Structure, dynamics, and trace gases variability within the Asian summer monsoon anticyclone in extreme El Niño of 2015-16

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Abstract: A weak El Niño during 2014-15 boreal winter was developed as a strong boreal summer event in 2015 which continued and even enhanced during the following winter. In this work, the detailed changes in the structure, dynamics and trace gases within the Asian summer monsoon anticyclone (ASMA) during extreme El Niño of 2015-16 is delineated by using Aura Microwave Limb Sounder (MLS) measurements, COSMIC Radio Occultation (RO) temperature, and NCEP reanalysis products. Our analysis concentrates only on the summer months of July and August 2015 when Nino 3.4 index started to exceed 1.5 values. The results show that the ASMA structure was quite different in summer 2015 as compared to the long-term (2005-2014) mean. In July, the spatial extension of the ASMA shows larger than the long-term mean in all the regions except over northeastern Asia, where, it exhibits a strong southward shift in its position. The ASMA splits into two and western Pacific mode is evident in August. Interestingly, the subtropical westerly jet (STJ) shifted southward from its normal position over northeastern Asia as resulted mid-latitude air moved southward in 2015. Intense Rossby wave breaking events along with STJ are also found in July 2015. Due to these dynamical changes in the ASMA, pronounced changes in the ASMA tracers are noticed in 2015 compared to the long-term mean. A 30% (20%) decrease in carbon monoxide (water vapor) at 100 hPa is observed in July over most of the ASMA region, whereas in August the drop is strongly concentrated in the edges of the ASMA. Prominent increase of O_3 (>40%) at 100 hPa is clearly evident within the ASMA in July, whereas in August the increase is strongly located (even at 121 hPa) over the western edges of the ASMA. Further, the temperature around the tropopause shows significant positive anomalies (~5K) within the ASMA in 2015. The present results clearly reveal the El Niño induced dynamical changes caused significant changes in the trace gases within the ASMA in summer 2015.

Keywords: Trace gases, El Niño, Asian summer monsoon anticyclone, tropopause

1. Introduction

The Asian summer monsoon anticyclone (ASMA) is a distinct circulation system in the upper troposphere and lower stratosphere (UTLS) during northern hemisphere boreal summer, centered at ~25ºN and extending roughly between 15ºN to 40ºN (Park et al., 2004; Randel et al., 2010). It is encircled by the subtropical westerly jet stream to the north and by the equatorial easterly jet to the south (Randel and Park, 2006). It is well recognized that the ASMA circulation is a prominent transport pathway for troposphere pollutants to enter the stratosphere (Randel et al., 2010). Previous studies have concluded that deep convection during summer monsoon can effectively transport the pollutants, aerosols and tropospheric tracers from the boundary layer into the UTLS region (Vogel et al., 2016; Santee et al., 2017). These transported pollutants, tracers and aerosols become confined in the ASMA and, consequently, affect the trace gas composition in the UTLS region (Randerl et al., 2010; Solomon et al., 2010; Riese et al., 2012; Hossaini et al., 2015). It is clearly evident from the previous studies that the ASMA has a higher concentrations of tropospheric tracers such as carbon monoxide (CO), hydrogen cyanide (HCN) and Methane (CH_4) and lower concentrations of stratospheric tracers including Ozone (O_3) and nitric acid (HNO_3)

(Park et al., 2004; Li et al., 2005; Park et al., 2008; Randel et al., 2010; Vernier et al., 2015; Yan and Bian, 2015; Yu et al., 2017; Santee et al., 2017; Vernier et al., 2018). The comprehensive study on the climatological composition within the ASMA can be found in Santee et al. (2017). The ASM convection and orographic lifting are the primary mechanisms for the higher concentrations of the tropospheric tracers in the ASMA (Li et al., 2005; Park et al., 2009; Santee et al., 2017). Apart from these trace gases a strong persistent tropopause-level aerosol layer called as 'Asian Tropopause Aerosol Layer' (ATAL) also existed between 12 to 18 km within the ASMA and it was first detected from the CALIPSO measurements (Vernier et al., 2011).

Similarly, higher concentrations of water vapor (WV) within the ASMA during the summer monsoon is well documented in the literature (Gettelman et al., 2004; Park et al., 2007; Randel et al., 2010; Bian et al., 2012; Xu et al., 2014; Jiang et al., 2015; Das and Suneeth, 2020). It is well known that most of the WV enters the stratosphere through the tropical tropopause (Fueglistaler et al., 2009) and the temperature presented at the tropical tropopause strongly controls the WV entering the lower stratosphere (LS). It is also well documented that several processes such as convection, strength of the Brewer-Dobson circulation, El Niño–Southern Oscillation (ENSO) and Quasi-Biennial Oscillation (QBO) are responsible for the WV transport to the UTLS region (Holton et al., 1995; Dessler et al., 2014; Jiang et al., 2015). Other factors such as gravity waves and horizontal advection can also influence the WV transport in the UTLS region. For example, Khan and Jin (2016), studied the effect of gravity waves on the tropopause and WV over Tibetan Plateau and reported that the gravity wave is the source for the WV transport from the lower to higher altitudes. Recently, Das and Suneeth (2020) reported about the distributions of WV in the UTLS over the ASMA during summer using 13 years of Aura Microwave Limb Sounder observations. They concluded that WV in the UTLS region inside the central part of ASMA is mostly controlled by horizontal advection and very less from the local process and tropopause temperature in both summer and winter.

Convection during the summer monsoon is one of the major sources to transport the boundary layer pollutants into the UTLS region (Randel et al., 2010). It is well established fact that the ENSO has a strong influence on convection and circulation changes over the Asian monsoon region (Kumar et al., 1999; Wang et al., 2015; Gadgil and Francis, 2016). Enhanced (suppressed) convection over the Asian monsoon region generally observed in the cold phase of ENSO (warm phase of ENSO) known as La Niña (El Niño). Few studies have existed to date on the impact of ENSO on the ASMA trace gas composition changes and its dynamical changes. For example, Yan et al. (2018) reported the influence of ENSO on the ASMA with a major focus on how the ENSO winter signal propagates into the following seasons. They showed the weaker O_3 transport into the tropics during the onset of the ASMA after boreal winter El Niño events, but the difference between El Niño and La Niña composites becomes insignificant in the summer. In another study, Tweedy et al. (2018) demonstrated the impact of boreal summer ENSO events on O_3 composition within the ASMA in different phases of ENSO events. They reported that the ASMA forms earlier and stronger in the La Niña period that leads to greater equatorward transport of O_3-rich air from the extra-tropics into the northern tropics than during El Niño periods. Recently, Fadnavis et al. (2019) reported higher concentrations of aerosol layers observed in the ATAL region during the El Niño period over the northern part of South Asia. However, the above- mentioned studies are mainly focused on changes in the ASMA with respect to ENSO on seasonal scales or mature stage of monsoon (combined mean of July and August)..

Based on the above-mentioned studies, it can be concluded that the ENSO also has a strong influence on the ASMA structure and its composition. The recent 2015-16 El Niño event was recorded as an extreme and long-lasting event in the 21st century (Huang et al., 2016; Avery et al., 2017). It was started as a weak El Niño during 2014-15 boreal winter and it developed as a strong boreal summer El Niño event in 2015 (Tweedy et al., 2018). Further, this strong boreal summer event was continued and significantly enhanced until the boreal winter of 2015-16. . In this event, several unusual changes occurred in the tropical UTLS region including, the strong enhancement in the lower stratosphere WV (higher positive tropopause temperature anomalies) over Southeast Asia and western Pacific regions (Avery et al., 2017) and anomalous distribution of trace gases in the UTLS region (Diallo et al., 2018; Ravindra Babu et al., 2019a). Similar way, the response of different trace gases (O_3, HCl, WV) to the disrupted 2015–2016 quasi-biennial oscillation (QBO) associated with 2015-16 El Niño event is also reported by Tweedy et al. (2017). Dunkerton (2016), discussed the possible role of unusual warm ENSO event in 2015-2016 to the QBO disruption by triggering the extratropical planetary waves. Therefore, in the present study, we investigated the detailed changes observed in the ASMA 2015 particularly by focusing on the structure, dynamics and trace gases variability within the ASMA in July and August 2015 by using satellite observations and reanalysis products. The present research article is organized as follows. Database and methodology adopted in this study are discussed in Section 2. The results and discussions are illustrated in Section 3. Finally, the summary and conclusions obtained from the present study are summarized in Section 4.

2. Database and Methodology

2.1. Microwave Limb Sounder (MLS) measurements

In the present study, version 4.2 Aura MLS measurements of CO, O_3 and WV are utilized. The MLS data of July and August months in each year from 2005 to 2015 period are considered. The vertical resolution for CO is in the range 3.5–5 km from the upper troposphere to the lower mesosphere and the useful range is 215–0.0046 hPa. The horizontal resolution for CO is about 460 km at 100 hPa and 690 km at 215 hPa. For WV, the vertical resolution is in the range of 2.0 to 3.7 km from 316 to 0.22 hPa and the along-track horizontal resolution varies from 210 to 360 km for pressure greater than 4.6 hPa. For O_3, the vertical resolution is ~2.5 km and the along-track horizontal resolution varies between 300 and 450 km. The precision (systematic uncertainty) for WV is ~ 10-40% (~10-25%), for O_3 is ~0.02–0.04 (~0.02–0.05) ppmv and for CO, it is ~ 19 ppbv (30%), respectively. More details about the MLS version 4 level 2 data can be found in Livesey et al. (2018).

2.2. COSMIC Radio Occultation measurements

To see the changes in the tropopause temperature and height within the ASMA, we used high-resolution, post-processed products of level 2 dry temperature profiles obtained from Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) Radio Occultation (RO). Each month of July and August from 2006 to 2015 are considered. The data is downloaded from the COSMIC Data Analysis and Archival Center (CDAAC) website. We used 200 m vertical resolution temperature profiles in the study. Details of the temperature retrieval from the bending angle and refractivity profiles obtained from the RO sounding are presented well in the literature (Kursinski et al. 1997; Anthes et al. 2008). The COSMIC temperature have a precision of 0.1% between 8 and 25 km (Kishore et al. 2009; Kim and Son, 2012). The temperature accuracy in the UTLS is better than 0.5 K for individual profiles and ~0.1 K for averaged profiles (Hajj et al. 2004). It is noted that for individual RO temperature profiles, the observational uncertainty estimate is 0.7 K in the tropopause region, slightly decreasing into the troposphere and gradually increasing into the stratosphere (Scherllin-Pirscher et al., 2011a). For monthly zonal-averaged temperature fields, the total uncertainty estimate is smaller than 0.15 K in the UTLS (Scherllin-

Pirscher et al., 2011b). Overall, the uncertainties of RO climatological fields are small compared to any other UTLS observing system for thermodynamic atmospheric variables. Note that these data are compared with a variety of techniques including GPS radiosonde data and observed good correlation particularly in the UTLS region (Rao et al. 2009; Kishore et al. 2009). The COSMIC RO profiles have been widely used for studying the tropopause changes and its variabilities (Kim and Son, 2012; RavindraBabu et al. 2015; RavindraBabu and Liou, 2021).

2.3. National Centers for Environmental Prediction (NCEP) Reanalysis data

We also utilized monthly mean Geopotential height (GPH) and wind vectors (zonal and meridional wind speed) from the NCEP-DOE Reanalysis 2 (Kanamitsu et al.,2002), covering the same time period as the MLS observations (2005-2015). NCEP-DOE Reanalysis 2 is an improved version of the NCEP Reanalysis I model that fixed errors and updated parametrizations of physical processes. The horizontal resolution of NCEP-DOE Reanalysis 2is 2.5° × 2.5°, respectively.

Apart from the above-mentioned data sets, we also used European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis potential vorticity (PV) data particularly at 350K isentropic surface in July and August 2015 (ERA-Interim; Uppala et al., 2005; Dee et al., 2011).

2.5. Methodology

Daily available MLS profiles of O_3, CO, and WV in each month are constructed and gridded by averaging the profiles inside bins with a resolution of 5° latitude × 5° longitudes. The following equation is used to estimate the relative change in percentage.

$$\text{Relative change in percentage} = \left(\frac{x_{i-\bar{x}}}{\bar{x}}\right) \times 100 \qquad (1)$$

where x_i represents the monthly mean of July/August in 2015, and $\bar{x}$ is the corresponding monthly long-term mean which is calculated by using the data from 2005 to 2014.

3. Results and Discussion

It is well reported that the ASMA is highly dynamic in nature with respect to its position and shape. Also it varies at different time scales i.e day-to-day, weekly and monthly scales caused by internal dynamical variability (Randel and Park, 2006; Garny and Randel, 2013; Pan et al., 2016; Nützel et al., 2016; Santee et al., 2017). The intensity and spatial extension of the ASMA are prominent in July and August where the monsoon was in the mature phase (Santee et al., 2017; Basha et al., 2019). It can be noticed that the 2015-16 El Niño event was one of the strongest boreal summer events that occurred in the entire MLS data record (Tweedy et al., 2018). In this event, the Nino 3.4 data was exceeded +1.5 in July and +1.8 in August (**Fig. 1**). Therefore, in the present study, we mainly focused on ASMA behavior and trace gases changes within the ASMA on monthly scales particularly in July and August 2015 which represents strong El Niño.

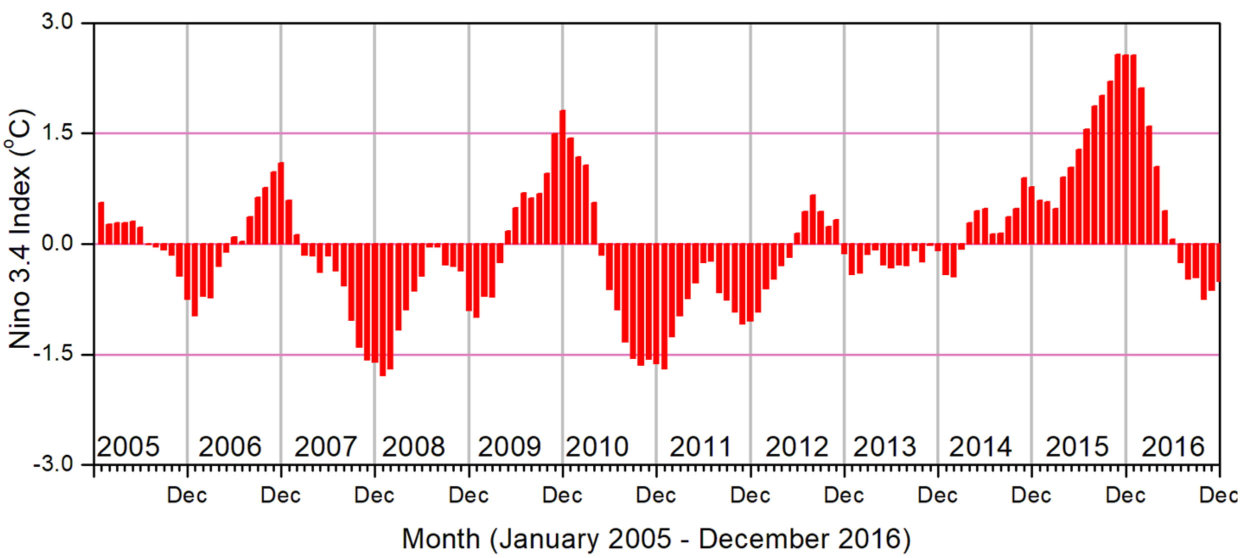

Figure 1. Temporal evolution of observed Niño3.4 Index data from January 2005 to December 2016.

3.1. Structure and dynamical changes in ASMA during 2015

In general, the studies looking at monthly or seasonal timescales related to the thermo-dynamical features in the ASMA, the anticyclone region is mostly defined from the simple constant GPH contours at different pressure levels (Randel and Park, 2006; Yan et al., 2011; Bergman et al., 2013; Basha et al., 2019). Previous researchers used different GPH contours at 100 hPa to define the anticyclone region. For example, Yan et al. (2011) used 16.7 km, Bergman et al. (2013) used 16.77 km and recently Basha et al. (2019) used 16.75 km GPH contour as the anticyclone region. In a similar manner, we also defined the ASMA region based on NCEP-DOE Reanalysis 2 obtained GPH at 100 hPa and considered the 16.75 km GPH contour as the anticyclone region.

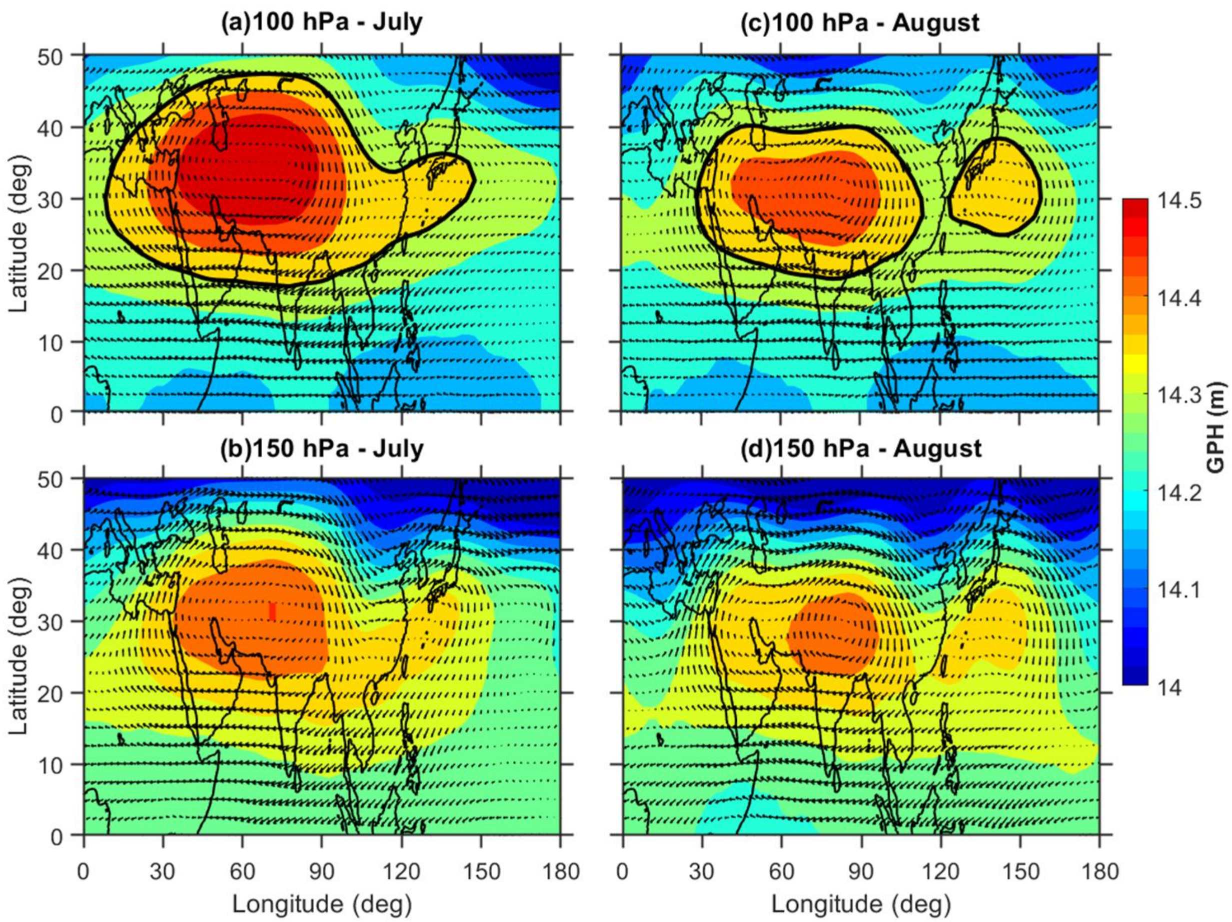

Figure 2. Spatial distribution of geopotential height obtained from NCEP-DOE Reanalysis 2 data during July 2015 (a) at 100 hPa and (b) 150 hPa superimposed with wind vectors at the respective corresponding levels. Subplots of (c) and (d) are the same as (a) and (b) but for the month of August. The black color solid contour lines represent the ASMA region at 100 hPa (16.75 km GPH contour).

The spatial distribution of GPH at 100 hPa and 150 hPa for the month of July (August) is shown in **Fig. 2a and 2b (Fig. 2c and 2d).** The corresponding monthly mean winds at respective pressure levels are also shown in **Fig.2**, respectively. The black solid line represents the ASMA region at 100 hPa based on 16.75 km GPH contour. The GPH distribution in **Fig. 2** shows clear distinct variability in the ASMA spatial structure between July and August at both pressure levels. For example, at 100 hPa, the maximum GPH center was located over western side in July whereas it was located over near to the Tibetan region in August. Interestingly the ASMA itself separated into two anticyclones (16.75 km GPH contour black solid line in the figure) in August compare to July. The center of the small anticyclone was located over the Northwestern Pacific near 140^{o}E with the closed circulation indicated by the wind arrows.

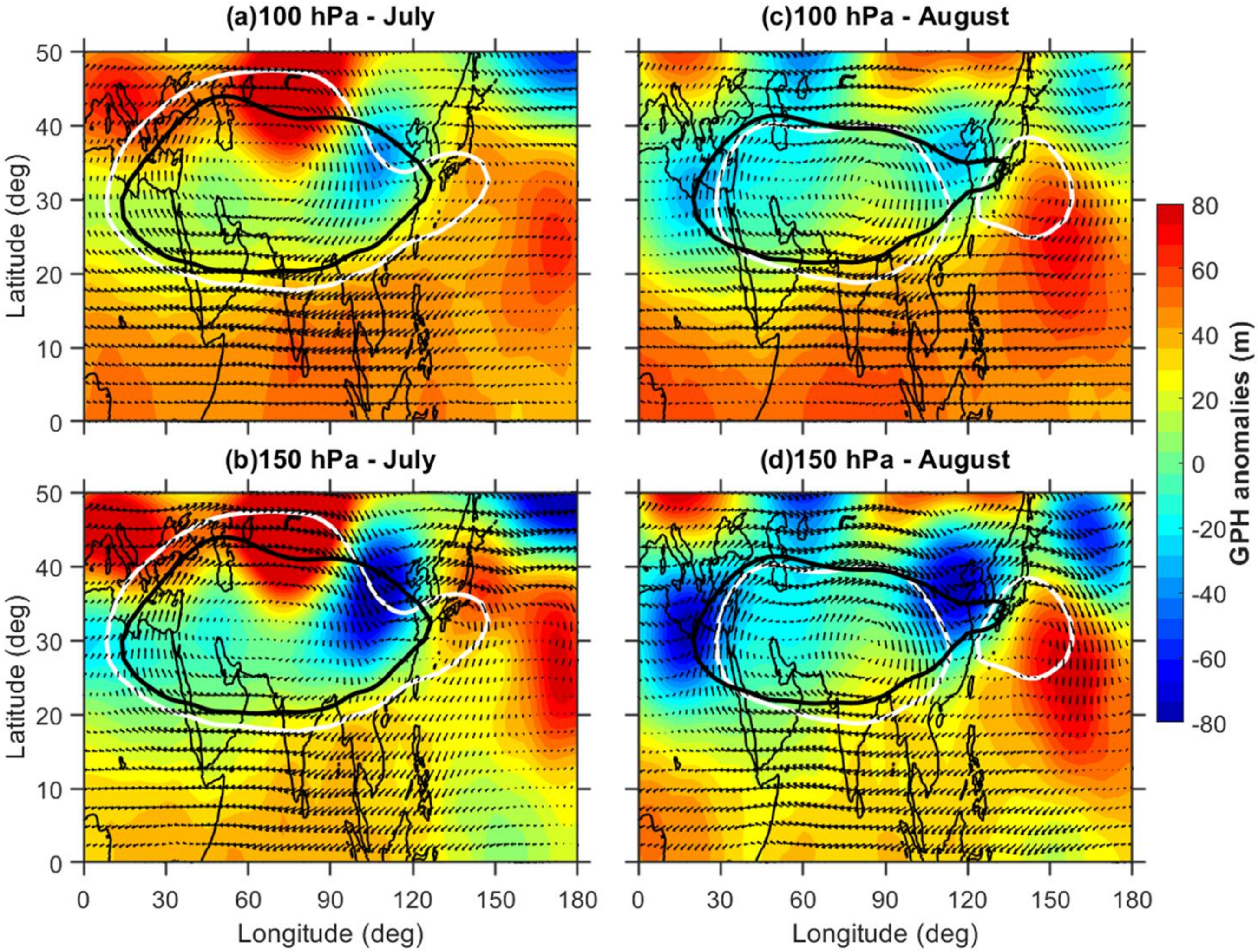

Figure 3. Spatial distribution of geopotential height anomalies obtained from NCEP-DOE Reanalysis 2 data during July 2015 (a) at 100 hPa and (b) 150 hPa superimposed with wind vectors at the respective corresponding levels. (c) and (d) same as (a) and (b) but for the month of August. The white color solid contour lines represent the ASMA region at 100 hPa (16.75 km GPH contour) observed in 2015 whereas the black color line represents the mean of 2005-2014.

Further, we compared the ASMA structure in 2015 with referenced long-term mean. For this, we obtained the GPH anomalies by subtracting the background long-term mean (2005-2014) from 2015. **Figure 3** shows the latitude-longitudinal distribution of GPH anomalies (color shaded) along with wind vectors depicting circulation pattern at 100 hPa as well as at150 hPa during July and August. The white (black) color contour represents 16.75 km GPH at 100 hPa for the corresponding month in 2015 (long-term mean). The GPH anomalies at both pressure levels show quite different features in July and August. A clear wave-like structures can be observed from the GPH anomalies. In July, the GPH anomalies exhibit strong negative maxima over 25-40^{o}N, 90-120^{o}E and positive maxima over 40-50^{o}N, 60-80^{o}E regions. The 16.75 km GPH contour lines in the ASMA region exhibits higher extension in all the directions except over the northeastern edges of the ASMA in July compared to the long-term mean. At the same location (northeastern edges), the ASMA exhibits a pronounced southward extension in July. Distinct features of GPH anomalies are noticed in August as compared to July. In August, the strong negative GPH anomalies are situated over the west and north-eastern edges of the ASMA.

It is well known that the subtropical westerly jet is an important characteristic feature of the ASMA (Ramaswamy 1958), and thus its changes during 2015 are also investigated. As the peak intensity of the westerly jet was located at 200 hPa (Chiang et al., 2015), we focused mainly on 200 hPa zonal wind changes in July and August. **Figure 4a and 4c** (**Fig. 4b and 4d**) show the spatial distribution of long-term (2015) monthly mean zonal wind at 200 hPa during July and August. In general, the subtropical westerlies are located near to ~40^{o}N latitude during the mature phase of the monsoon period (Chiang et al., 2015). Compared to long-term mean, a significant weakening of the subtropical westerlies is noticed in 2015. Further, a strong southward shift in the westerlies is observed over the northeastern Asia region. This southward shift is moved even up to 30^{o}N in both months. From zonal wind at 200 hPa (**Fig. 4**) and wind vectors at 100/150 hPa (**Fig. 2**), it is clear that anomalous changes have occurred in the subtropical westerlies over the northeastern parts of the AMSA around 30-40^{o}N, 90-120^{o}E during July and August 2015. The southward shift in the westerlies is strongly associated with the southward extension of the ASMA over the northeastern side of the ASMA (**Fig. 2**). This is strongly supported by the previous findings by Lin and Lu (2005) where they showed the southward extension of the South Asian High could lead to the southward shift of the westerlies.

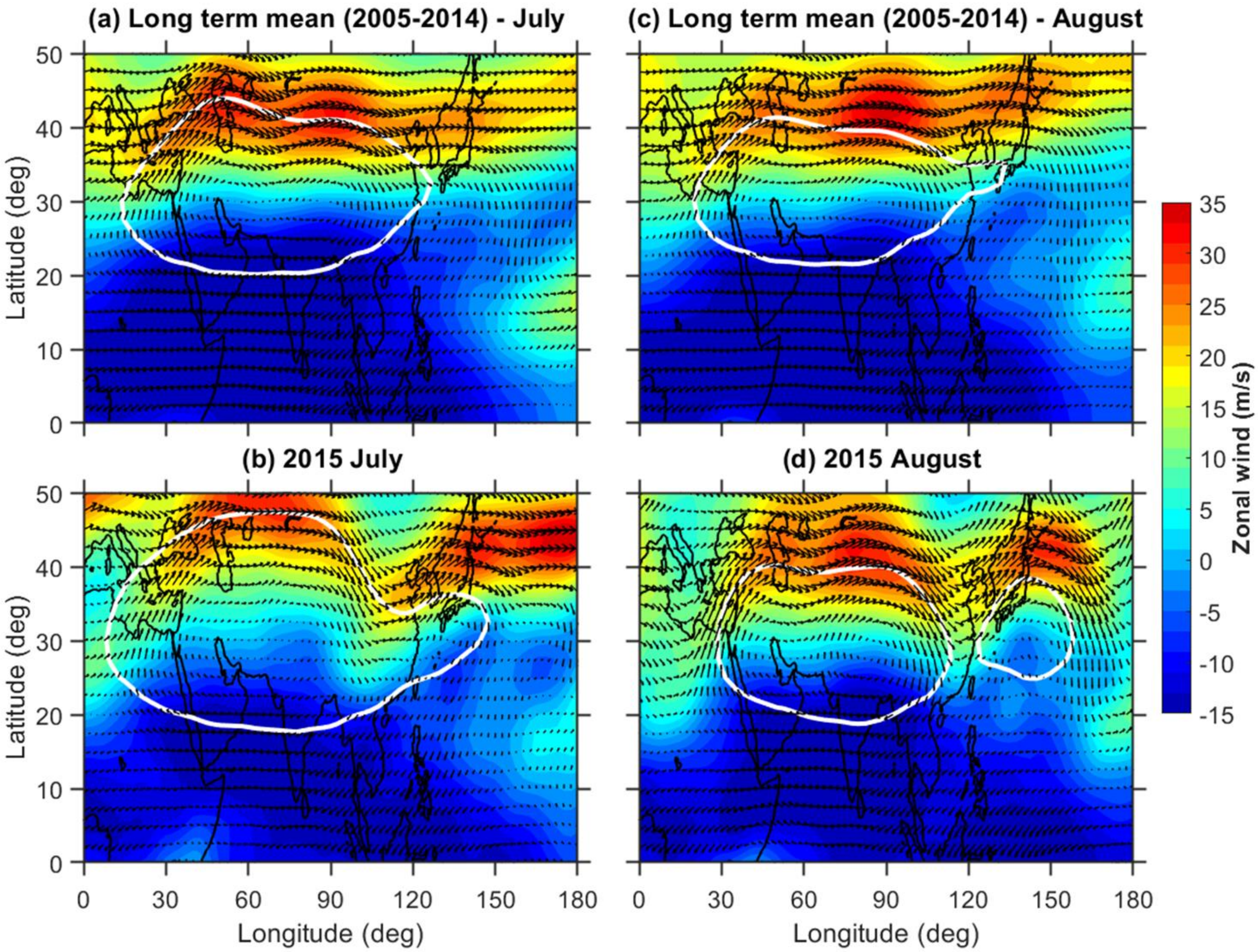

Figure 4. Spatial distribution of monthly mean zonal winds obtained from NCEP-DOE Reanalysis 2 data at 200 hPa during July during (a) 2005-2014 (b) 2015 year. (c) and (d) same as (a) and (b) but for the month of August. The white color solid contour lines represent the ASMA region at 100 hPa (16.75 km GPH contour).

From the GPH and winds observations, it is clear that pronounced changes are evident in the dynamical structure of the ASMA in 2015 and also relatively different features are noticed between July and August months. Interestingly the ASMA itself separated into two anticyclones during August 2015 and the separation exactly coincided with the strong negative GPH anomalies and southward meandering of subtropical westerlies over the northeastern side of the ASMA. The Western Pacific (WP) mode of the anticyclone is visible in August. The split of the anticyclone and the formation of the WP mode are in agreement with previous studies reported by few researchers earlier (e.g. Honomichl and Pan, 2020). The presence of the WP mode may be due to the eastward eddy shedding of the ASMA system in the process of its sub-seasonal zonal oscillation (Honomichl and Pan, 2020) or Rossby wave breaking (RWB) in the subtropical westerly jet (Fadnavis and Chattopadhyay, 2017). Fadnavis and Chattopadhyay (2017) also identified the split of ASMA into two anticyclones: one over Iran and another over the Tibetan region due to the RWB in June 2014 monsoon period. To see any signatures of these RWB in 2015, we further analyzed the RWB through the ERA interim reanalysis potential vorticity (PV) data. Based on previous studies, it is reported that RWBs can be identified from PV distribution at 350 K isentropic surface (Samanta et al. 2016; Fadnavis and Chattopadhyay, 2017). We used 350 K isentropic surface PV data in July and August 2015 in the present analysis.

Figure 5a–b shows the distribution of ERA interim monthly mean PV at the 350 K isentropic surface during July and August 2015. It can be seen that, during July and August 2015, clear RWB signatures evident near 100^{o}E. It is noted that the equatorial advection of high PV values with a steep gradient and the southward movement of PV from the westerly jet are the basic features of the RBW (Vellore et al., 2016; Samanta et al. 2016). These features are clearly exhibited in **Figure 5** with higher PV values extends up to ~ 30^{o}N in both months over 100^{o}E region. The location of this RWB is significantly correlated with a southward meandering of westerlies and strong negative GPH anomalies. However, the observed RWB signatures in both months are from monthly mean PV data. Further, to see the clear signatures of these RWB, we made weekly based analysis for July month. For this we considered 1-7 July as week-1 and 8-14 July as week-2 so on.

The weekly mean distribution of 350K isentropic surface PV during July is shown in **Fig. 6**.

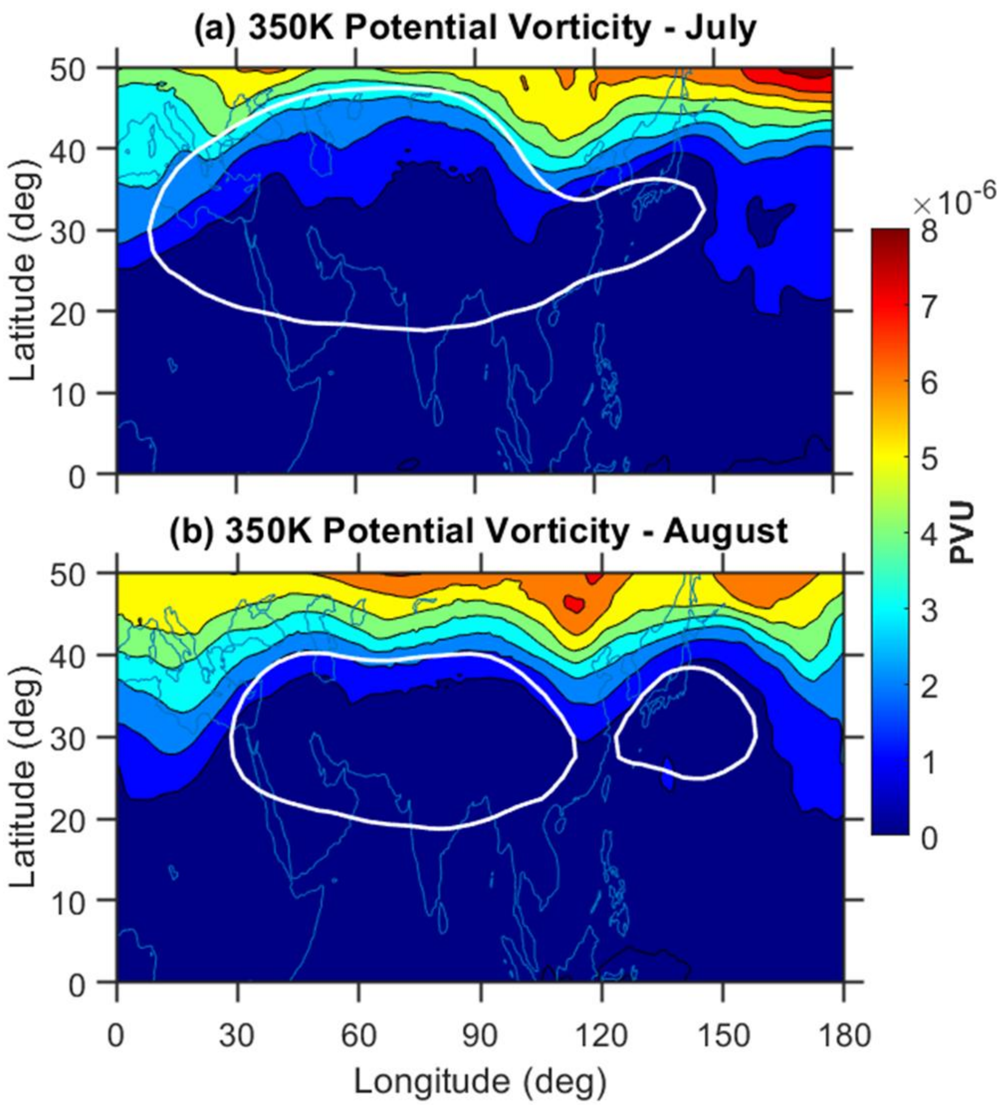

Figure 5. ERA Interim observed spatial distribution of potential vorticity (PV) on a 350 K isentropic surface in PVU (1 PVU = 10^{-6} K m^2 $kg^{-1}s^{-1}$) : (a) monthly mean of July and (b) monthly mean of August 2015. The white color solid contour lines represent the ASMA region at 100 hPa (16.75 km GPH contour).

The magenta colored arrows which are shown in the Fig. 6 represents the RBW events during July 2015. A clear signature of air with high values of PV traverses from extra-tropics to ASMA is evident from Fig.6. At weekly scales, clear RWB signatures are observed over the anticyclone region. For example, in week-1 and week-2, the RWB signatures are evident over the northern region of the ASMA. However, in week-3 and week-4, these RWB signatures are very clear over northeastern Asia even in week-5 (29July-04August), we noticed RWB signatures in PV data (Figure not shown). This clearly shows that The RWB splits the ASMA into two anticyclones: one over the Tibetan region and another over the WP region. It is clear that the equatorward penetration of extra tropical forcing through the subtropical westerly jet has started in July and further amplified by the splitting of the ASMA into two during August.

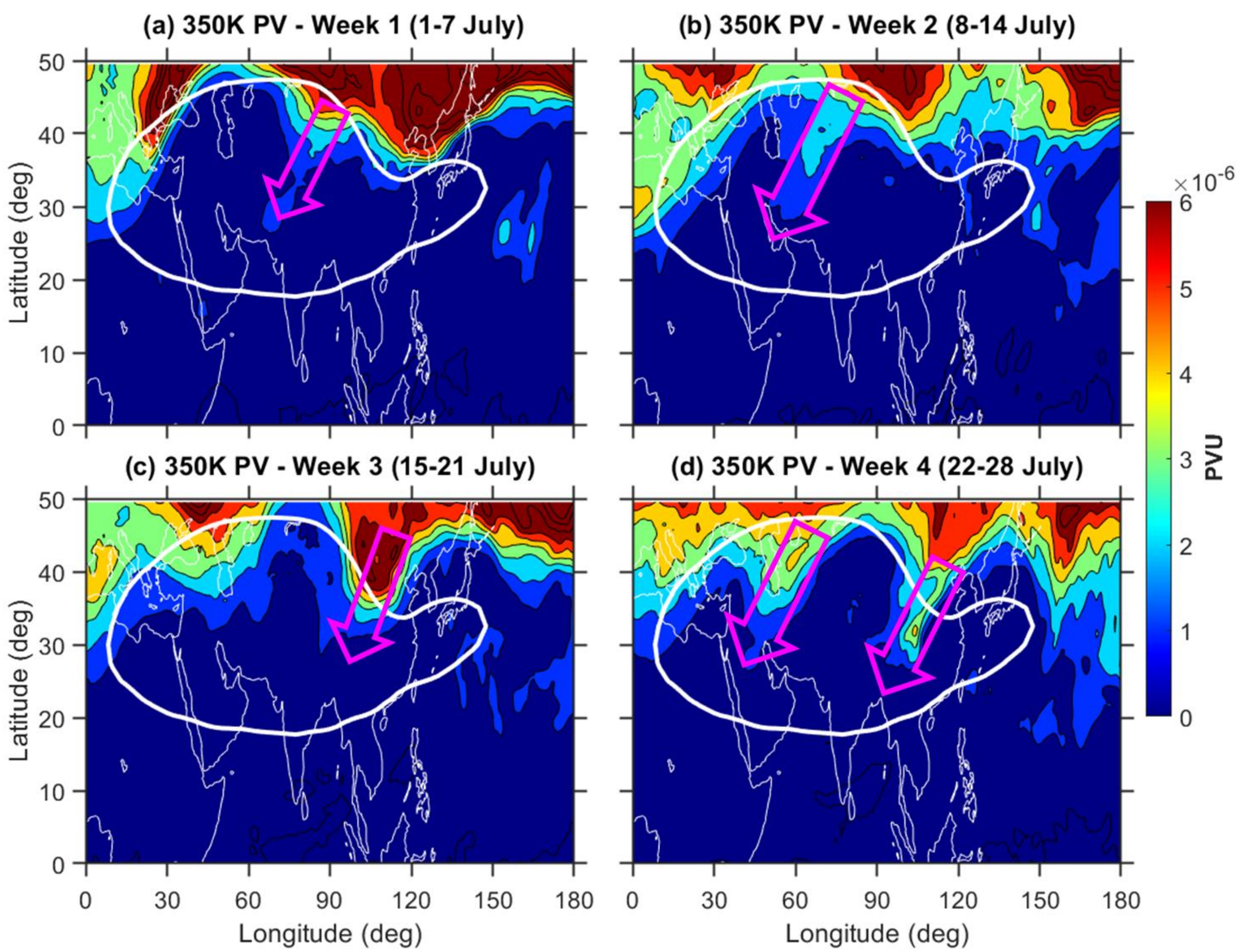

Figure 6. Same as **Figure 5**, but for the weekly distribution of PV in July 2015. Magenta colored arrows indicate the regions of RWB.

It is well known that the RWB is an important mechanism for horizontal transport between the extratropical lower stratosphere to the tropical UTLS region. These RWBs can act as an agent for the transport of extratropical stratospheric cold, dry, and O_3-rich air into the ASMA during the summer monsoon. Overall, it is concluded that the combination of the RWBs and strong southward meandering of the subtropical westerly jet in 2015 causes significant dynamical and structural changes in the ASMA. These changes in the ASMA dynamical structure in 2015 can influence the concentrations of the different trace gases within the ASMA. Further, we quantified the changes in O_3, CO and WV concentrations within the ASMA during 2015 caused by the dynamical effects. The changes that occurred in the O_3 and CO, WV, are discussed in the following sections.

3.2. Trace gases anomalies observed within the ASMA in 2015

It is well-documented that the ASMA contains low (high) concentrations of stratospheric tracers such as O_3 (tropospheric tracers such as CO, WV and etc.) and higher tropopause height compared to the region outside the ASMA during boreal summer (Park et al., 2007; Randel et al., 2010; Santee et al., 2017; Basha et al., 2019). Differences of the trace gases within and outside of the ASMA are attributed to the strong winds and closed streamlines associated with the ASMA, which act to isolate the air (Randel and Park 2006; Park et al. 2007). To see the changes in the trace gases during 2015, we generated the background long-term mean of CO, O_3, and WV by using 10 years of MLS trace gas data from 2005 to 2014. Here the results are discussed mainly based on the percentage changes relative to the respective long-term monthly mean trace gases using **Equ. 1**.

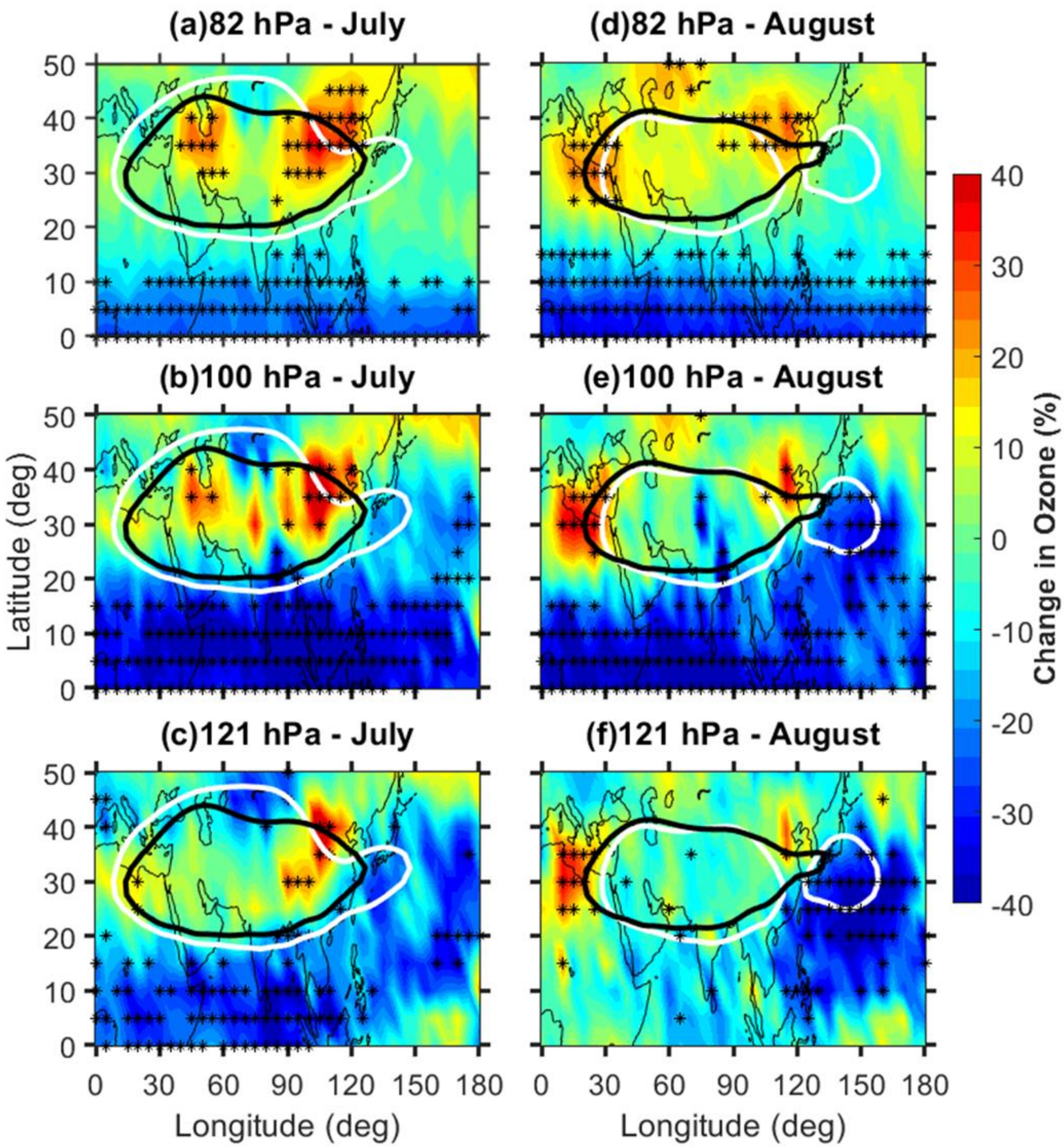

Figure 7. Ozone relative percentage change in July 2015 with respect to background climatological monthly mean observed at (a) 82 hPa, (b) 100 hPa and (c) 121 hPa. (c) and (d) same as (a) and (b) but for the month of August. The white (black) color contour represents 16.75 km geopotential height at 100 hPa for the corresponding month in 2015 (mean of 2005-2014). The star symbols (black) shown in figure represent the anomalies greater than the ±2σ standard deviation of long-term mean. The results are obtained from MLS measurements.

Figure 7a-c (**Fig. 7d-f**) shows the distribution of relative percentage change in the O_3 concentrations within the ASMA at 82 hPa, 100 hPa and 121 hPa during July (August) 2015. The anomalies larger than ±2σ standard deviation of long-term mean are highlighted with star symbols in the respective figures. The spatial distribution of changes in the O_3 (Fig. 7) shows a clear increase in the O_3 mixing ratios (>40%) within the ASMA in 2015. The observed increase within the ASMA is quite distinct between July and August. In July, the O_3 shows a pronounced increase within the ASMA at all the pressure levels. Note that the observed increase was statistically significant with larger than 2σ standard deviation of long-term mean (see the star symbols). This increase is quite significant over the northeastern edges of the ASMA and quite high at 100 hPa compared to 82 hPa and 121 hPa. In August, the O_3 shows quite different features compared to July (Fig. 7d-f). A strong increase in the O_3 is observed over the western and eastern edges of the ASMA at all the pressure levels. The increase is quite significant at 100 hPa and even at 121 hPa. The increase of O_3 is still appearing over the northeastern edges of the ASMA in August as observed in July. Overall, a significant enhancement of O_3 within the ASMA is clear evidence in July and August 2015.

The significant increase of O_3 within the ASMA in 2015 might be due to the transport from the mid-latitudes through the STJ and also due to the stratosphere to the troposphere transport. For example, the strong enhancement of O_3 within the ASMA at 100 hPa in July was strongly matched with the observed high values of PV at 350 K isentropic surface (Fig. 6). This is further supported by the strong southward meandering of STJ in July (Fig. 3), respectively. Thus, a clear transport of mid-latitude air with high PV and high O_3 is evident during 2015. At the same time, the enhancement of O_3 was clearly observed at all the pressure levels from 82 hPa to 121 hPa which is further supported for the stratosphere to the troposphere transport. Note that 82 hPa can represent the lower stratosphere and 121 hPa for the upper troposphere (Das et al., 2020). It can be noticed that the ASMA is strongly associated with troposphere-stratosphere transport as well as stratosphere-troposphere transport (Garny and Randel, 2016; Fan et al., 2017). Also, it is well reported that the northern part of the ASMA is an active region for stratosphere-troposphere transport processes (Sprenger et al., 2003; Škerlak et al., 2014).

Similarly, significant lowering of O_3, particularly at 100 hPa and 82 hPa is clearly noticed over the tropics (Fig. 7). This is quite expected due to the enhanced tropical upwelling (bringing poor O_3 air from troposphere) caused by the strong El Niño conditions in July and August 2015. As mentioned in the previous sections, strong El Niño conditions are clearly evident in July and August 2015 (Fig. 1). The observed strong negative O_3 anomalies over the tropics from the present study are well matched with the previous studies (Randel et al., 2009; Diallo et al., 2018). From the present results, it is very clear that there is a significant decrease over the tropics and the increase over the mid-latitudes in 2015. These changes observed in the O_3 (decrease and increase) are attributed due to the strengthening of the tropical upwelling and enhanced dowelling from the shallow branch of the Brewer-Dobson circulation in the mid-latitudes due to the strong El Niño conditions in 2015. Overall, it is concluded that initially, during July, the O_3 is transported into the anticyclone from the northeastern edges of the ASMA region through the sub-tropical westerlies and then it is isolated within the ASMA region. This is further supported by the southward meandering of the westerly jet and southward shift of the ASMA (negative GPH anomalies) over the same region in July (**Fig. 3**). Also, significant transport of mid-latitude dry air is clear from the Fig. 6. Thus, it is clear from the results that the stratosphere to troposphere transport and horizontal advection along with the subtropical jet caused the strong enhancement of the O_3 within the ASMA in 2015.

Figure 8a-b (**Fig. 8c-d**) shows the spatial distribution of CO relative percentage change at 100 hPa and 146 hPa observed during July (August) 2015. The white (black) color contour represents 16.75 km GPH at 100 hPa for the corresponding month in 2015 (climatological mean). The observed changes in the CO clearly exhibit quite distinct features between July and August as observed in the O_3. A significant decrease (~30%) is noticed in the CO concentrations over most of the AMSA in July. The maximum decrease of CO is noticed over the northeastern edges of the ASMA, located ~ 30-45^{o}N, 90-120^{o}E region. Whereas in August, the decrease of CO is more concentrated over the east and western edges of the ASMA at both the pressure levels. Overall, the MLS observed CO was ~30% below average (percentage decrease) compared to the climatological monthly mean within the ASMA in July and edges of the ASMA in August 2015. It is noted that there is a considerable year-to-year variability of the CO sources over the ASM region (Santee et al., 2017). The major sources of the CO over the ASM region are from the biomass burning and industrial emission. The observed decreased CO within the ASMA in 2015 might be due to the year-to-year variability in the CO sources and the weaker vertical transport due to the El Niño conditions in 2015.

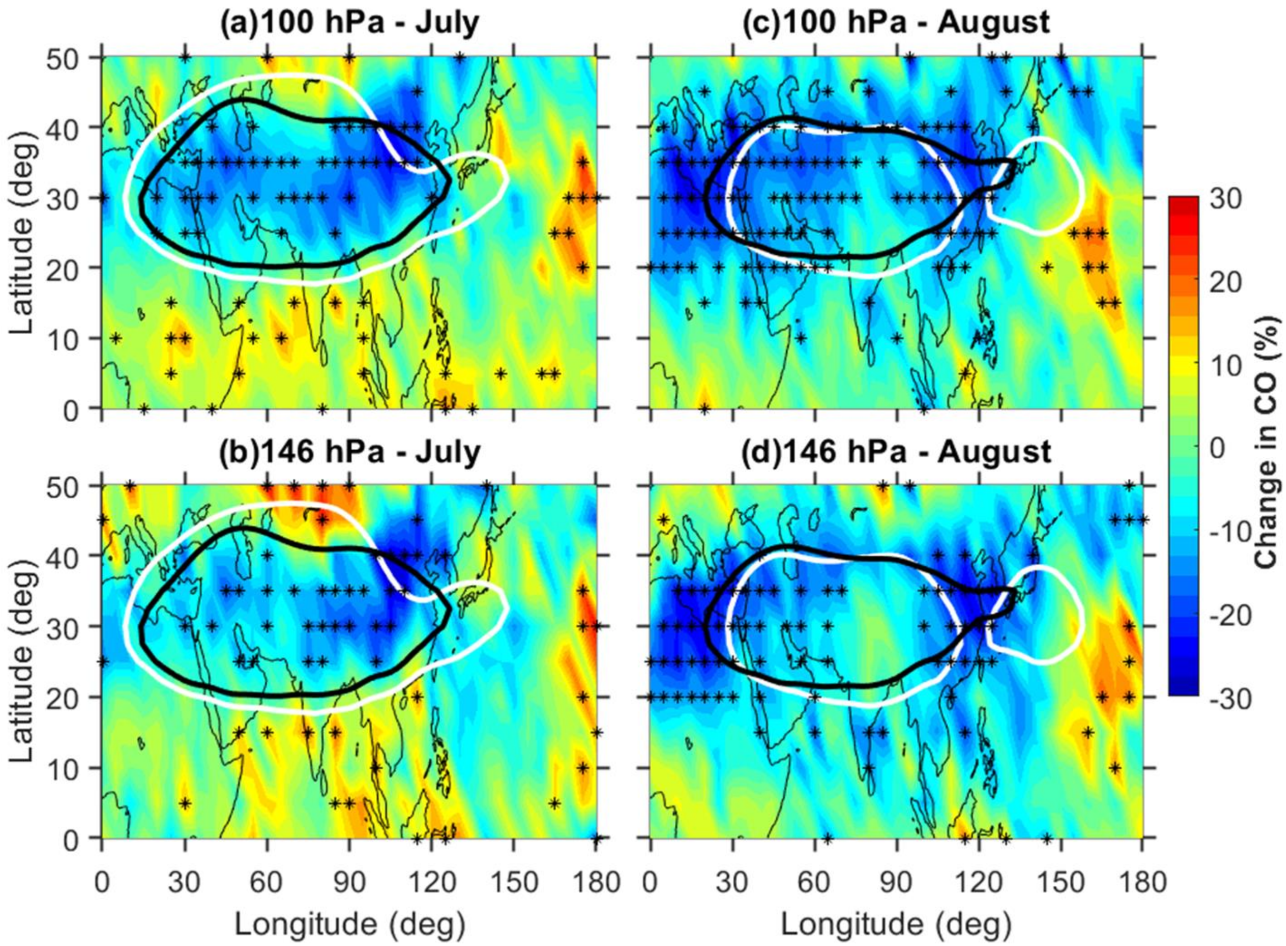

Figure 8. Carbon monoxide relative percentage change during July 2015 with respect to climatological monthly mean observed at (a) 100 hPa and (b) 146 hPa. (c) and (d) same as (a) and (b) but for the month of August. The white (black) color contour represents 16.75 km geopotential height at 100 hPa for the corresponding month in 2015 (mean of 2005-2014). The star symbols (black) shown in figure represent the anomalies greater than the ±2σ standard deviation of long-term mean. The results are obtained from MLS measurements.

Similarly, the WV relative percentage change at 82 hPa, 100 hPa and 146 hPa in July (August) 2015 are shown in **Fig. 9a-c** (**Fig. 9d-f**). The WV shows quite different changes at all the pressure levels in July and August. At 146 hPa, the WV exhibits a strong decrease > 20%) within the ASMA in July as well as in August also. However, at 100 hPa and 82 hPa, the WV shows a relatively significant decrease within the ASMA in July compared to August. From the WV observations, it is concluded that the WV is strongly decreased at 146 hPa in both months. Whereas at 100 hPa and 82 hPa, the decrease in WV is quite high in July compared to August. It is also observed from the Fig. 9 that there is a significant enhancement of WV over the tropics at 146 hPa in both months. But the WV enhancement is quite significant at 100 hPa, particularly during August compared to July. This enhancement in the WV around the tropical tropopause region in August is quite expected due to the El Niño conditions (Randel et al., 2009; Konopka et al., 2016). Overall, the tropospheric tracers (CO and WV) significantly decreased (~30% and 20%) within the ASMA during July and August 2015. These changes in the tropospheric tracers are might be due to the weaker vertical motions during the 2015 monsoon. A weaker vertical transport from the boundary layer to the UTLS is generally observed over the ASM region during El Niño period (Fadnavis et al., 2019). The El Niño conditions will suppress the monsoon convection and cause weaker vertical transport during monsoon. Also it is reported that the summer monsoon in 2015 was weaker monsoon due to the strongest El Niño conditions existed in 2015 (Tweedy et al., 2018; Yuan et al., 2019; Fadnavis et al., 2019).

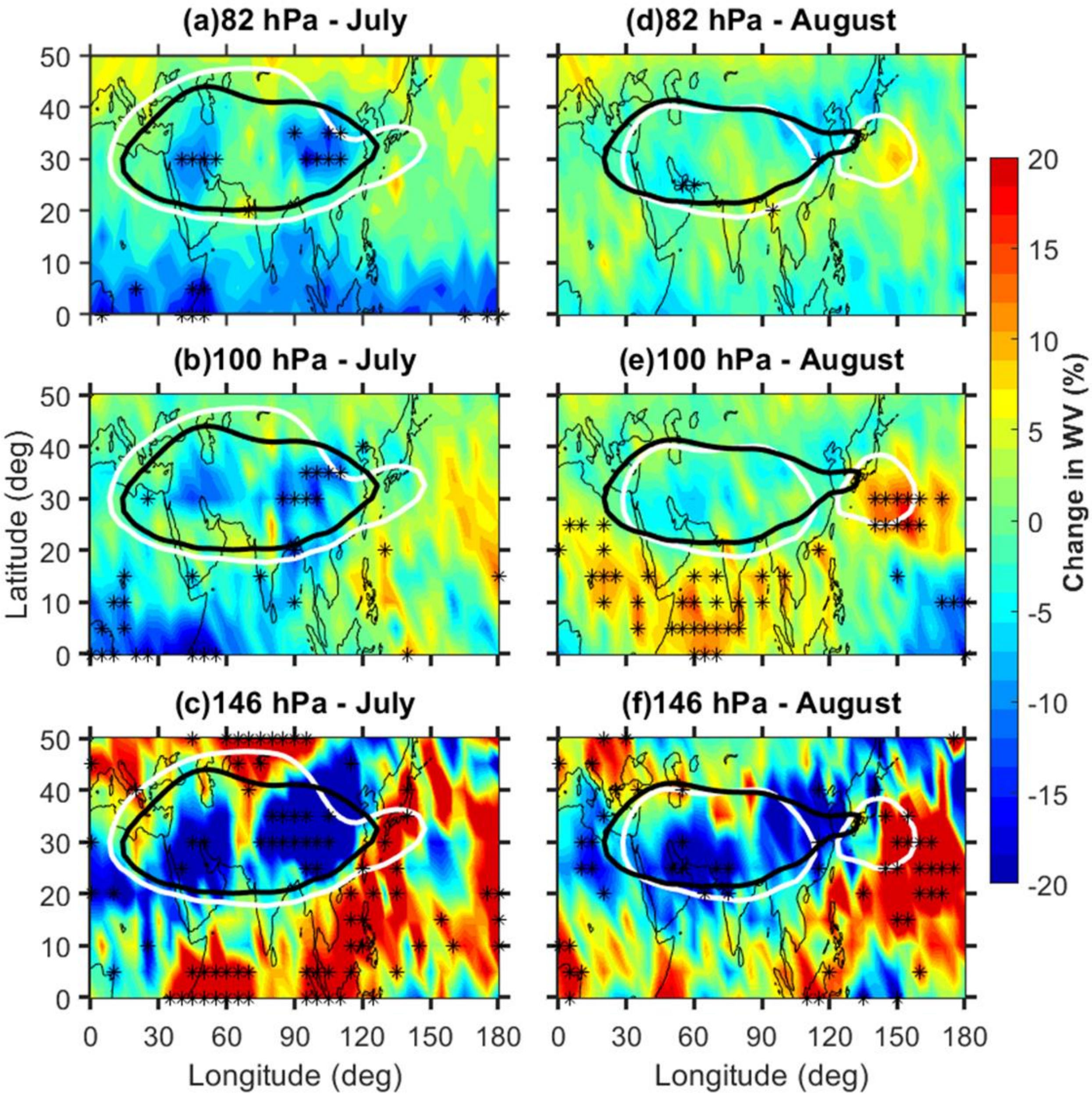

Figure 9. Water vapour relative percentage change in July 2015 with respect to background climatological monthly mean observed at (a) 82 hPa, (b) 100 hPa and (c) 146 hPa. (c) and (d) same as (a) and (b) but for the month of August. The white (black) color contour represents 16.75 km geopotential height at 100 hPa for the corresponding month in 2015 (mean of 2005-2014). The star symbols (black) shown in figure represent the anomalies greater than the ±2σ standard deviation of long-term mean. The results are obtained from MLS measurements.

From these results, it is clear that the enhancement of O_3 and lowering of CO/WV is evident in July and August 2015 compared to the long-term monthly mean. The observed high O_3 and low

WV within the ASMA from the present study are consistent and well-matched with the previous study reported by Li et al. (2018). They demonstrated the importance of the large-scale atmospheric dynamics and the stratospheric intrusions for high O_3 and low WV over Lhasa within the ASMA by using in-situ balloon-borne measurements. The O_3/WV changes strongly influence the background temperature structure within the UTLS region (Venkat Ratnam et al., 2016; RavindraBabu et al., 2019b). Further, we investigated the tropopause temperature changes within the ASMA by using COSMIC RO data. The results are presented in the next following section.

3.3. Tropopause temperature anomalies in 2015

It is well known that the tropopause plays a crucial role in the exchange of WV, O_3 and other chemical species between the troposphere and the stratosphere. Most of these exchanges (WV to the lower stratosphere and O_3 to the upper troposphere) known as stratosphere troposphere exchange (STE) take place around the tropopause region (Fueglistaler et al., 2009; Venkat Ratnam et al., 2016; Ravindra Babu et al., 2019b). It is well reported that the tropopause within the ASMA is higher than the outside regions at the same latitude (Randel et al., 2010; Santee et al., 2017). In the present study, we mainly focused on changes in the cold point tropopause temperature (CPT) and lapse rate tropopause temperature (LRT) within the ASMA in July and August 2015. The July and August 2015 monthly mean tropopause parameters are removed from the respective climatological monthly mean which is calculated by using COSMIC RO data from 2006 to 2014. One can note that we have strictly restricted our analysis within 40ºN region for the cold point tropopause. **Figure 10a-b** (**Fig. 10c-d**) shows the CPT and LRT anomalies observed in July (August) 2015. The tropopause temperature anomalies (CPT/LRT) also exhibit a distinct pattern in July and August as observed in O_3 (**Fig. 7**). In July, the CPT/LRT show strong positive anomalies (~5 K) in most of the ASMA region. High positive CPT/LRT anomalies are also noticed over the

NWP region particularly below 20°N. These CPT/LRT anomalies observed over the NWP region might be due to the El Niño induced changes in the Walker circulation and convective activity. Previous studies also observed significant warm tropopause temperature anomalies over WP and maritime continent during the El Niño period (Gettleman et al., 2001). In August, the strong positive CPT/LRT anomalies (~5K) are concentrated over the northeastern edges of the anticyclone where the WP mode of the anticyclone was separated from the ASMA. The temperature anomalies at 1 km above and below the CPH also show similar behavior as seen in the CPT/LRT during August 2015 (figures not shown). Overall, the tropopause temperature anomalies in July and August 2015 within the ASMA are well correlated with the strong enhancement in the O_3 as shown in **Fig. 7.** However, the enhanced O_3 anomalies (heating due to the O_3) itself cannot explain the observed positive tropopause temperature anomalies within the ASMA in 2015. This might be due to the El Niño induced changes in the convective activity and the circulation. It is well known that the reversal of walker circulation and the shifting of the convective activity (suppressed convective activity over ASM region) are generally observed during the warm phase of ENSO. One can be noticed that apart from the convection, other factors such as stratospheric QBO, atmospheric waves (gravity waves and Kelvin waves) also strongly influenced the tropopause temperatures.

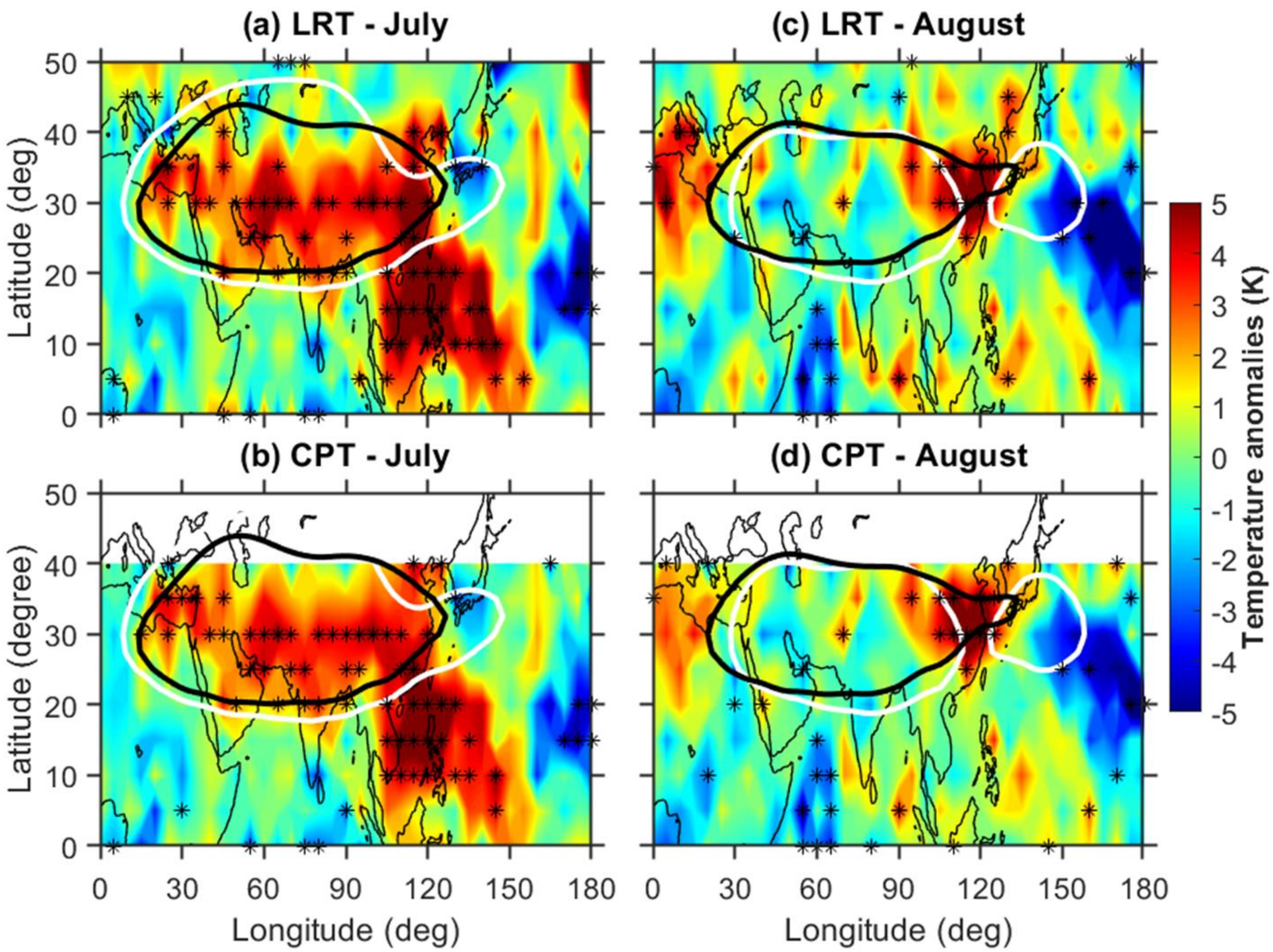

Figure 10. Spatial distribution of (a) lapse rate tropopause temperature (LRT), (b) cold point tropopause temperature (CPT) anomalies during July 2015. (c) and (d) same as (a) and (b) but for the month of August 2015. The white (black) color contour represents 16.75 km geopotential height at 100 hPa for the corresponding month in 2015 (mean of 2005-2014). The star symbols (black) shown in figure represent the anomalies greater than the ±2σ standard deviation of long-term mean.

4. Summary and Conclusions

In this study, we investigated the detailed changes observed in the structure, dynamics and trace gases (Ozone, Water Vapor, Carbon Monoxide) variability within the ASMA in 2015 by using reanalysis products and satellite observations. The tropopause temperature (CPT and LRT) on monthly scales particularly during July and August 2015 also discussed. To quantify the changes that happened within the ASMA region, 11 years (2005-2015) of O_3, WV and CO observations from the Aura-MLS data and 10 years (2006-2015) of tropopause temperature data from the COSMIC RO temperature profiles are used. The NCEP-DOE Reanalysis 2 observed winds and GPH data from 2005 to 2015 are also utilized. The results are obtained by comparing the trace gas quantities in July and August 2015 with corresponding long-term monthly mean quantities.

The trace gases within the ASMA exhibit substantial anomalous behavior in July and August 2015. During July and August 2015, we observed an enhancement of O_3 and the lowering of CO and WV over most of the ASMA region. The decrease of the tropospheric tracers (CO and WV) is quite expected due to the weaker upward motions from the weak monsoon in 2015. This is supported by a recent study reported by Fadnavis et al. (2019). They showed weaker upward motions and deficient rainfall in the 2015 monsoon due to the strong El Niño conditions. However, the strong enhancement in the stratospheric tracer (O_3) within the ASMA particularly over the northeastern edges of the ASMA during July is quite interesting. This is might be due to the stratospheric intrusions as well as transport from the mid-latitudes. Based on Fishman and Seiler (1983), it was stated that the positive correlation between CO and O_3 indicates, the O_3 is produced by in-situ in the troposphere whereas the correlation is negative means the O_3 originates from the stratosphere. We noticed a strong negative correlation between CO and O_3 in the present study with increased O_3 and decreased CO from the MLS measurements. This clearly reveals that the observed increased O_3 within the ASMA during 2015 is the stratospheric origin. This is further supported by higher negative GPH anomalies associated with a southward meandering of the subtropical westerly jet over northeastern Asia in July (**Fig. 3** and **4**). Further, the increased O_3 at 100 hPa and 121 hPa over western edges of the ASMA during August clearly indicates the transport of the O_3 towards outer regions through the outflow of the ASMA (**Fig. 7e-f**). Interestingly, the tropopause temperature obtained from the COSMIC RO data in July 2015 shows strong positive temperature anomalies (~5 K) over the entire ASMA region. These warm tropopause temperatures again supported the increased O_3 within the ASMA during 2015. The major findings obtained from the present study are summarized in the following.

- ❖ The spatial extension of the ASMA region shows higher than long-term mean except over northeastern Asia where it exhibits a strong southward shift in July. Whereas in August, the AMSA further separated into two anticyclones and the western Pacific mode anticyclone is clearly evident in August.
- ❖ The combination of Rossby wave breaking and pronounced southward meandering of subtropical westerlies play a crucial role on the dynamical and structural changes in the ASMA in 2015.
- ❖ Strong enhancement in O_3 at 100 hPa (>40%) is clearly evident within the ASMA and particularly higher over the northeastern edges of the ASMA in July. The enhanced O_3 is strongly associated with a dominant southward meandering of the subtropical westerlies. In August, the increased O_3 is significantly located over the western edges of the ASMA. This clearly indicates the transport from the ASMA to the edges through its outflow.
- ❖ A significant lowering of CO and WV within the ASMA is clearly noticed during summer 2015. The lowering of WV is higher at 146 hPa than 100 hPa.
- ❖ Significant positive tropopause temperature anomalies (~5 K) is observed in the entire ASMA region in July whereas, in August, the strong positive anomalies are concentrated over the northeastern side of the ASMA.

The changes in the O_3 concentrations (increase/decrease) within the ASMA are one of the possible mechanisms to strengthening/weakening of the ASMA (Braesicke et al., 2011). By using idealized climate model experiments, Braesicke et al. (2011) clearly demonstrated that the strengthening (weakening) of the ASMA occurred when the O_3 is decreased (increased) within the ASMA. The increased O_3 within the ASMA warms the entire anticyclone region and weakens the ASMA (Braesicke et al., 2011). Our results from the present study also in agreement with the results of Braesicke et al. (2011). We also observed a pronounced increase of O_3 within the ASMA associated with significant warming of tropopause as well as above and below the tropopause region in 2015. By using precipitation index, wind data and stream functions, previous studies reported that the ASMA circulation in 2015 was weaker than the normal (Tweedy et al., 2018; Yuan et al., 2019). Based on our present results, the strongly enhanced O_3 within the ASMA also might be one of the plausible reasons for weakening of the ASMA in 2015.

Author contributions: SRB designed the study, conducted research, performed initial data analysis and wrote the first manuscript draft. MVR, GB, SKP and NHL edited the first manuscript. All authors edited the paper.

Data Availability: All the data used in the present study is available freely from the respective websites. The MLS trace gases data obtained from Earth Science Data website. The NCEP_Reanalysis 2 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their web site (http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm) The COSMIC data is available from COSMIC CDAAC website (http://cdaac-www.cosmic.ucar.edu/cdaac/products.html).

Competing interests: The authors declare that they have no conflict of interest.

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