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Influence of Indian Summer Monsoon on Tropopause, Trace Gases and Aerosols in Asian Summer Monsoon Anticyclone Observed by COSMIC, MLS and CALIPSO

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Abstract: The existence of the Asian Summer Monsoon Anticyclone (ASMA) during the summer in the northern hemisphere, upper troposphere and lower stratosphere (UTLS) region plays a significant role in confining the trace gases and aerosols for a long duration, thus affecting regional and global climate. Though several studies have been carried out, our understanding of the trace gases and aerosols variability in the ASMA is limited during different phases of the Indian monsoon. This work quantifies the role of Indian Summer Monsoon (ISM) activity on the tropopause, trace gases (Water Vapor (WV), Ozone (O₃), Carbon Monoxide (CO)) and aerosols (Attenuated Scattering Ratio (ASR)) obtained from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), Microwave Limb Sounder (MLS), Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite observations, respectively, during the period 2006–2016. Enhancement in the tropopause altitude, WV, CO, ASR and low tropopause temperatures, O₃ in the ASMA region is clearly noticed during peak monsoon months (July and August) with large inter-annual variability. Further, a significant increase in the WV and CO, and decrease in O₃ during the active phase of the ISM, strong monsoon years and strong La Niña years in the ASMA is noticed. An enhancement in the ASR values during the strong monsoon years and strong La Niña years is also observed. In addition, our results showed that the presence of deep convection spreading from India land regions to the Bay of Bengal with strong updrafts can transport the trace gases and aerosols to the upper troposphere during active spells, strong monsoon years and La Niña years when compared to their counterparts. Observations show that the ASMA is very sensitive to active spells, strong monsoon years and La Niña years compared to break spells, weak monsoon years and El Niño years. It is concluded that the dynamics play a significant role in constraining several trace gases and aerosols in the ASMA and suggested considering the activity of the summer monsoon while dealing with them at sub-seasonal scales.

Keywords: anticyclone; monsoon; temperature; water vapor; ozone; COSMIC; MLS; CALIPSO

1. Introduction

The Asian Summer Monsoon Anticyclone (ASMA) is one of the dominant circulation patterns in the Upper Troposphere and Lower Stratosphere (UTLS) region in the Northern Hemisphere (NH) persisting during summer and has a significant influence on the global atmospheric circulation [1]. During the peak monsoon months of July and August, the ASMA spans nearly half of the globe in its horizontal distribution stretching from west

Africa to western Pacific Ocean [2]. The ASMA is bounded by a westerly (easterly) jet in the north (south) side and prominent for a long duration of air confinement [3]. The location and shape of the ASMA vary at different time scales, i.e., inter-seasonal, inter-annual and longer time scales [2,4]. Previous studies reported the intensification and expansion of the South Asian High [5]. Although it is a strong and steady seasonal phenomenon, it varies at sub-seasonal time scales [6].

The features of the ASMA were studied extensively by several authors [7–9]. There are also studies focused on transport pathways for stratosphere–troposphere exchange (STE) during summer into the lower-most stratospheric layer and into the upward branch of Brewer–Dobson Circulation (BDC), particularly with regard to water vapor (WV) and pollutants [10–14]. The ASMA is characterized by persistent deep convection over the Bay of Bengal (BoB), north India and the South China Sea [11,15], surface heating over the Tibetan Plateau [16] and orographic uplifting over the south/south-west slants of the Himalayas, which contribute to an overall ascension of air to higher altitudes (up to ~200 to 100 hPa). Recent studies found an enhancement of aerosols near the tropopause in the anticyclone region named as the ‘Asian Tropopause Aerosol Layer (ATAL)’ [17,18]. The layer serves as a significant source for the stratospheric aerosols. A larger amount of CO, Carbonaceous aerosols (CA) and dust are found in the ASMA that resulted from the biomass burning and dust transport from the Middle East deserts through westerly winds. Upon entering in to the UTLS region, the pollutants are capped near the tropopause layer, advected and dispersed by the anticyclonic circulation [19]. Recent studies showed that the ASMA is composed of 40% sulphate, 30% secondary and 15% primary organic aerosols, 14% ammonium aerosols from Community Atmosphere Model (CAM5) and the MAM7 (Modal Aerosol Model) simulations [20]. The ATAL causes significant regional radiative forcing, which further causes the cooling of Earth’s surface and is, therefore, important for a more detailed assessment of climate [21].

Several studies reported the variability (day-to-day and long-term), transport of pollutants and tracers from the boundary layer to tropopause, formation of aerosols in the ASMA [22]. During the monsoon season, maximum rainfall occurs over India. Thus, small changes in these trace gases and aerosols can alter the tracer composition and thermodynamics of the anticyclone region. Basha et al. [2] reported the spatial variability of the ASMA during different phases of the Indian monsoon. However, the present study aims to demonstrate the variability of the tropopause altitude/temperature, Water Vapor (WV), Ozone (O₃), Carbon Monoxide (CO) and aerosols (Attenuated Scattering Ratio (ASR)) with respect to active and break days within monsoon season, strong and weak monsoon years and strong El Niño–Southern Oscillation (ENSO) years using long-term satellite measurements. Further, we have also studied the transport processes and convection variability during different phases of the monsoon. The rest of this paper is organized as follows. After a brief description of data and methodology (Section 2), we discussed the spatial mean variability and inter-annual variation of the tropopause altitude/temperature, WV, O₃, CO and ASR (Section 3). Focus is placed on the influence of the Indian monsoon on the spatial variability of tropopause parameters and tracers, ASR (Section 3). Finally, Section 4 summarizes and concludes the study.

2. Data Base

2.1. COSMIC GPSRO Observations

The tropopause altitude and temperature in the ASMA is obtained from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) Global Positioning System Radio Occultation (GPSRO) satellite. COSMIC GPSRO consists of six satellites launched in April 2006 into a circular orbit with an inclination of 72° to an altitude of 512 km [23]. The COSMIC satellite can track both the rising and setting of an occultation with an open loop tracking technique. This technique significantly lowers the RO inversion biases by removing tracking errors [24]. The GPSRO receiver measures the phase delay of radio wave signals that are occulted by the Earth’s atmosphere. The bending angle and

refractivity profiles can be derived from phase delay measurements. The temperature can be derived from refractivity observations with an accuracy of <0.5 K [25]. The temperature profiles compared very well with radiosonde, reanalysis and model data sets [26,27]. In the present study, we have used the COSMIC data during the period 2006–2016. The vertical resolution of COSMIC GPSRO data varies from 100 to 300 m. However, we have interpolated the temperature profile to 200 m vertically. The lapse rate tropopause is utilized for studying the tropopause variability [28–32].

2.2. Microwave Limb Sounder (MLS) Measurements

For understanding the distribution of trace gases in the ASMA, we make use of MLS measurements. The MLS uses the limb sounding technique for measuring the WV, O₃, CO and other tracers in the UTLS region. This satellite was launched as a part of NASA's Earth Observing Systems onboard the Aqua spacecraft in August 2004. The MLS scans limb vertically in the orbit plane and gives a latitude coverage ranging from 82°N to 82°S. In the present study, MLS data of version 4.2 WV, O₃ and CO mixing ratios were utilized. The MLS WV has a precision of 0.4 ppmv for individual profile measurements at 100 hPa level [32]. The vertical resolution of the WV in the lower stratosphere is about 3 km [33]. The O₃ has a vertical resolution of 3 km at 100 hPa [33]. The CO has a root mean square precision of 20 ppbv at 100 hPa with a possible bias of ± 20 ppbv. Refer to Livesey et al. [33] for more details about version 4.2 of MLS data.

2.3. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Stratospheric Aerosol Data

In order to understand the aerosol distribution in the ASMA region, we considered the CALIPSO measurements. The CALIPSO was launched in April 2006 at an inclination of 98.2° to an altitude of 705 km to a sun-synchronous polar [34]. The CALIPSO satellite crosses the equator nearly at 01:30 and 13:30 h with a repetitive rate of 16 days [34]. The CALIOP was one of the main instruments of CALIPSO with a dual-wavelength of 532 nm and 1064 nm of CALIPSO satellite. CALIPSO satellite provides the vertical distribution backscatter coefficient and extinction coefficient. The monthly gridded level three stratospheric profile data (ASR) were used in this present study (https://eosweb.larc.nasa.gov/project/calipso/cal_lid_l3_stratospheric_apro-standard_v1-00 accessed on 15 July 2017). These profiles are available from 8.2 to 36.2 km with 900 m vertical resolution in the tropical latitudes. We have gridded all the data sets to $2.5^\circ \times 2.5^\circ$ grid from their native resolution.

We have also used geopotential height (GPH), zonal, meridional and vertical winds from National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis data for interpretation of various aspects of the ASMA [35]. In addition, outgoing longwave radiation (OLR) from the US National Oceanic and Atmospheric Administration (NOAA) is examined as a proxy for convection. The OLR values less than 200 W/m² considered for deep convection. The interpretation of figures with respect to NCEP reanalysis data should be conducted with caution. Further, from the India Meteorological Department (IMD) high-resolution ($0.25^\circ \times 0.25^\circ$) gridded precipitation data, we have identified the active and break phases during June, July and August from 1951 to 2016 [36]. The active and break days are derived based on daily rainfall data in the monsoon core zone (18 to 28°N and 65 to 88°E) of India during July and August [36]. The normalized anomalies are derived from the average daily rainfall then subtracted from its long-term (1951–2000) mean and dividing by its daily standard deviation [36]. From the normalized anomaly when rainfall is greater (less) than -1.0 ($+1.0$) for three consecutive days or more, the active (break) phases were identified. We have selected the strong El Niño (2015) and La Niña (2007, 2010) from the website <https://ggweather.com/enso/oni.htm> (accessed 15 on July 2017) for studying the variability in the tropopause parameters, tracers and aerosols.

3. Results and Discussion

3.1. Climatological State of ASMA during Summer Monsoon

The climatological GPH superimposed with wind vectors at 100 hPa obtained from NCEP/NCAR reanalysis data during July and August months from 2006 to 2016 is shown in Figure 1. A strong anticyclonic flow is evident from the figure that lies between $\sim 22.5\text{--}40^\circ\text{N}$ and $30\text{--}120^\circ\text{E}$ in the NH. The area with the highest GPH (in red) displays the ASMA region. The intensity of the anticyclone is large exactly over the Tibetan Plateau. The wind vectors clearly represent the anticyclone circulation, which isolates air from its surroundings. The climatological mean (July and August averaged from the year 2006–2016) spatial distribution of tropopause altitude/temperature from COSMIC, the WV, O_3 and CO from MLS at 100 hPa and the ASR from CALIPSO averaged in the range of 15–18 km along with wind vectors at 100 hPa from NCEP reanalysis data is presented in Figure 2. The brown line represents the 16.75 km GPH value at 100 hPa, which represents the core of the anticyclone [2]. Higher tropopause altitude, WV, CO and low tropopause temperature and O_3 are evident within the ASMA. Globally the highest tropopause altitude is observed over the ASMA region, which is balanced by a dynamical structure tied to the strong anticyclonic circulation [37]. The tropopause height reaches a maximum altitude of about $\sim 18\text{--}18.5$ km in the south-west of the ASMA. Conversely, the minimum temperature exists over the BoB and southern parts of India compared to the anticyclone region (Figure 2b). The tropopause temperature shows low values in the monsoon core region compared to the anticyclone region. WV increases spatially at 100 hPa in the anticyclone region during the summer monsoon (referred as July and August months) as shown in Figure 2c. Over the Tibetan Plateau, i.e., north-east of the anticyclone, a large amount of WV is noticed. Within the anticyclone, CO has a broad maximum toward the south and south-west of the anticyclone, which coincides with the low values of O_3 . The increase/decrease in trace gases in the ASMA is due to the bulging of the tropopause altitude [38]. Figure 2f shows the clear enhancement in the aerosols in the middle and southern parts of the ASMA. These signatures clearly represent the existence of aerosols in the ASMA (ASR values in the range of 1–1.15). There is a clear offset between the trace gases, aerosols distribution and the core of the anticyclone [39].

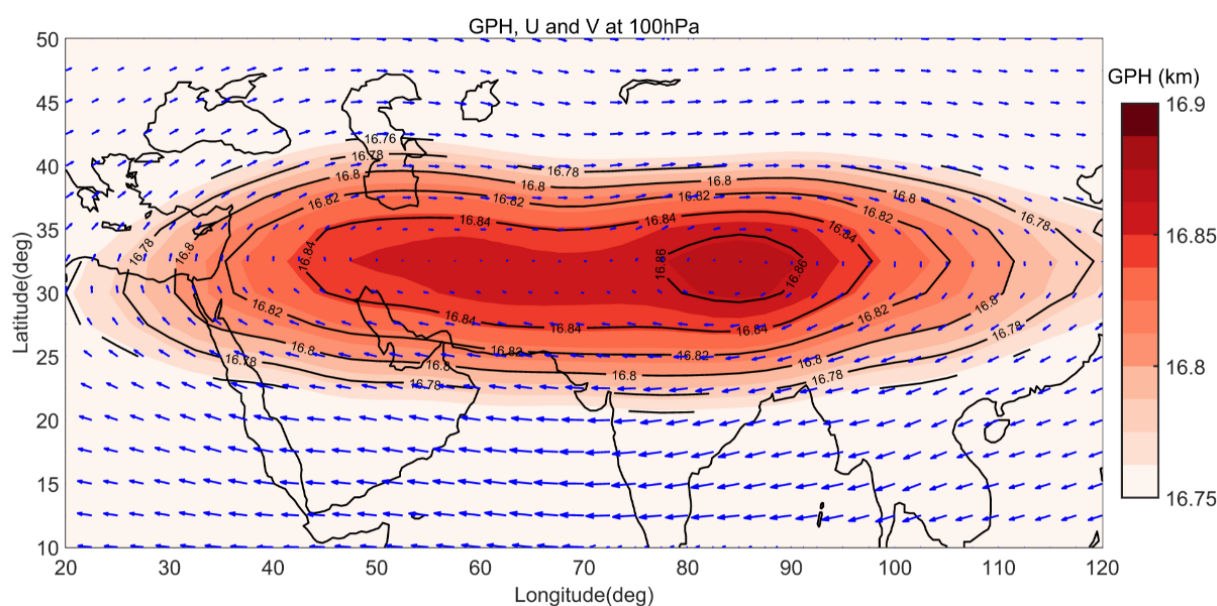


Figure 1. Mean GPH superimposed with wind vectors at 100 hPa from NCEP/NCAR reanalysis data during July and August months averaged from the year 2006–2016. The area with GPH values ranging from 16.75–16.9 km is considered as an anticyclone region.

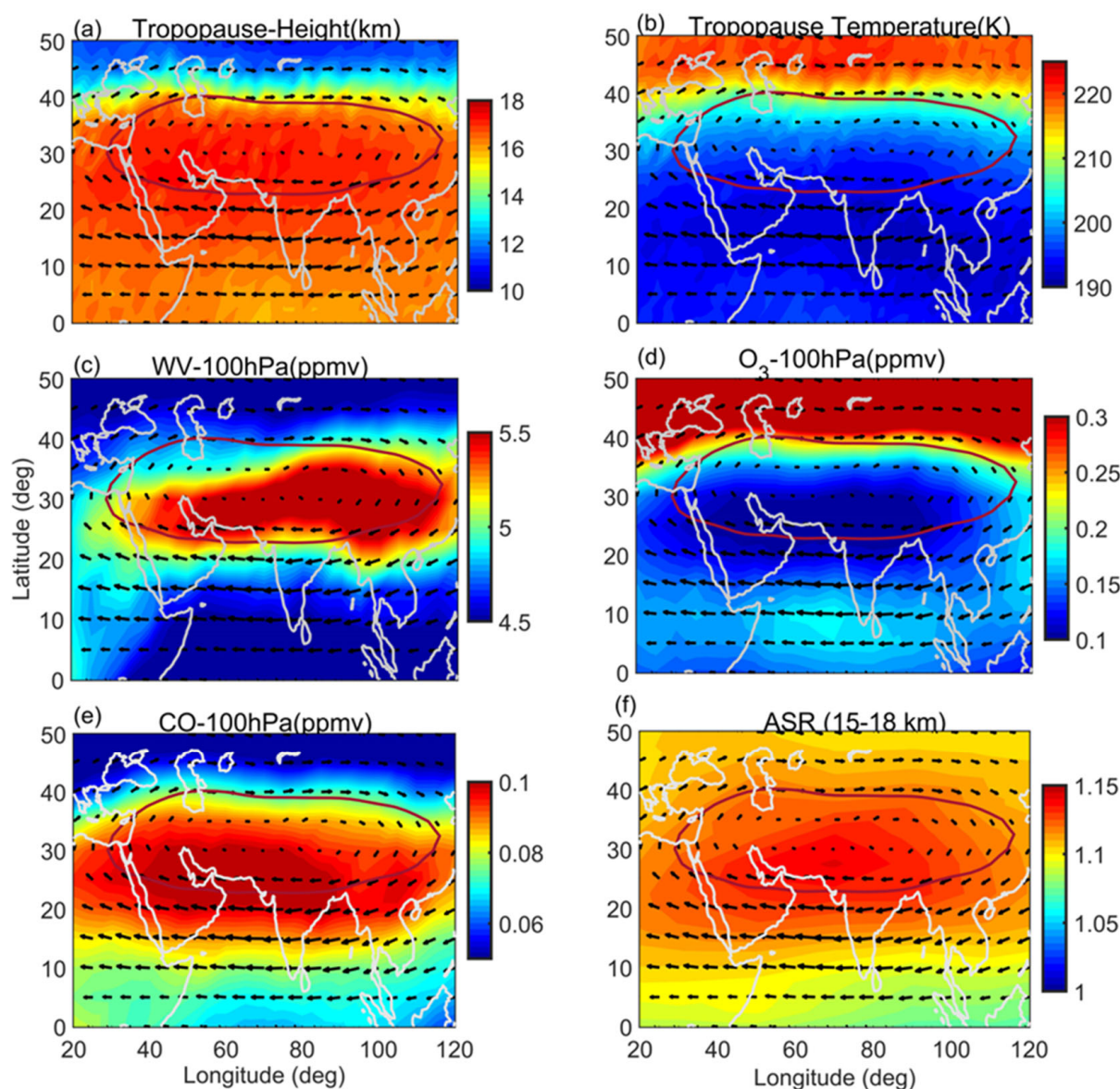


Figure 2. Spatial mean distribution of (a) tropopause altitude and (b) tropopause temperature obtained from COSMIC satellite observations, (c) Water Vapor (WV), (d) Ozone (O_3) and (e) Carbon monoxide (CO) obtained from MLS satellite data at 100 hPa and (f) Attenuation Scattering Ratio (ASR) from CALIPSO stratospheric aerosol product averaged between 15–18 km altitudes. All the data sets were obtained during July and August and superimposed with wind vectors of 100 hPa obtained from NCEP/NCAR reanalysis data during 2006–2016. The brown line indicates the GPH contour line at 16.75 km, which represents the anticyclone.

Figure 3 shows the monthly mean vertical variation of the UTLS temperatures, WV, O_3 , CO and ASR averaged over the anticyclone region (in the grid of 30–110°E longitude and 22.5–40°N latitude of Figure 2) for the period 2006–2016, superimposed with tropopause altitude. Significant seasonal variability is observed in all the parameters (Figure 3). The coldest temperatures are noticed in the range of 15–18 km throughout the year. During July and August, very low temperatures are observed compared to other months with the highest tropopause altitude. The tropopause altitude starts increasing from the month of April and reaches its peak in August, whereas the temperature starts decreasing in April and reaches a minimum in July. The lowest tropopause temperatures are observed exactly above the tropopause altitude during June–July, whereas WV shows a peak during August. Similarly, a low O_3 and higher WV and CO are noticed in July and August. Further, O_3 reaches its minimum in September and CO in July. The tropopause altitude and WV

show a maximum during August, whereas O_3 is lowest during September. The most striking feature is the tape recorder signal observed in the anticyclone region from the monthly mean distribution of water vapor at stratospheric altitudes. This effect explains the seasonal cycle of water vapor that is imposed on air entering the stratosphere and is then transported upwards by the Brewer–Dobson circulation [40]. Above the tropopause, an enhancement in the aerosols is observed, which indicates that air enters into the lower stratosphere through the anticyclone region [2].

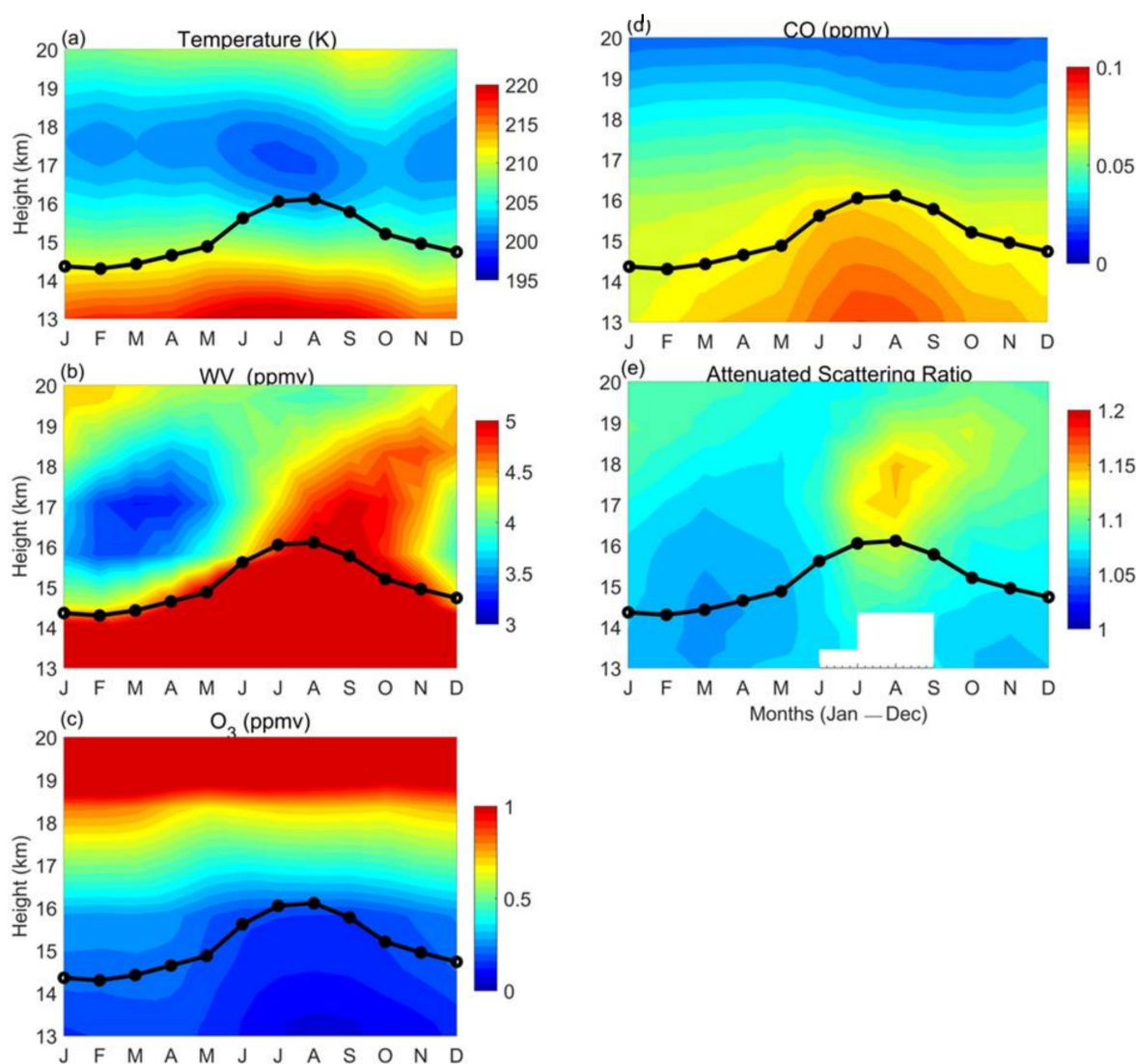


Figure 3. Time–height section averaged in the grid 30–110°E longitude and 22.5–40°N latitude of monthly mean (2006–2016) (a) temperature obtained from COSMIC, (b) Water Vapor (WV), (c) Ozone (O_3) and (d) Carbon monoxide (CO) obtained from MLS satellite and (e) Attenuation Scattering Ratio (ASR) from CALIPSO stratospheric aerosol product. The white patch in ASR values in June, July and August is due to monsoon clouds where CALIPSO signal does not penetrate to the lower altitudes. The black line denotes the tropopause altitude derived from COSMIC satellite data during the same period.

Figure 4 shows the interannual variation in the temperature, WV, O_3 , CO and ASR averaged in the anticyclone region along with the volcanic explosivity index (VEI). The lowest values in temperature are observed between 16 and 18 km in the anticyclone region. Both the temperature and tropopause altitude show considerable inter-annual variation. This variation is much more pronounced in the WV, O_3 and CO. There is a clear relationship between the tropopause altitude and the tracers in the anticyclone region. The tape recorder effect is clearly observed in the inter-annual variation of the WV obtained from the MLS

data in the anticyclone region, which represents large-scale upward transport [40]. The peak values of the ASR are observed during July and August every year.

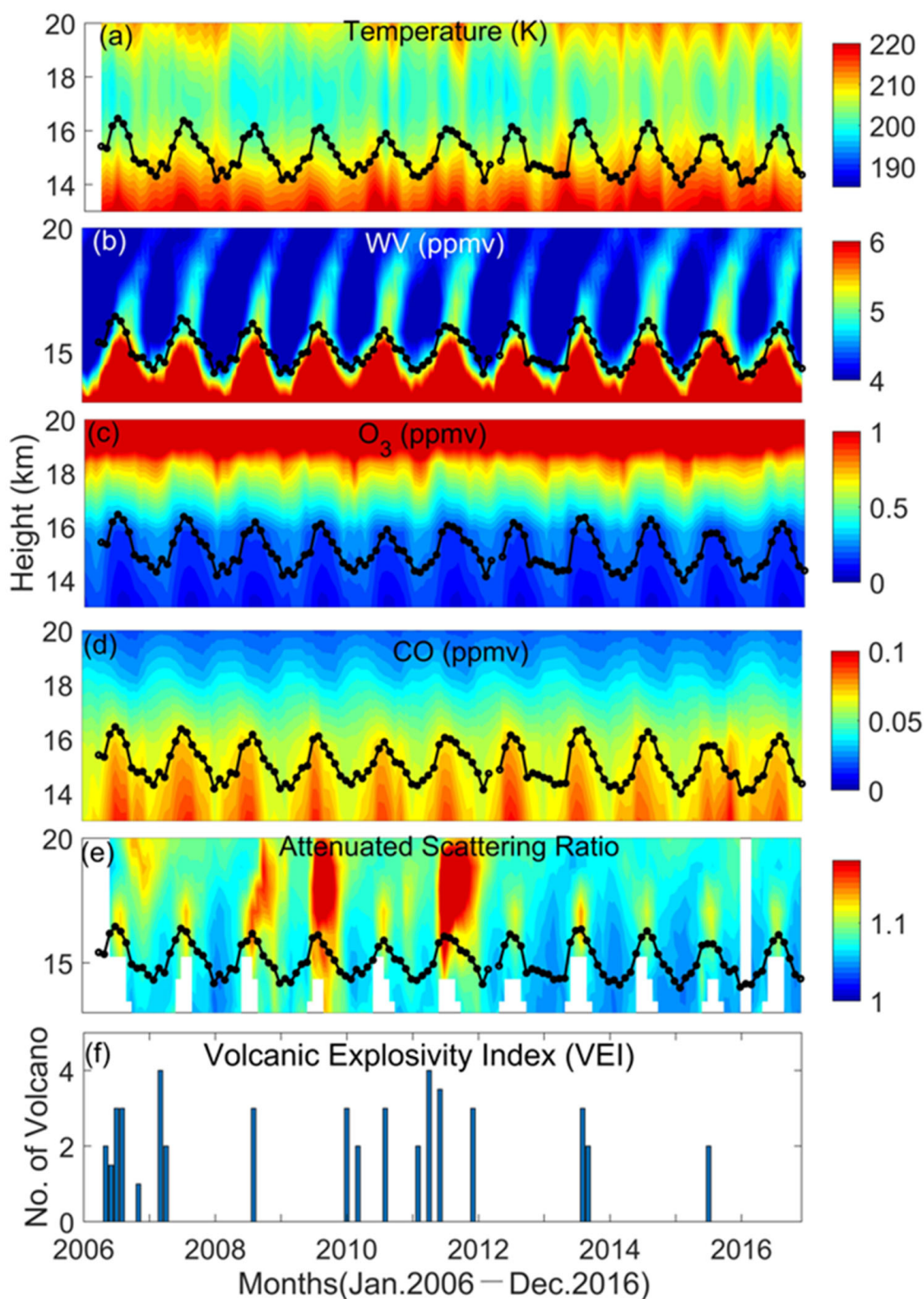


Figure 4. Inter-annual variation observed in (a) temperature, (b) Water Vapor (WV), (c) Ozone (O₃), (d) Carbon monoxide (CO) obtained from MLS satellite data and (e) Attenuation Scattering Ratio (ASR) from CALIPSO averaged in the grid 30–110°E longitude and 22.5–40°N latitude from 2006–2016. (f) Volcanic explosivity index. The black line denotes tropopause altitude derived from COSMIC satellite measurements.

Due to a volcanic eruption in August 2008, volcanic aerosols were transported towards Asia from Okmok. On 7th June 2009, the Sarychev volcano (Russia) injected 1 Tg of SO₂ into the lower stratosphere. Due to this volcano, huge values of the ASR are found during the years 2009. Similarly, in 2011, Nabro, a stratovolcano in northeast Africa, erupted on 12 June 2011; these signals are also observed in the inter-annual variation of the ASR. This was supported by the VEI, which is a measure of the explosiveness of a volcanic eruption (Figure 4f).

3.2. Influence of Asian Summer Monsoon Activity

The Indian monsoon varies at different time periods, i.e., at daily, sub-seasonal, inter-annual, decadal and centennial scales [36]. During monsoon season, rainfall varies at intra-seasonal time scales between active (high rainfall days) and break (low rainfall days) spells. Thus, any small change in the rainfall pattern will affect the tracer composition in the anticyclone due to the thermodynamics involved in it. In this section, we examined the variability of tropopause altitude/temperature, WV, O₃ and CO during the active and break spells of the ISM in the anticyclone region. The identification of active and break spells was discussed in the data section. The composite mean picture of the tropopause altitude, temperature, WV, O₃ and CO during the active and break spells is illustrated in Supplementary Figure S1. An enhancement in the tropopause altitude, WV and CO and decrease in the tropopause temperature and O₃ are evident during active spells. A clear distinction in the spatial variation of the WV and CO is observed between the active and break spells in the ASMA. The spatial mean difference between the active and break spells in different parameters are represented in Figure 5. The brown color line indicates the 16.75 km GPH, which represents the core anticyclone region.

The scattered pattern (increasing and decreasing) is noticed in the spatial variability of tropopause height/temperature in the mean difference between active and break spells. The increase/decrease in tropopause altitude/temperature is observed over the BoB during active days. A decrease in O₃ is depicted over the east and south, whereas CO shows enhancement over the north-east and the head of the BoB. These anomalies in different variables are related to deep convective activity over the BoB region, which is discussed in Figure 6. The latitude–height cross-section (averaged in the longitude band of 60–120°E), longitude–latitude cross-section (averaged in the latitude band of 15–35°N) of Outgoing Longwave Radiation (OLR) and the vertical wind during the active and break spells is shown in Figure 6. The OLR serves as a proxy for convection and low values in OLR over the monsoon regions represent deep moist convection, whereas high OLR values indicate a scarcity of cloud cover. Negative (positive) vertical wind represents updrafts (downdrafts). The spatial distribution of convection is dominant over central India the northern part of the BoB, and the west coast of India. Moreover, during active spells, the convection tends to deepen. During break spells, deep convection is not significant over the Indian land mass while it is still significant over the BoB, and the Tibetan Plateau is less affected. Accordingly, strong updrafts are being noticed over the BoB, irrespective of the monsoon activity. The longitude–height cross-section shows the ascending motion (vertical transport) from the surface to the upper troposphere covering land region during active spells, while the transport process shifts completely towards the ocean region (80–100°E) in break spells (Figure 6b,e). Although the active spells occur less frequently than break spells, they may have a larger bearing on the composition of the Tropical Tropopause Layer within the ASMA. Particularly, the anthropogenic pollution that will be dominant over the central/northeast of India and these air masses may reach the TTL during active spells and from the head of the BoB during both active and break spells.

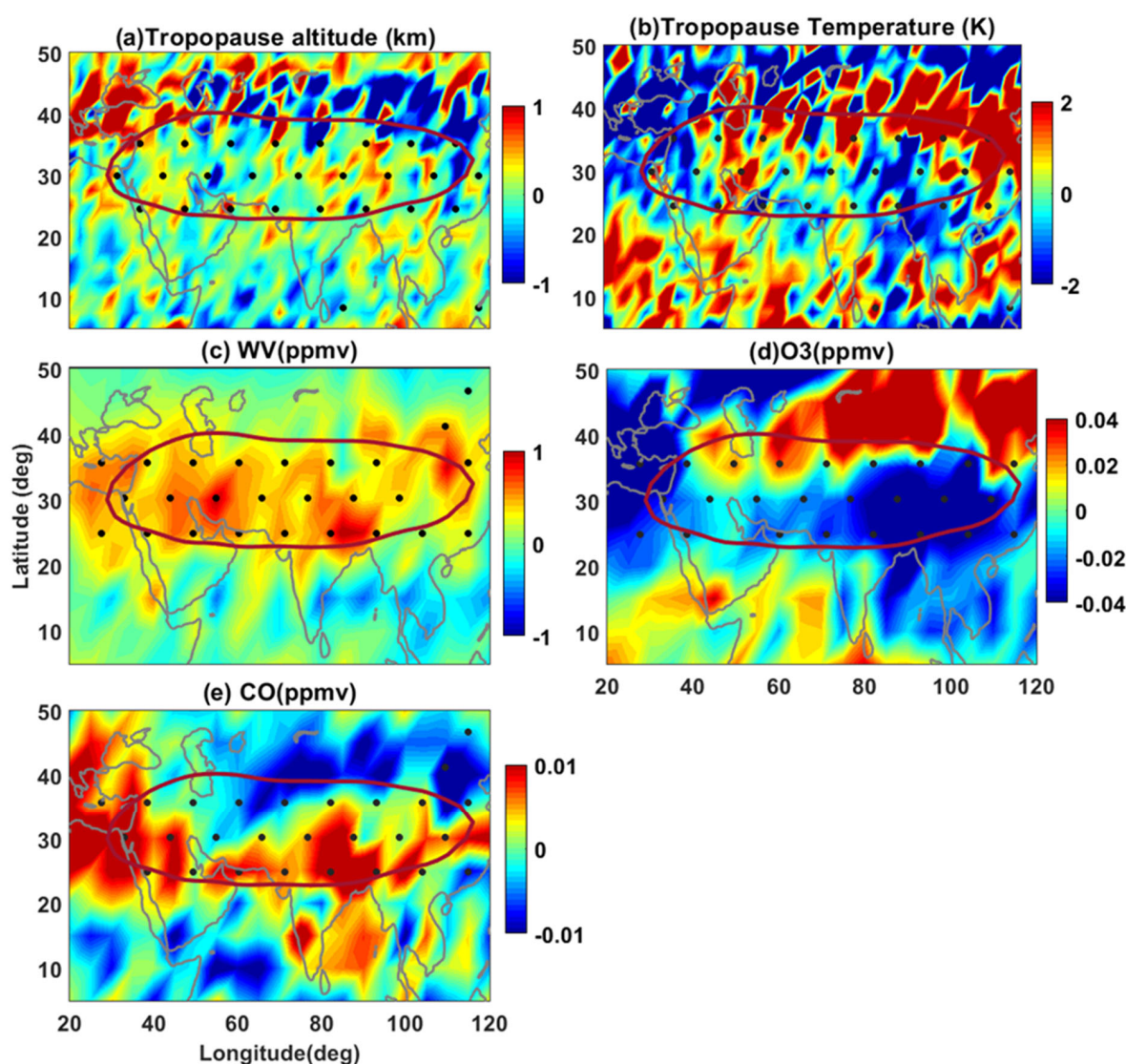


Figure 5. Longitude, latitude section of the mean difference between active and break spells observed in the (a) tropopause altitude (km), (b) tropopause temperature (K), (c) Water Vapor (WV), (d) Ozone (O_3) and (e) Carbon monoxide (CO) obtained from MLS satellite data at 100 hPa. Brown line denotes the GPH at 16.75 km, which represents the core of the anticyclone. Star marks (black colour) indicates grids with 90% confidence level. The star marks (black color) represent the 90% confidence level, which is determined at each grid point and was computed by using Student's *t*-test.

The strong and weak monsoon years are obtained based on IMD rainfall ($0.25^\circ \times 0.25^\circ$ grid) data from 2006 to 2016. We have chosen the domain ($5\text{--}30^\circ\text{N}$, $70\text{--}95^\circ\text{E}$) to identify the strong and weak monsoon years [41]. The mean precipitation over the selected domain during July and August is subjected to de-trend analysis. The strong (weak) monsoon years were identified where rainfall was above (below) the one standard deviation. The strong (weak) monsoon years were 2010, 2011, 2013 (2014, 2015). The spatial mean composite picture for various parameters during the strong and weak monsoon years is shown in Supplementary Figure S2. The strong monsoon years clearly represent the higher WV, CO and ASR, whereas this feature is absent in weak monsoon years. The averaged spatial difference among strong and weak monsoon years in all the parameters is shown in Figure 7. In the ASMA region, the tropopause altitude and temperature show a moderate increase and decrease, respectively. The WV, CO and O_3 show significant (at 90% confidence level shown with green dots) changes in the anticyclone region. The WV and CO increase significantly during the strong monsoon years where O_3 decreases. Strong updrafts are observed in the latitude–altitude cross-section during strong monsoon

years (Supplementary Figure S4a). A similar pattern is observed in weak monsoon years, however with less magnitude (Supplementary Figure S4d). In the case of the longitude–altitude cross-section, the updrafts are stretched from 65–100°E, i.e., over the land region where the deep convection exists (Supplementary Figure S4b,c). The strong updrafts are observed over 82–100°E during weak monsoon years. Compared to weak monsoon years, convection dominates during strong monsoon years over the land region, which can transport trace gases and aerosols to the upper troposphere. An increase in WV above the tropopause over eastern part of India is evident due to the convective transport that reduces the O₃ values drastically. An increase in the ASR is noticed over the north of the anticyclone region. It can be noticed that aerosols are confined to the NH in the latitude band of 30–40°N.

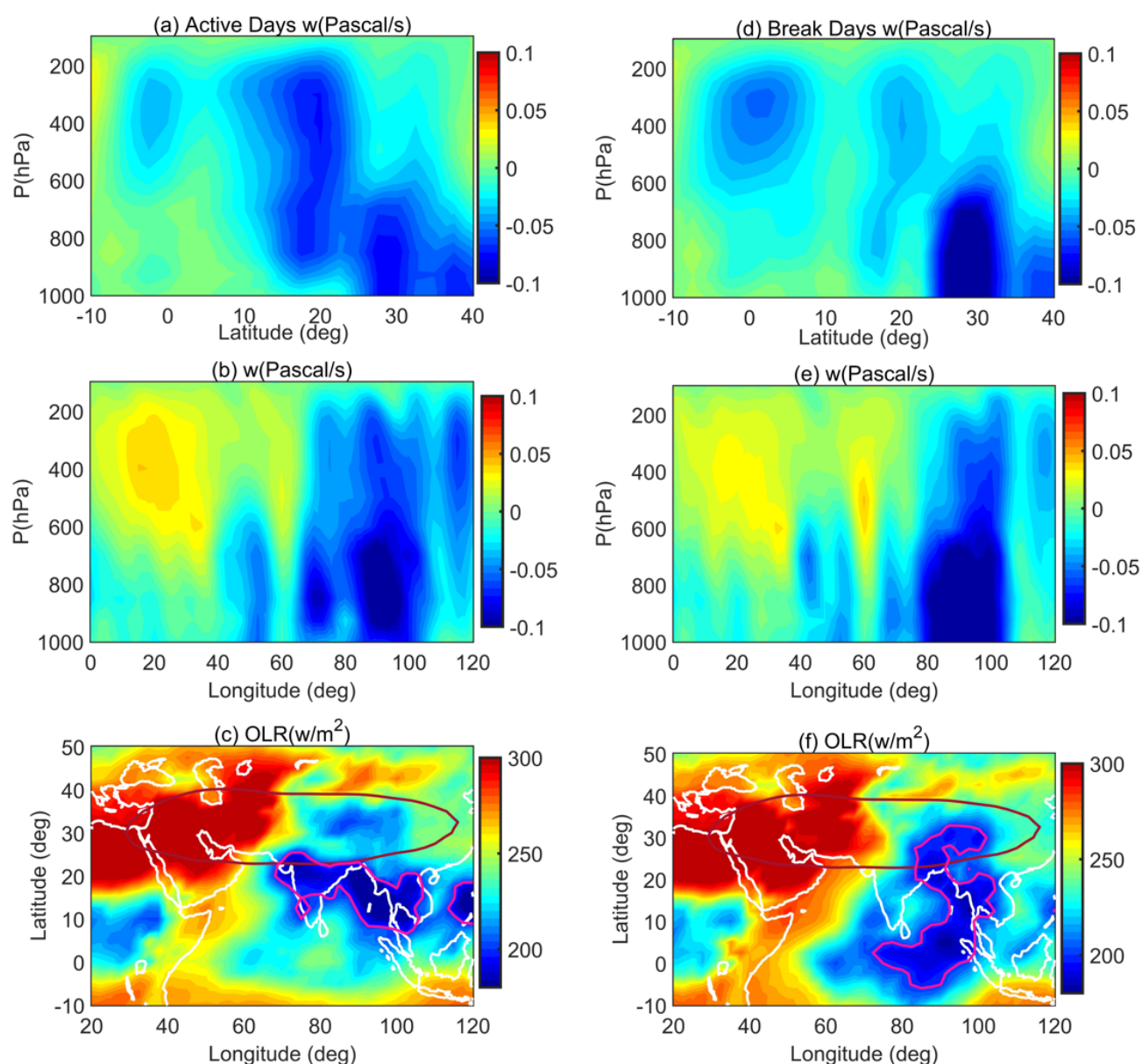


Figure 6. Variability of vertical wind and OLR during active and break days. (a,d) Latitude–pressure cross-section of vertical wind averaged in the longitude band of 60–120°E. (b,e) Longitude–pressure cross-section of vertical wind averaged in the latitude band of 15–35°N. (c,f) Latitude–longitude section of the OLR during active and break days. Brown line denotes the GPH at 16.75 km, which represents the core of the anticyclone. Magenta line indices the OLR values less than 200 W/m².

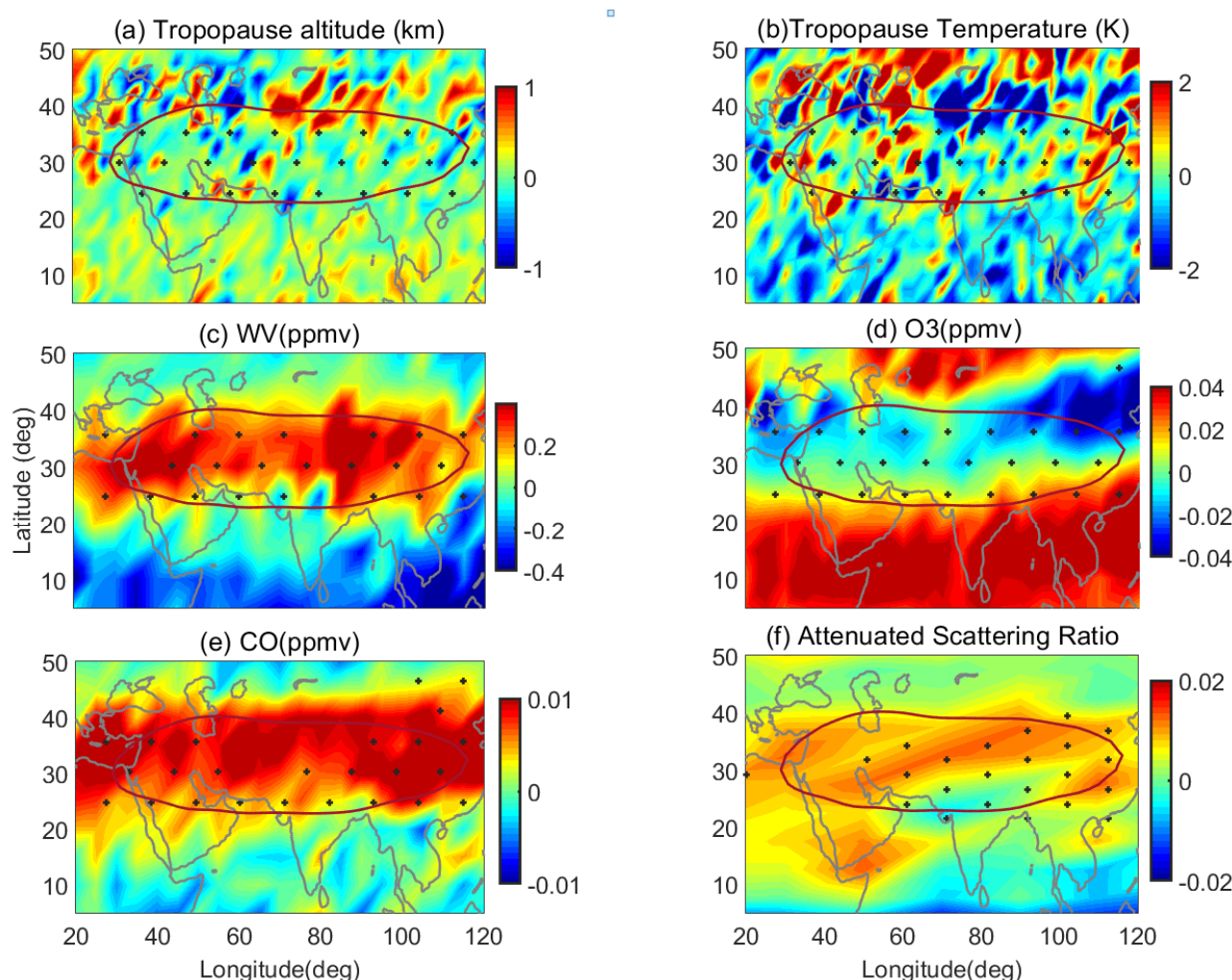


Figure 7. Longitude, latitude section of the mean difference between strong and weak monsoon years in the (a) tropopause altitude, (b) tropopause temperature, (c) Water Vapor (WV), (d) Ozone (O_3), (e) Carbon monoxide (CO) at 100 hPa and (f) Attenuation Scattering Ratio (ASR) from CALIPSO averaged between 15–18 km from 2006 to 2016 at 100 hPa. Brown line denotes the GPH at 16.75 km, which represents the core of the anticyclone. Star marks (black color) indicates grids with 90% confidence level.

Further, it is well known that ENSO influences the Indian summer monsoon—the large-scale circulation pattern that brings the Indian subcontinent the vast majority of its annual rainfall. In this study, we discuss the spatial mean difference between La Niña (2007, 2010) and El Niño (2015) years in tropopause parameters, trace gases and aerosols. The strong ENSO years are selected from the website <https://ggweather.com/enso/oni.htm> (accessed on 15 July 2017). In addition, we have obtained only one year for El Niño and this year also corresponds to a weak monsoon year. The spatial composite mean picture during La Niña and El Niño and the differences are represented in Supplementary Figure S3 and Figure 8. The increase in tropopause altitude and decrease in tropopause temperature is clearly evident during strong La Niña years (Figure 8a,b). The increase in WV and CO and the decrease in O_3 is large compared to strong monsoon years. The ASR also increases in the strong La Niña compared to the El Niño years. Similar features are observed during La Niña (El Niño) years as that of strong (weak) monsoon years in the case of vertical transport and convection (Supplementary Figure S5). Strong convection exists over land region during La Niña years, which transports (strong updrafts in the vertical wind) a large amount of trace gases and aerosols to the upper troposphere (Supplementary Figure S5c). Deep convection occurs over the Indian subcontinent and over the BoB that transports a

large amount of WV and CO into the upper troposphere. The enhanced aerosols present above the tropopause altitude suggest that air enters the stratosphere within the anticyclone region during La Niña and strong monsoon years. The increase in ASR values may be attributed to the dry aerosols through nucleation processes [20]. In recent times, the increase in forest fires transports the pollutants to the ATAL region and enhances the aerosol concentration, which will have climate changes effects [4,42,43]. Thus, ISM activity plays an important role on the ASMA and, hence, on its tracers and aerosol distribution. Our results support the issue that has been discussing by several authors on the importance of the convection and transport of air masses into the upper troposphere process over the Indian region [44–48].

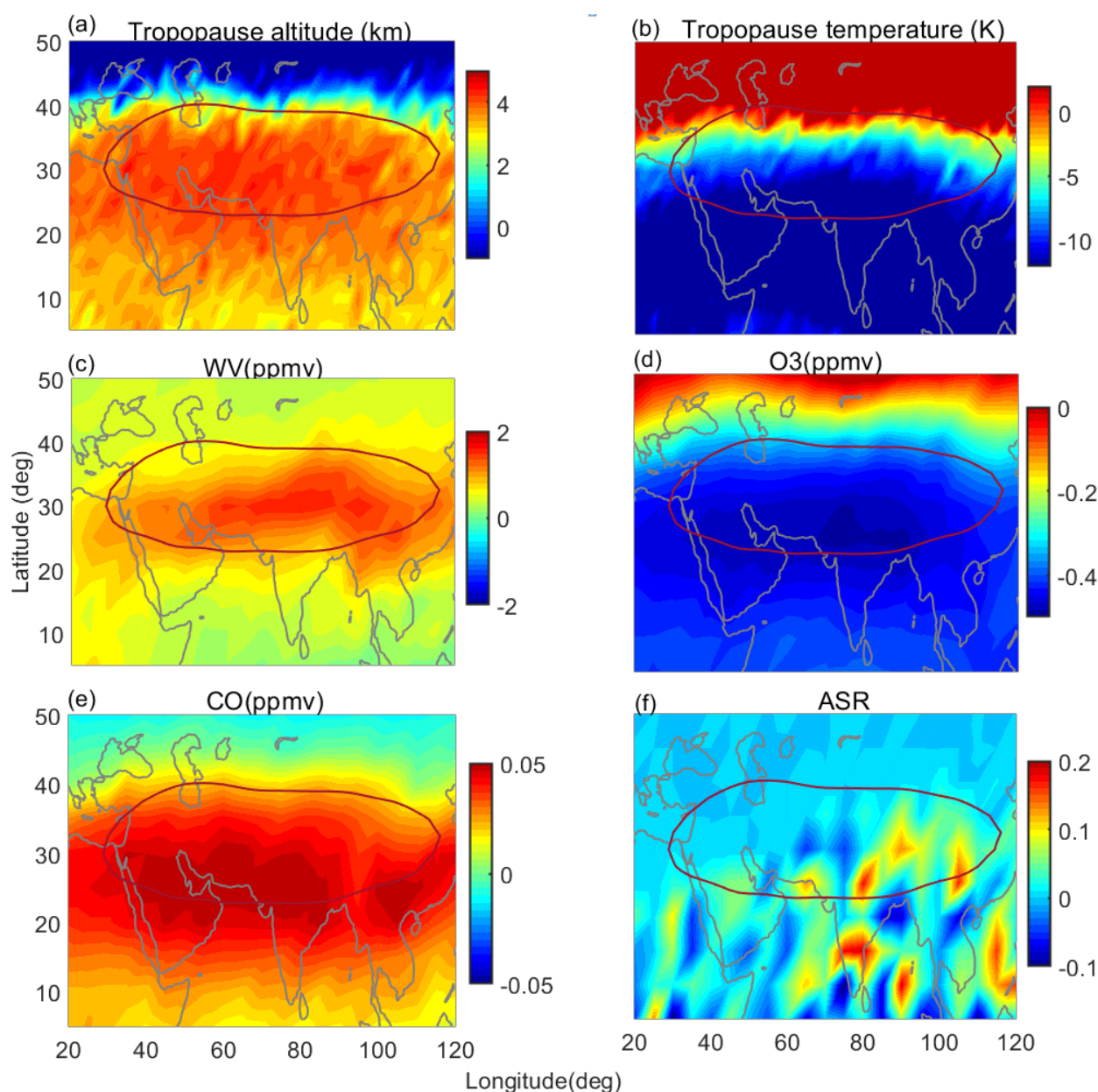


Figure 8. Longitude, latitude section of the mean difference between La Niña and El Niño in (a) tropopause altitude, (b) tropopause temperature, (c) Water Vapor (WV), (d) Ozone (O_3), (e) Carbon monoxide (CO) at 100 hPa and (f) Attenuation Scattering Ratio (ASR) from CALIPSO averaged between 15–18 km from 2006 to 2016 at 100 hPa. Brown line denotes the GPH at 16.75 km, which represents the core of the anticyclone.

4. Summary and Conclusions

It is well known that the ASMA is a large-scale dominant feature in the NH during monsoon season in the UTLS region. The weak winds of the ASMA act to isolate air from the surrounding areas that affect the tropopause parameters, tracers and aerosols observations in the ASMA in the UTLS region. The spatial distribution of these parameters shows a distinct maximum/minimum in the ASMA during the ISM months (July and August). Over the Indian region, maximum rainfall occurs during the monsoon, which alters the tracer composition and thermodynamics that are transported to the higher altitudes. Further, the amount of rainfall that occurs depends upon the different phases of the Indian monsoon (active days, strong monsoon years and during La Niña years). Therefore, in this present study, we investigated the changes in the tropopause parameters, tracers and aerosols variability during the different phases of the ISM, i.e., active and break spells, strong and weak monsoon years and strong ENSO years. The main highlights of the present study are summarized below.

1. Strong seasonal variability is observed in all the parameters in the ASMA. Enhancement in the WV, CO and ASR and decrease in the tropopause temperature and O₃ are found exactly below the tropopause altitude. During 2008, 2009 and 2011, higher ASR values are present above the tropopause altitude, which corresponds to moderate volcanic eruptions.
2. The tropopause altitude and tropopause temperature in the ASMA during the monsoon season show an increasing and decreasing pattern, respectively. This increase and decrease are not observed clearly during active spells and in strong monsoon years, whereas, during La Niña years, a clear increase (decrease) in the tropopause altitude (temperature) is observed.
3. In the ASMA region, an enhancement in the WV and CO and decrease in O₃ are observed during active spells, strong monsoon years and during strong La Niña years (Figures 5, 7 and 8) when compared to their counterparts.
4. The convection during active spells, strong monsoon years and during strong La Niña years is dominant, and spatially homogenized over land region compared to the ocean with strong updrafts that transport large amounts of rich moisture air and ozone poor air to the upper troposphere. Irrespective of the monsoon activity, deep convection is noticed over the BoB. Thus, vertical transport is possible throughout the monsoon season through strong updrafts (deep convection) from this region. During the pre-monsoon season, burning of agricultural waste and forest clearing is common in major places of Southeast Asia, which releases huge CO emissions. The CO can be easily transported to higher altitudes with the existence of ascending motion over the monsoon region.
5. The ASR is large during the strong monsoon years and during strong La Niña years in the ASMA region. During strong La Niña and strong monsoon years, the aerosol layer that existed at top of the tropopause altitude provides evidence that boundary air enters into the stratosphere within the ASMA. It is noticed that aerosols are confined to the NH in the latitude band of 30–40°N.

It is clear that the tracers and aerosols in the ASMA are significantly impacted by the transport processes of moisture and pollutants during the different phases of the Indian monsoon. Thus, it is prudent to conclude that monsoon activity needs to be considered while estimating the radiative forcing due to these tracers and aerosols within the ASMA region.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/rs13173486/s1>, Figure S1: Composite mean spatial variability, tropopause height, temperature, WV, O₃, CO during active (top panel) and break days (bottom panel) of Indian monsoon, Figure S2: Composite mean spatial variability tropopause height, temperature, WV, O₃, CO and ASR during strong monsoon (top panel) and weak monsoon years (bottom panel) of Indian monsoon; Figure S3: Composite mean spatial variability tropopause height, temperature, WV, O₃, CO and ASR during La

Niña (top panel) and El Niño (bottom panel) of Indian monsoon; Figure S4: Variability of vertical wind and OLR during strong and weak monsoon years; Figure S5. Variability of vertical wind and OLR during La Niña and El Niño years.

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