to quantify its relationship

150	The temporal variability of H_{CPT} and H_{TEJ} on day to day scale during JJA 2006 is shown
151	in Fig. 2a and for JJA 2007-2014 in the Supplementary Figures S3a-S10a, respectively. In general,
152	H_{CPT} (H_{TEJ}) has a large day to day variability (Mehta et al., 2010; Ratnam et al., 2011) and varies
153	in the range of 15.2–19 km (13–19 km) within the monsoon season itself. Though CPT is generally
154	lower during JJA, it can occur as high as 19 km on a few occasions (Mehta et al., 2011). We have
155	calculated H_{CPT} tendency (day-to-day difference) as shown in Supplementary Fig. S11a and
156	observed that H_{CPT} remains unchanged for ~ 2% times while it increases (decreases) for ~ 52%
157	(46%) times. Similarly H_{TEJ} remains unchanged for ~6% times while it decreases (increases) for
158	~ 48% (46%) times. H_{CPT} (H_{TEJ}) changes (absolute value) within 1 km, 1-2 km, 2-3 km, 3-4 km
159	and >4 km ~ 38% (70%), 26% (19%), 17% (4%), 10% (1%) and 4% (0%) times, respectively (Figs
160	S11a-b) indicating that H_{CPT} has larger day to day variability when compared to H_{TEJ} . It also
161	means that H_{TEJ} is governed by synoptic-scale process while H_{CPT} is the balance between radiative
162	and convective processes. Generally, H_{TEJ} fluctuates abruptly especially during early June when
163	synoptic-scale forcing is weak (Figs 2a & S3a-S10a). We observed that H_{TEJ} often occurs closer
164	to H_{CPT} , however, they coincide only ~6% times. The absolute difference between H_{CPT} and H_{TEJ}
165	is found to be within 1 km, 1-2 km, 2-3 km and 3-4 km for about 63%, 20%, 9% and 2% times,
166	respectively (Supplementary Fig S11c).

167 From Figures 2a and S3a-S10a, it is clear that the H_{CPT} and H_{TEJ} variability can be mainly 168 classified into following two categories. In one category they either coincide or occur close to each 169 other and vary in a similar phase. In the second category, they occur far apart and appear to vary 170 out of phase. To quantify the relationship between H_{CPT} and H_{TEJ} , we have obtained their absolute 171 difference ($\overline{\Delta H}_{CPT-TEJ}$) and the climatological mean $\overline{\Delta H}_{Clim}$ over JJA 2006-2014 as shown in 172 Figure 2b (for JJA 2006) and Supplementary Figures S3b-S10b (for JJA 2007-2014). The $\overline{\Delta H}_{Clim}$

is found to be 0.85 km. It is observed that the days during which H_{CPT} and H_{TEI} are close to each 173 other (far apart), $\overline{\Delta H}_{CPT-TEI}$ occurs below (above) the $\overline{\Delta H}_{Clim}$. Generally, H_{CPT} and H_{TEI} "close 174 to each other" and "far apart" occur in a group. After examining all these cases, the following 175 criterion is evolved for defining the relationship between H_{CPT} and H_{TEI} . The days during which 176 $\overline{\Delta H}_{CPT-TEI}$ is lower (greater) than the $\overline{\Delta H}_{Clim}$ for three consecutive days or more are classified as 177 category1 (category2). As CPT has a structure and may coincide TEJ for isolated (one or two) 178 days randomly hence three days or more are considered to represent a synoptic-scale feature. For 179 JJA 2006 five episodes of category1 and three episodes of category2 are observed (Figs 2a-b). 180

However, as we know that tropopause structure can be significantly modified due to 181 convection (Sherwood et al., 2003; Muhsin et al., 2018) and associated planetary wave propagation 182 (Boehm and Verlinde, 2000; Munchak and Pan, 2014), their possible roles in association with 183 relationship between CPT and TEJ are also analyzed. The presence of the convective activities is 184 investigated using IRBT data as shown in Fig 2c and Figs. S3c-S10c. From Fig 2, it is observed 185 that H_{CPT} are affected due to deep convection activities. However, both category1 and category2 186 occur during the clear sky days as well as convective days indicating that the relationship between 187 H_{CPT} and H_{TEI} is not always linked to local convection and appears to be a response of large-scale 188 synoptic condition (Supplementary Fig. S12). To examine the role of planetary wave, the 189 continuous timeseries of the temperature anomalies averaged over 16-17 km observed from 26 190 June -22 August 2006 is subjected to Morlet wavelet analysis (Figure 2d). It is seen that the waves 191 with periods 8–12 days are significant (above the cone of influence) during 20 July to 09 August 192 2006 during which H_{CPT} coincides with H_{TEJ} . However, they also coincide other timings 193 irrespective of the wave occurrence. The wavelet analysis for JJA 2008-2014 is shown in 194

Supplementary Figs S4d-S10d except JJA 2007 which has a large data gap. The one-day data gaps 195 are filled by linear interpolation to have continuous times for the wavelet analysis. 196

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3.3 Statistical analysis of the relationship between TEJ and CPT: Plausible link with adiabatic and diabetic processes 198

In total 707 days observations of H_{CPT} and H_{TEJ} are available out of 828 days during JJA 199 2006–2014. After filling one day data gap, in total 731 days data are available for the analysis. 200 Out of which 471 (65%) days and 260 (35%) days are observed for the cases when H_{CPT} and H_{TEJ} 201 are "close to each other" and "far apart" respectively. Among these "close to each other" cases, 202 203 352 (76%) are found under category1 and the remaining 115 (24%) cases are found to be isolated. Similarly, among all these "far apart" cases 114 (44%) are observed under category 2 and rest 146 204 (56%) cases are found to be isolated. Figures 3a-c show the probability distribution of the 205 difference between H_{CPT} and H_{TEI} (hereafter $\Delta H_{CPT-TEI}$) for overall monsoon season, category1 206 and category2, respectively. $\Delta H_{CPT-TEI}$ ranges from -2.9 to 4.0 km (overall monsoon), between -207 0.9 to 0.9 km (category1) and between -2.9 to -1.0 km and 1 to 4 km (category2). The overall 208 probability distribution of $H_{CPT-TEI}$ indicates that 60% and 34% times TEJ occurs above and 209 below the CPT, respectively while remaining 6% times coincides with CPT. For the category1, 210 TEJ occurs 46 % (48%) times and below (above) the CPT whereas for category 2, 89% (11%) 211 times TEJ occurs below (above) the CPT. The peak or mode (mean and standard deviation) of the 212 distribution is found to be $\sim 0.0 \text{ km} (0.54 \pm 1.1 \text{ km}), -0.2 \text{ km} (0.06 \pm 0.43 \text{ km})$ and $\sim 2.5 \text{ km} (1.67 \pm 1.4 \text{ km}), -0.2 \text{ km} (0.06 \pm 0.43 \text{ km})$ 213 km) for overall monsoon season, category1 and category2, respectively. 214

215 Figures 3d–f show the scatter plots of H_{CPT} and H_{TEI} indicating the random relationship in the overall data while they are strongly correlated (r = 0.70) significant at 95% confidence level 216 217 under the category1 and no correlation under the category2. Note that when considering all the 218 H_{CPT} and H_{TEJ} "close to each other" and "far apart" cases, results remain the same (Figs 3e-f). A 219 good correlation between H_{CPT} and H_{TEJ} under the category1 indicates TEJ is linked to the 220 variation of the CPT. That is if TEJ lies in the tropopause vicinity influences the H_{CPT} variabilities. 221 In category2, TEJ does not affect the CPT variability.

Figures 3g-i show the scatter plots of T_{CPT} and H_{TEI} for overall monsoon data, category1 222 and category2, respectively. In the overall monsoon data, T_{CPT} and H_{TEI} are moderately 223 anticorrelated (r = -0.32) significant at 95% confidence level (Figure 3g) unlike the correlation 224 between H_{CPT} and H_{TEI} . It indicates that T_{CPT} is more sensitive to tropospheric processes 225 especially infrared warming and therefore tropospheric temperature profile (Thuburn & Craig, 226 2000). Whereas the weak correlation observed between H_{CPT} and H_{TEI} in overall monsoon data 227 (Figure 3d) indicates that H_{CPT} is more sensitive to the ozone heating and dynamical warming 228 (Thuburn & Craig, 2000) associated with stratospheric meridional circulation (Yulaeva et al., 229 1994). T_{CPT} and H_{TEI} are moderately anticorrelated (r = -0.55) significant at 95% confidence level 230 and weakly anticorrelated (r = -0.16) but not significant under the category1 and category2, 231 respectively (Figures 3h-i). Thus, day to day variability of H_{CPT} , T_{CPT} and H_{TEI} are linked under 232 the category1. 233

It is interesting to observe that H_{CPT} and T_{CPT} are moderately anticorrelated in the overall monsoon season (r = -0.36) as well as under the category1 (r = -0.55) significant at 95% confidence level while weakly anticorrelated (r = -0.20) but not significant under the category2 as shown in Figures 3j-1. Thus, it appears that the adiabatic process is prominent when TEJ is nearby the CPT. However, H_{CPT} and T_{CPT} may not always be driven by adiabatic processes alone and can be affected by diabatic processes such as dynamical heating, ozone heating and occurrence of cirrus clouds (Mehta et al., 2010; Reid & Gage, 1996; Thuburn & Craig, 2000) which may be dominant in controlling CPT variability when TEJ occurs far away from CPT. The above findings
are also consistent with analysis of each monsoon season from 2006 to 2014 except for 2011 and
2014 listed in the supplementary tables ST1 and ST2.

3.4 Mean temperature and zonal wind profiles for overall, under category 1 and category 2

Figure 4 presents the mean and standard deviation of the temperature and zonal wind 246 profiles during the overall monsoon season, under the category1 and category2. On an average 247 T_{CPT} (~193 K) almost remains the same and TEJ peak speed (~ 35-39 m/s) shows a little variation 248 among overall monsoon season and the two categories. Whereas, H_{CPT} (H_{TEI}) is at 16.6 km (16.2 249 250 km), 16.5 km (16.3 km) and 16.9 km (15.6 km) in overall monsoon season, category1 and category2, respectively. Note that the mean H_{CPT} (T_{CPT}) obtained by averaging the daily values 251 are found to be 16.8±0.6 km (191.4±2.1 K) for overall data, 16.6±0.5 km (191.4±2.0 K) for 252 category1 and 17.1 ± 0.6 km (191.4 ±2.0 K) for category 2 which are relatively higher by 0.1 - 0.2253 254 km (colder by ~ 2.0 K) when compared to those obtained from the corresponding mean profiles. TEJ peak speed and H_{TEJ} obtained from averaging daily data are found to be 40.7±6.9 m/s and 255 16.3±0.9 km for overall data, -42.1±6.7 m/s and 16.5±0.6 km for category1 and -40.0±6.7 m/s and 256 15.5 ± 1.3 km for category2 which are also relatively faster by ~ 3 – 5 m/s and higher by ~ 0.1 – 0.2 257 km respectively when compared to those obtained from the mean profile. It indicates that results 258 for overall, category1 and category2 obtained from the mean profiles and individual profiles 259 remain consistent. On average TEJ occurs 0.2 km (1.3 km) below the CPT under the category1 260 (category2). Both temperature and zonal wind profiles have sharper peaks under the category1 261 whereas under the category2 they are relatively broader. Also, TEJ becomes relatively stronger 262 263 when it is closer to the CPT which can enhance the troposphere-stratosphere exchange processes

due to horizontal advection (Holton et al., 1995; Park et al., 2007; Das et al., 2011). The probability distribution of T_{CPT} indicates that $T_{CPT} < 191$ K occurs more frequently under the category1 when compared to category2 (Figure not shown). Therefore, entry of water vapor from the troposphere to the stratosphere with the mixing ratio less than 3 ppmv is likely to occur more frequently in category1.

269 **4 Summary and Conclusions**

TEJ shows a large day to day variability which is expected because of variation in the meridional 270 temperature gradient due to ISM variability. About 65% times of the total observations H_{TEI} and 271 H_{CPT} occurs "close to each other" and 35% times occur "far apart". Out of these "close to each 272 273 other" cases, 76% times they occur continuously for three days or more (category1) during which adiabatic processes dominate. Finding from this study has far-reaching implications in 274 understanding the variability and trend of surface energy balance and stratospheric chemistry due 275 to enhanced cross-tropopause transport of the surface pollutants via Asian summer monsoon 276 anticyclone (Pan et al., 2016; Mehta et al., 2020). The plausible relationship between H_{CPT} and 277 H_{TEI} investigated over a tropical station Gadanki using high-resolution daily radiosonde 278 observations (JJA 2006-2014) are summarized below: 279

1. The effect of the TEJ is observed in the CPT when they occur close to each other. H_{TEJ} and H_{CPT} show in phase variation and are significantly correlated under this category. Whereas TEJ does not affect CPT when they are far apart.

283 2. When CPT and TEJ are close to each other, H_{CPT} and T_{CPT} are significantly anticorrelated 284 indicating the prevalence of the adiabatic processes, whereas when they are far apart, no 285 relationship found between them indicating the dominance of the diabatic processes.

3. Thus, when TEJ and CPT are close to each other it can serve as an indicator for the dominance
of adiabatic processes.

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Figure 1. Typical temperature and zonal wind profiles showing (a-b) sharp tropopause and TEJ observed on 02 July 2006. (c – f) and (e – f) are the same (a-b) but observed on 12 June 2010 and 09 July 2010 showing broad and multiple tropopauses and TEJ cases, respectively. Solid dots and open circles denote the H_{CPT} and H_{TEJ} , respectively.



Figure 2. Time series of (a) H_{CPT} and H_{TEJ} , (b) $\overline{\Delta H}_{CPT-TEJ}$ (c) IRBT and (d) wavelet spectrum of temperature (in terms of power) at 16-17 km during JJA 2006. The up (green) and down(magenta) hatches indicate the catogory1 (category2) case. Horizontal dashed line in (b) represents $\overline{\Delta H}_{Clim}$ over the period 2006-2014 and white curve in (d) represents the cone of influence.



Figure 3. Probability distribution of $H_{CPT-TEJ}$ during (a) overall monsoon, (b) category1, (c) category2. (d-f), (g-i) and (j-l) are the same as (a-c) but for scatter plot between H_{CPT} and H_{TEJ} , H_{TEJ} and T_{CPT} , and H_{CPT} and T_{CPT} , respectively. Grey bars in (b-c) and scatters in (e-f) indicate "close to each other" and "far apart" cases.

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Figure 4. Average profiles of temperature (T; black line) and zonal wind (U; red line) along with their one standard deviation during (a) overall monsoon, (b) category1 and (c) category2. CPT altitude and temperature and TEJ altitude and TEJ peak value are also shown.

Supporting Information for

Relationship between the tropical tropopause and tropical easterly jet streams over Indian monsoon region

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Introduction

This supporting information provides the additional figures and tables and their description to support the main article.

Adiabatic and Diabatic Processes

As there is no heat input in the adiabatic process, an increase in height of the parcel will lead to a decrease in its temperature and vice versa i.e. height and temperature are out of phase. However, in the diabatic process, heat is added (diabatic heating) or removed (diabatic cooling) to system from the surrounding will increase or decrease the temperature of the parcel (Wallace & Hobbs, 2006).

Similarity between Zonal Wind and Temperature

To examine the similarity of zonal wind temperature, we have obtained the correlation between them over the altitude of ~12-22 km (Supplementary Fig. S1). It is found that 27% profiles are strongly correlated (r > 0.7) and 55% of the profiles are moderately correlated (0.3 < r < 0.7) while remaining 15% profiles shows no dependence and 3% profiles are anti-correlated. That is ~ 82% profiles more or less show a similarity between temperature and zonal wind. We have also checked the sensitivity of the correlation on the choice of the altitude and obtained the correlation between temperature and zonal wind over 14-20 km which does not show any major difference. Such similarity between temperature and zonal wind indicates the possibility of a relationship between TEJ and CPT.



Figure S1. The percentage of the occurrence strong (r>0.7), moderate (0.3<r<0.7) and weak (r<0.3) correlation between temperature and zonal wind profiles from the altitude of ~12-22 km over the period JJA 2006-2014.

Thermal wind balance

To illustrate the thermal wind balance due to TEJ streams we have obtained the temperature profiles from the India Meteorological Department (IMD) station, Chennai (13.0°N, 80.04°E) which is meridionally separated by about half a degree from Gadanki. The IMD radiosonde data for Chennai (Madras) station code (43279 or VOMM) is available from the link http://weather.uwyo.edu/upperair/sounding.html. However, as the radiosonde observations over Chennai simultaneous to Gadanki observations on the typical dates mentioned in Figure 1 (main article) were not available. Thus, we have taken another set of similar typical examples as shown in Figure S2. For the sharp case, H_{CPT} and H_{TEI} occur at the same altitude ~ 16.6 km as observed on 10 July 2013. A strong TEJ stream with peak speed ~53 m/s located exactly in the vicinity of the tropopause ($T_{CPT} \sim 190$ K) is observed. We have calculated the meridional temperature gradient between Chennai (13.0 N) and Gadanki (13.48 N) and then obtained the right-hand side term of equation 1 (hereafter referred as meridional temperature gradient $\left(\frac{\partial T}{\partial y}\right)$ term). It is observed that the zonal wind shear $\left(\frac{\partial U}{\partial z}\right)$ and $\frac{\partial T}{\partial y}$ term between the altitudes 15.1 -17.7 km are roughly the same indicating that the TEJ is in the thermal wind balance in the above-mentioned layer. Similarly, the case observed on 18 August 2010 when TEJ has broad (15.9-16.9 km) peak, the tropopause is also observed to be relatively broader. The presence of the temperature inversions at 15.9 km and 16.9 km on the lower and upper edges of the TEJ broad peak can also be noticed. In this case, $\frac{\partial U}{\partial z}$ and $\frac{\partial T}{\partial y}$ term show a good similarity between 14.4 -17.4 km indicating that TEJ is in thermal wind balance. In the case of the multiple TEJ peaks observed at 16 km (speed ~39.4 m/s) and 18 km (speed ~ 34 m/s) are associated with multiple tropopauses occurring at the same altitudes 16 km (temperature ~193.2 K) and 18 km (T_{CPT} ~191 K) respectively. In this case peak of the TEJ (H_{TEI}) lies ~ 2 km below the H_{CPT} coinciding with temperature inversion present in the UT (Fujiwara et al. 2003) which is in thermal wind balance.



Figure S2. Typical profiles of (a) temperature, (b) zonal wind and (c) zonal wind shear (left-hand side of equation 1) and the term involving meridional temperature gradient (right-hand side of equation 1) for sharp tropopause and TEJ observed on 10 July 2013. (d-f) and (g-i) are the same as Figures 1a-c but for broad tropopause and TEJ and multiple tropopauses and TEJ observed on 23 July 2013, respectively. Dashed and dash-dotted lines represent the altitudes between which TEJ is in the thermal wind balance.





Figure S3(a) Day to day variability of H_{CPT} and H_{TEJ} during the Indian summer monsoon seasons 2006. (b) Time series of ΔH (the difference between H_{CPT} and H_{TEJ}) along with mean ΔH over the period. (c) day to day variation of the infrared brightness temperature (IRBT).



Figure S4 (a) Day to day variability of H_{CPT} and H_{TEJ} during the Indian summer monsoon seasons 2006. (b) Time series of ΔH (the difference between H_{CPT} and H_{TEJ}) along with mean ΔH over the period. (c) day to day variation of the Infrared brightness temperature (IRBT) and (d) Wavelet spectrum of temperature (in terms of power) at 16 km altitude. White curve represents cone of influence.



Figure S5. (a)-(d) are same as Figure S4 (a)-(d) but observed during JJA 2009.



Figure S6. (a)-(d) are same as Figure S4 (a)-(d) but observed during JJA 2010.



Figure S7. (a)-(d) are same as Figure S4 (a)-(d) but observed during JJA 2011.



Figure S8. (a)-(d) are same as Figure S4 (a)-(d) but observed during JJA 2012.



Figure S9. (a)-(d) are same as Figure S4 (a)-(d) but observed during JJA 2013.



Figure S10. (a)-(d) are same as Figure S4 (a)-(d) but observed during JJA 2014.



Probability of distribution of day-to-day difference of H_{CPT} and H_{TEJ} and $\overline{\Delta H}_{CPT-TEJ}$

Figure S11. (a)The percentage of the occurrence of the absolute change of the H_{CPT} tendency within 1 km, 1-2 km, 2-3 km, 3-4 km and >4 km calculated over the period JJA 2006-2014. (b) ate (c) are the same as (a) but for the H_{TEJ} tendency and $\Delta H_{CPT-TEJ}$, respectively.

Role of the convection on the relationship between H_{CPT} and H_{TEI}

We have investigated the roles of the convection occurring at different heights (convection top height; CTH) on the relationship H_{CPT} and H_{TEJ} using threshold criteria following Meenu et al., (2010). We have obtained the IRBT probability distribution for category1 (category2) which shows that about 4% (5%), 13% (8%), 10% (13%), 42% (36%), 16% (18%) and 15% (20%) data falls under <220K, 220-235K, 235-245K, 245-270K, 270-280K and >280K, representing the CTH >12 km, 10-12km, 8-10 km, 5-8 km, 2-5 km and no convection, respectively. It is observed occurrence of the category1 and category2 does not depend upon the local convection.



Figure S12. Probability distributions of the (a) category1 and (b)category2

Relationship between CPT, LRT and TEJ

During ISM season deep convections occur frequently and it is known that H_{CPT} and altitude of the lapse rate tropopause (LRT) (H_{LRT}) may coincide at the same altitude (Seidel et al., 2001). Note that LRT is defined based on the lapse rate criteria (Highwood & Hoskins, 1998). To understand the relationship between H_{CPT} , H_{LRT} and H_{TEI} , their day to day variations are shown in Supplementary Figure S11. We found that LRT coincides to the CPT ~26% times under category1 while 15% times under category2. Out of these coincident cases, the majority (89% under category1 and 85% under category2) occurs during convection however not necessarily with deep convection always. TEJ lies in between CPT and LRT ~24% and 7% times under category 1 and category 2, respectively. Note that TEJ frequently (77% times) occur above the LRT under category1 while it frequently (74% times) occur below the LRT under category2. However, as LRT has limited physical relevance, we have focused on the relationship between CPT and TEJ only.



Figure S13. Day to day variability of H_{CPT} , H_{LRT} and H_{TEJ} during the Indian summer monsoon seasons (2006-2014).

Correlation analysis

Table ST1 lists the correlation coefficients between H_{CPT} and H_{TEI} , T_{CPT} and H_{TEI} , H_{CPT} and T_{CPT} estimated for overall data, and category1 for each monsoon season during the period 2006 – 2014. For category 2, only number of the days observed are listed in the Table ST1. As adequate data was not available under category 2 for the correlation analysis, we have obtained the correlation coefficients tropopause and TEJ parameters for all the cases belonging to "far apart" cases as well as "close to each other" cases as listed in the Supplementary Figure ST2. From Tables ST1 and ST2, we observed that our findings for category 1 and category 2 do not change even when all the cases belonging to "close to each other" and "far apart" respectively are taken into consideration. Similar to overall data, no correlation is observed between H_{CPT} and H_{TEI} for each monsoon season. As the total data in a monsoon season is an amalgam of partly in phase and partly out of phase variations that results in no correlation between H_{CPT} and H_{TEI} . However, it is interesting to note that H_{CPT} and H_{TEI} show moderate to strong correlation (r = 0.43 - 0.78) significant at 95% confidence level under the category1 during each monsoon season (2006–2014) except 2014. For the year 2014, we have observed four episodes on 23 July -02 August, 7-12 August, 16–19 August and 25–27 August under the category1, in which the first episode shows that H_{CPT} and H_{TEI} are not in phase as an exceptional case of category1 resulting in an insignificant correlation.

 T_{CPT} and H_{TEI} are significantly anti-correlated (r = (-0.32) - (-0.40)) during different monsoon season except 2011 and 2014. T_{CPT} and H_{TEI} are also significantly anti-correlated (r =(-0.48) - (-0.79) under category1 for each monsoon year except 2011. For each monsoon season, out of phase variation of T_{CPT} and H_{TEI} are more dominant when compared to their inphase variation resulting in significant correlation except during the monsoons of 2011 and 2014. Similar to overall data, H_{CPT} and T_{CPT} show weak to moderate (r = (-0.23) - (-0.63))correlation significant at 95% confidence level during different monsoon years. The correlation between H_{CPT} and T_{CPT} under category 1 shows moderate to strong anticorrelation (r = (-0.47) -(-0.83)) between them for all the monsoon seasons except the monsoon season 2011 suggesting a lack of adiabatic influence in this year. It is to be noted that H_{CPT} and T_{CPT} may not always be driven by adiabatic processes alone and can be affected by other processes such as dynamical heating, ozone heating and occurrence of cirrus clouds (Mehta et al., 2010; Reid & Gage, 1996; Thuburn & Craig, 2000). Thus, when TEJ occurs very close to the CPT and they are strongly correlated it can be considered as an indicator of the prevalence of adiabatic processes. On the other hand, in category2 both H_{CPT} and H_{TEI} and H_{CPT} and T_{CPT} are poorly correlated which indicates the dominance of the diabatic processes.

Table ST1. Correlation coefficients between H_{CPT} and H_{TEJ} , T_{CPT} and H_{TEJ} and H_{CPT} and T_{CPT} observed for overall data, category1 and category 2 during the monsoon season 2006–2014. The number of observations is shown under the parentheses. The correlation coefficients shown with an asterisk are significant at 95% confidence level.

Mons	$H_{CPT} \times H_{TEJ}$			$T_{CPT} \times H_{TEJ}$		$H_{CPT} \times T_{CPT}$	
oon							
Year							
(JJA)							
	Overall	Category1	Category	Overall	Category	overall	Category
			2		1		1
2006	-0.02 (83)	0.72* (50)	14	-0.35*	-0.48*	-0.27*	-0.53*
2007	0.17 (54)	0.78* (27)	6	-0.37*	-0.70*	-0.63*	-0.83*
2008	-0.01 (85)	0.64* (54)	5	-0.32*	-0.46*	-0.23*	-0.47*
2009	0.19 (91)	0.68* (25)	21	-0.36*	-0.64*	-0.42*	-0.72*
2010	0.09 (91)	0.75* (48)	16	-0.35*	-0.61*	-0.26*	-0.55*
2011	0.08 (87)	0.43* (40)	17	-0.13	-0.12	-0.29*	0.10
2012	0.09 (84)	0.56* (45)	3	-0.34*	-0.52*	-0.39*	-0.60*
2013	0.18 (85)	0.70* (35)	17	-0.40*	-0.68*	-0.40*	-0.66*
2014	-0.07 (70)	0.32 (21)	13	-0.18	-0.79*	-0.51*	-0.50*

Table ST2. Correlation coefficients between H_{CPT} and H_{TEJ} , T_{CPT} and H_{TEJ} and H_{CPT} and T_{CPT} observed for "close to each other" and "far apart" cases during the monsoon season 2006–2014. The number of observations is shown under the parentheses. The correlation coefficients shown with an asterisk are significant at 95% confidence level.

Mons	$H_{CPT} \times H_{TEJ}$		$T_{CPT} \times H_{TEJ}$		$H_{CPT} \times T_{CPT}$	
oon	Close to each	Far apart	Close	Far	Close to	Far apart
Year	other	-	to each	apart	each	-
(JJA)			other		other	
2006	0.69* (61)	-0.03 (20)	-0.45*	-0.17	-0.60*	0.01
2007	0.71* (40)	-0.04 (14)	-0.61*	0.03	-0.78*	-0.40
2008	0.66* (64)	-0.06 (20)	-0.49*	-0.21	-0.52*	-0.10
2009	0.81* (46)	0.31 (42)	-0.48*	-0.23	-0.59*	-0.27
2010	0.76* (59)	-0.15 (32)	-0.58*	-0.26	-0.47*	-0.12
2011	0.76* (52)	0.18 (39)	-0.38	-0.29	0.32*	-0.26
2012	0.68* (58)	0.08 (25)	-0.57*	-0.39	-0.59*	-0.17
2013	0.73* (53)	0.31 (32)	-0.61*	-0.27	-0.59*	-0.10
2014	0.67* (38)	-0.16 (32)	-0.62*	-0.30	-0.66*	-0.61*

GPS Radiosonde Data

The radiosonde data used in this study is available from dropdown "**view & download data**" listed on the "**Data/Experiment**" tab of the NARL website (<u>www.narl.gov.in</u>)

Steps to download the radiosonde data from NRAL wesite (<u>www.narl.gov.in</u>)

- 1. Click the tab,"Data/Expreiment"
- 2. Click on "View & Download data"
- 3. Click on "GPS radiosonde" tab



Page-1: NARL website main page



Page-2: Available data page, GPS radiosonde is enricle by green line to download individual date data. One can acess meta data and view the availability of the datasets which can be requested send the link to download it as instructed.



Page-3: Select date and wait for plot to be generated nd fill the required and then dowload. Here typical example is shown for the date 09-07-2010.

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