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Influence of background dynamics on the vertical distribution of trace gases (CO/WV/O$_3$) in the UTLS region during COVID-19 lockdown over India

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ABSTRACT
The COVID-19 pandemic lockdown has led to the significant reductions in the pollutant levels across the globe. Several studies have been carried out for examining and quantifying the improvement in the air quality due to the reduction of the pollution at the surface. Unlike most of the studies carried out earlier on COVID-19 lockdown, this study investigates the role of the dynamics on the vertical distribution of the trace gases (Carbon monoxide (CO), Water Vapor (WV) and Ozone (O$_3$)) over India in the Boundary Layer (BL), Middle Troposphere (MT) and Upper Troposphere (UT) during COVID-19 lockdown using satellite observations and re-analysis data products obtained during 2010–2020. Substantial differences in the time series and variability have been observed over different zones of India in different atmospheric layers. The changes observed in these species are large over Central India compared to South India and Indo-Gangetic plain regions. An enhancement in CO (~25–40%) and WV (50–60%) has been noticed over Central India in the UT at 147 hPa and 215 hPa, respectively, during lockdown. The strong updrafts before the lockdown and the extended weak zonal wind aloft over this region are found responsible for the observed enhancement in these trace gases in the UT. In spite of the non-availability of the anthropogenic pollution during the lockdown, this study highlights the transport of pollutants through long-range transport (always present even before lockdown) dominance over the Indian region not only near the surface but also aloft due to associated atmospheric dynamics.

1. Introduction
Many countries have taken preventive measures to restrict the spread of the Corona Virus Disease 2019 (COVID-19) pandemic by imposing lockdown. The Government of India had also imposed a strict nationwide lockdown from 25 March-14 April 2020 (Phase 1). The lockdown imposed has been extended further till 31 May 2020 with additional lockdowns with some relaxations in Phase 2 (15 April-3 May), Phase 3 (4–17 May) and Phase 4 (18–31 May), respectively (Jain et al., 2021). During the lockdown, close to 95% of the industries and transportation in India have been suspended except for essential and emergency services. Though the lockdowns have been for short periods and temporary, they have shown significant impact on the air quality especially in the pollution hotspots like urban environments (Bauwens et al., 2020; Berman and Ebisu, 2020; Fan et al., 2020; Nakada and Urban, 2020; Shi and Brasseur, 2020; Xu et al., 2020). Overall a reduction in the range of 15–50% in criteria pollutants considered for calculating the air quality is noticed resulting in the significant improvement of the same (Sharma et al., 2020; Singh et al., 2020). However, Venkat Ratnam et al. (2021b) observed 50–60% enhancement in AOD over central India during the lockdown and attributed to the long-range transport of aerosol and prevailing dynamical conditions. This observation was further supported using WRF-Chem model simulations (Venkat Ratnam et al., 2021c) where an elevated aerosol layer was noticed.

The studies conducted so far have mainly addressed the lockdown influence on the surface pollutants. However, the vertical extent of these chemical constituents also becomes important because of their transport to the higher altitudes. For example, knowledge on the vertical distribution of the Carbon monoxide (CO), Water Vapor (WV), Ozone (O$_3$) and aerosols is important because of their involvement in the troposphere chemistry. They have strong radiative and thermo-dynamical effects (Imran and Nair, 2014; Lal et al., 2014; Venkat Ratnam et al., 2021a; Satheesh et al., 2009). CO which is produced by the incomplete combustion processes of industry, biomass burning (Holloway et al., 2000) plays a crucial role in the formation of troposphere ozone (Kondratyev and Varotsos, 2001; Novelli et al., 1998) by reacting with OH radicals and influencing the NO to NO$_2$ conversion mechanisms. Several studies have been carried out to investigate and understand vertical variability

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of ozone using in-situ ozonesonde observations, re-analysis datasets and model outputs (Akhil Raj et al., 2015; Hemanth Kumar et al., 2018; Satheesh Chandran et al., 2021; Zhang et al., 2021a, 2021b). The vertical transport between troposphere and stratosphere will change the tropopause layer characteristics which lead to the variation in the radiative budget (Hemanth Kumar and Ratnam, 2021; Venkat Ratnam et al., 2016). The vertical transport of aerosols also lead to the formation of Asian Tropopause Aerosol Layer (ATAL) which was detected by CALIPSO observations and confirmed through solar occultation observations by Stratospheric Aerosol and Gas Experiment (SAGE) II by improving the cloud-aerosol separation approach using the ratio between aerosol extinction coefficients resulted at two wavelengths (Thomason and Vernier, 2013; Vernier et al., 2011; Vernier et al., 2015). The vertical variability in ATAL is also confirmed from the observations made by stratospheric balloon experiment using portable optical counter (POP) (Zhang et al., 2020).

The influence of the reduced aerosol concentration on the vertical thermal structure during the lockdown is explained using simulation experiments (Gettelman et al., 2021). The atmospheric chemistry in the warmer and high-pressure environment (near surface) is quite different from the relatively colder and lower pressure environment (aloft). To the best of our knowledge, there are no studies which focused on the vertical distribution of these CO, WV and O3 species and their impact on the Temperature (T) structure during the COVID-19 lockdown. This has provided the motivation for the current work to look into the changes in vertical distribution during the COVID-lockdown period of 2020 when compared to the previous normal years (business as usual-BAU years). Therefore, present study has been focused to investigate the vertical distribution of the chemical species (CO, WV, and O3) with special focus on Upper Troposphere and Lower Stratospheric region (UTLS) region during the lockdown (25th March-14th April) over India. The main objectives of the present study are to quantify the changes in the vertical distribution of these trace gases over the Indian region during the lockdown, to understand the causative mechanisms and their potential impacts. The details of the data used in the present study are briefly explained in Section 2. Satellite observations have been validated using the calibrated ground-based observations over Gadanki. Section 3 explains the results of the spatial distribution of the chemical constituents near surface (at 925 hPa) during the pre-lockdown and lockdown periods. The spatial distribution of these chemical species at 147 hPa followed by the vertical distribution and percentage difference of the chemical constituents in the UTLS region over different zones has been discussed. Section 4 discusses the background dynamical conditions in pre-lockdown and during the lockdown to understand the plausible mechanism for the observed variation in the UTLS region and its impact. The summary and conclusions drawn from this study are outlined in Section 5.

2. Data and methodology

To understand the influence of the lockdown on the chemical composition and thermal structure, the daily vertical profiles of CO, WV, O3 and T from Microwave Limb Sounder (MLS) and Atmospheric Infrared Sounder (AIRS) satellite observations have been used. Besides, the satellite observations, profiles of zonal wind (U), meridional wind (V) and pressure vertical velocity (ω) have also been used to investigate the dynamical impact on the vertical distribution of these chemical species. In this study, the data period considered is from 8 March to 14 April 2020. To investigate the influence of COVID-19 lockdown and to minimize the meteorological impacts due to seasonal transition (Winter to Summer), the pre-lockdown period from 8 to 21 March and lockdown period from 25 March to 14 April for the period 2010–2019 have been considered (as there was a strict lockdown). The percentage changes in 2020 have been calculated by taking the difference between 2020 and the long-term average obtained for the years 2010–2019 in respective time periods (pre-lockdown, lockdown). The data products used in this study along with the details related to the specifications are mentioned below.

2.1. AIRS satellite data

The daily vertical profiles of CO, WV and O3 from 8 March to 14 April for period of 2010–2020 have been obtained. Using 2378 hyper spectral infrared channels and four visible/near infrared channels, AIRS onboard AQUA satellite provides 3D information about the earth’s atmospheric temperature, trace gases along with surface and cloud properties (Aumann et al., 2003). The infrared spectrometer covers a wavelength range from 3.7 μm to 16 μm. The sounder uses 58 channels for temperature, 49 channels for WV and 26 channels for O3 (McMillan et al., 2005; Susskind et al., 2003). The comparison of AIRS retrieved CO profiles with in-situ measured profiles showed a bias of 6–10% between 900 hPa and 300 hPa with a root mean square error of 8–12% (McMillan et al., 2011). The comparison of O3 retrievals with the collocated Ozonesonde profiles obtained from World Ozone and Ultraviolet Radiation Data Center (WOUDC) archive showed a bias of less than 5% for both the troposphere and stratosphere. The RMS differences are less than 20% for the upper stratosphere and are close to 20% for the lower stratosphere and troposphere (Divakarla et al., 2008). The RMS difference of AIRS water vapor is close to 15% in 2-km layers with a sensitivity threshold of ~30 ppmv (Divakarla et al., 2006). The spatial IR resolution is ~13.5 km at nadir from the 705.3 km orbit. The spatial footprint of the infrared channel is 1.1” in diameter corresponding to 15 × 15 km at the ground in the nadir view.

2.2. MLS satellite data

Eleven years (2010–2020) of MLS (Microwave Limb Sounder) WV, CO, O3 and T data for the period 8 March to April 14 have been used in the present study. Using the spectral bands centered at 118 GHz, 190 GHz, 240 GHz, 640 GHz and 2250 GHz, the MLS satellite provides information of temperature and chemical constituents (WV, O3, CO, and other tracers) over a spatial domain of 82’S–82’N with a horizontal spacing of 1.5’ both in latitudes and longitudes. 190 GHz and 240 GHz spectral bands are used for retrieving profiles of WV and O3 respectively. The resolution in range of 316–100 hPa, 100–1 hPa and 1–0.1 hPa are 2–3 km, 4–6 km, and 8 km respectively (Schuebler et al., 2006). Accuracy in WV measurements is ±4–8.3% between 100 and 18 hPa, whereas the estimated O3 accuracy at ~40 ppbv is ±5% and the root mean square average of the estimated precision at 100 ppbv is 40 ppbv. The accuracy in CO for pressure levels of 147 hPa and less is estimated to be 30 ppbv ±30%. The details related to the retrieval algorithm and measuring technique are explained in Livesey et al. (2006) and (Waters et al., 2006), respectively. We have used version 4 (v4.0) of level 2 products (WV, O3, CO) downloaded from http://mirador.gsfc.nasa.gov. The accuracy in water vapor measurements at 316 hPa, 261 hPa, 215 hPa, 178 hPa, 147 hPa, 121 hPa, 100 hPa, 83 hPa and 68 hPa is 15%, 20%, 25%, 20%,15%,12%,8%, 9% and 9% respectively. Similarly, the accuracy in ozone measurements ranges between 7 and 10% in the pressure range 316 hPa–68 hPa. The accuracy for carbonmonoxide measurements at 215 hPa, 147 hPa, 100 hPa and 68 hPa is ±38 ppbv (±30%), ±26 ppbv (±30%), ±19 ppbv (±30%) and ±10 ppbv (±30%), respectively. The long atmospheric path length of the MLS observations of small concentrations in the UTLS and the viewing limb geometry offers good vertical resolution and provides reliable information in the upper troposphere compared to nadir viewing satellite (AIRS satellite in this study). Several studies have reported validation of MLS WV and O3 gases using Cryogenic Front Point Hygrometers and Ozonesondes, respectively (Akhil Raj et al., 2015; Emmanuel et al., 2018; Vomel et al., 2007). The vertical distribution of these species during the lockdown has been studied by dividing the atmosphere into three altitude (pressure) ranges like boundary Layer (BL-1000 hPa–850 hPa), mid-Troposphere (MT-700 hPa–300 hPa) and upper troposphere (UT-250–100 hPa).
The measurements from AIRS for BL and MT concentrations of CO, WV and O₃ and MLS measurements for UT concentrations of these species have been used in this study.

2.3. NCEP/NCAR reanalysis data

For understanding the dynamical conditions, the daily mean zonal wind (U), meridional wind (V) and pressure vertical velocity (w) which was jointly produced by National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) have been used. Global data products are available with a latitudinal and longitudinal spacing of 2.5° × 2.5° at 17 pressure levels from 1000 hPa to 10 hPa (Kalnay et al., 1996). In this study, we have made use of the data from 8 March-14 April for the period 2010 to 2020.

3. Results

3.1. Validation of satellite measurements at near surface using ground-based measurements

Validation of the satellite measurements with ground-based observations are essential before the satellite observations are considered for detailed analysis. This gives the confidence to use the satellite measurements. Satellite data retrieval has many prior assumptions which induce certain uncertainties in the retrieved data products. Fig. 1 shows the time series of CO, WV and O₃ obtained using satellite measurements compared with the ground-based measurements over Gadanki (13.5° N, 79.2° E). The satellite measurements obtained within ±1° latitude and longitude (78.2°E–80.2°E, 12.5°N–14.5°N) keeping Gadanki at the centre have been considered for comparison. The comparison between AIRS observations and ground based analyzers from 8 March to 14 April 2020 is shown in Fig. 1. Satellite measured CO (Fig. 1(a)), WV (Fig. 1(b)) and O₃ (Fig. 1(c)) concentrations at 925 hPa (near surface) have shown a slight underestimation and overestimation, respectively, when compared with ground-based observations. Both CO and WV have shown a gradual decrease in both the measurements soon after the implementation of lockdown. However, the satellite measured O₃ has shown decrease in the initial days of lockdown which is in contrast to the ground-based observations. Sampling volume, local emissions, etc., are mainly responsible for the observed differences between the satellite and ground based measurements. However, similar trends observed in the ground-based measurements is also seen in the satellite measurements with some magnitude difference.

The quality of the satellite measured concentrations has also been assessed by comparing the results obtained at other locations using a different network of observations. The studies made by Sharma et al. (2020) over different locations during lockdown in India using network observations also showed a reduction of 10% and 18% in CO, and NO₂, respectively. The comparison of the concentration changes noticed in PM₂.₅, PM₁₀, CO, and NO₂ over five megacities during March–April
2020 and March–April 2021 also revealed the same (Jain and Sharma, 2020). The comprehensive study conducted by making use of Central Pollution Control Board (CPCB) data over different Indian sites (zones) and cities also showed a significant reduction in NO2, CO and mixed behavior of O3 (slight increase in IGP region and decrease in South, North West and Central India regions) and WV (increase in Central India and decrease in other regions of India) (Navinya et al., 2020; Sharma et al., 2020; Singh et al., 2020). The changes observed in the satellite measurements have agreed qualitatively well with the point-based surface measurements conducted over different regions (Venkat Ratnam et al., 2021b, 2021c).

3.2. Trace gases distribution near surface during lockdown using AIRS observations

It has been found from the previous section that, the satellite measurements capture the gross features during the study period. These measurements have been used to study the spatial variability of these chemical species qualitatively. The mean concentrations of CO, WV and O3 over the Indian region at 925 hPa during the pre-lockdown and lockdown period have been obtained and shown in Fig. S1. The percentage difference in the concentrations of these species at 925 hPa between the pre-lockdown (08–21 March 2020) and lock-down (25 March–14 April 2020) have been calculated and presented in Fig. 2(a)–(c). A clear increase in CO concentrations over Central India (Fig. 2(a)) has been noticed during the lockdown compared to pre-lockdown period. Whereas, over the same region decrease and increase in WV (Fig. 2(b)) and O3 (Fig. 2(c)) concentrations have been observed. However, to minimize the meteorological impacts due to the seasonal transition (change from winter to summer), the percentage changes in CO, WV and O3 obtained at 925 hPa during lockdown have been compared with climatology (2010–2019) and shown in Fig. 2(d)–(f). During the lockdown, a decrease (~5–15%) in CO concentration has been observed over South India, adjoining oceans (Parts of Arabian Sea and Bay of Bengal) and IGP regions. An increase of about ~10% has also been noticed over Central India (Fig. 2(d)) extending from north Arabian Sea. An increase of ~25–40% has been noticed in WV concentration (Fig. 2(e)) over central India. It is over this region where high Aerosol Optical depth (AOD) is also observed during the lockdown (Venkat Ratnam et al., 2021b, 2021c). Interestingly, O3 showed a mixed behavior of no/insignificant change (over South India) to a decline (~20–30%) in other regions. The changes observed in CO, WV and O3 in the near surface level (~925 hPa) have been within the range of changes reported by other studies conducted over different sites (rural and urban) and cities of India (Jain and Sharma, 2020; Singh et al., 2020). From Fig. 2 and S1 it is clear that the effect of lockdown on these chemical constituents is different for different regions across India. Similar to that noticed at the surface level, the chemical constituents in the upper troposphere had also showed a heterogeneous distribution (Fig. S3). The background dynamical conditions are not same over the entire Indian region. This has given an insight to check the heterogeneity in the chemical constituents and relation to the background dynamics. Therefore, Indian region has been broadly divided further into three main zones like South India (10°–17.5° N, 75°–80° E), Central India (17.5°–25° N, 75°–80° E) and Indo-Gangetic Plain (IGP) (25°–30° N, 75°–85° E).

3.3. Trace gases distribution in UTLS during lockdown using MLS observations

In this study, the observations from MLS satellite have been directly used to understand the impact of lockdown on the UTLS. The mean concentrations of CO, WV and O3 over the Indian region at 147 hPa during the pre-lockdown and lockdown period have been obtained and show in Fig. S2. Fig. 3(a)–(c) show the percentage difference in CO, WV and O3 at 147 hPa between lockdown (25 March–14 April 2020) and pre-lockdown (8–21 March 2020) period. Increase in CO and WV concentrations over Central India have been observed during the lockdown period compared to pre-lockdown period. Whereas, a decrease in O3 concentration has been noticed. The percentage difference in the same between the lockdown of 2020 and same time window of lockdown during 2010–2019 is shown in Fig. 3(d)–(f). Similar to that noticed at the near surface level, the chemical constituents in the upper troposphere also showed a heterogeneous distribution over India. Decrease (~10–20%) over IGP and an increase of ~25–30% over Central India regions in CO concentration have been clearly noticed during the

Fig. 2. Percentage difference between lockdown (25 March–14 April 2020) and pre-lockdown period (8–21 March 2020) obtained at 925 hPa from AIRS satellite observations in the (a) CO mixing ratio, (b) WV mixing ratio and (c) O3 mixing ratio. (d), (e) and (f) are same as (a), (b) and (c) but calculated between lockdown period (25 March–14 April) and climatology obtained during the same days averaged during 2010–2019.
lockdown period compared to its long-term average (Fig. 3(d)). Similarly, an increase of ~30–35% in the WV has been noticed over Central India and with slightly lesser percentage throughout India (Fig. 3(e)). The O₃ concentrations have shown an enhancement and reduction of ~10–30% and ~15–25% over Central India, IGP regions and South India, respectively (Fig. 3(f)). The detailed comparison of these chemical species in the UTLS region over different zones and percentage changes in 2020 when compared with the long-term average has been explained below.

The time series of the CO, WV and O₃ obtained from MLS satellite observations for the study period covering both pre-lockdown and lockdown (8 March 2020–14 April 2020) is shown in Fig. 4. The vertical dashed line represents the start of the lockdown in India.
provides observations at these respective pressure levels. The maximum reduction (~60%) in the CO concentration have been noticed over South India (Fig. 5(c)) followed by Central India (Fig. 5(b)) and IGP (Fig. 5(a)). Similar to CO, the MLS WV observations in mid-troposphere (316 hPa) have also showed a reduction in concentration over all the zones soon after the lockdown (Fig. 4(d)–(f)). In these levels, the WV concentration has showed a decrease of 50–60% over all the regions when compared to the climatology (Fig. 5(d)–(f)). Soon after the lockdown, an increase of (~10–25%) in O₃ concentration in the mid troposphere levels (316 hPa) has been noticed over central India (Fig. 5(h)) and IGP (Fig. 5(g)) but not in South India (Fig. 5(i)).

In contrast to 316 hPa, it is surprising to see an enhancement in CO and WV concentrations in the UTLS region over all the zones. The increase of CO concentration has been observed maximum over Central India with an increase of ~25–40% at 147 hPa (Fig. 5(b)). The WV also showed an enhancement of ~50–60% over the same region but at 215 hPa (Fig. 5(o)). Perhaps some dynamical aspects might have played a role on the observed increase in these trace gases. However, a clear decrease in O₃ concentration has been noticed during the lockdown near tropopause region over all the regions with maximum decrease of ~50–60% over South India (Fig. 5(i)). High values of potential vorticity (~3.5 PVU) have been observed (Fig. S3) over IGP region during 12–16 March 2020 indicating the presence of strong PV intrusion before the lockdown. There are no such major intrusions during the lockdown except one during 29–31st of March, which is not so strong.

4. Background dynamical conditions during pre-lockdown and lockdown

To investigate the influence of the background atmospheric conditions on these trace gases during the lockdown, the percentage differences in the vertical profiles of zonal wind (U), meridional wind (V) and pressure vertical velocity (ω) over South India, Central India and IGP regions with the climatology is shown in Fig. 6. A prolonged decrease of ~10–25 m/s in zonal wind in the upper troposphere before and during the lockdown has been clearly observed particularly over Central India (Fig. 6(b)). A significant reduction in the meridional wind in all the regions can be noticed immediately after the lockdown (Fig. 6(d–f)). The stronger updrafts (negative values) in the mid troposphere just before the lockdown over South India (Fig. 6(i)) and Central India (Fig. 6(h)) might have transported CO and WV to the higher levels. In addition to that, the reduced zonal wind (Fig. 6(b) and (a)) would have confined the pollutants resulting in the higher concentrations of CO and WV near the UTLS region (Fig. 5(b),(e)).

Though the Indian region experiences convective updrafts associated with the migration of ITCZ during the pre-monsoon period, the prolonged weakening of the zonal wind strength particularly over central India during the lockdown has led to the increase in the concentrations of CO and WV. This type of enhancement in CO and WV and background dynamics in the upper troposphere during the same time has not been observed on other years (Figure not shown). A wavy pattern in both wind (meridional and zonal wind) and temperature can be seen from Figs. 6 and 7. This pattern is found in the pressure levels between 500 hPa and 100 hPa which can be clearly observed in the meridional wind particularly over Central India and IGP regions. The spectral analysis of zonal wind, meridional wind at 200 hPa, temperature and WV mixing ratio at 216 hPa has been performed and shown in Fig. S4. The periodicity observed in the wind and temperatures are significantly different. The meridional wind has shown a period of ~10 days particularly over Central India and IGP regions (Fig. S4). Similarly, the periodicity noticed in temperature and water vapor is different which clearly indicates that the changes observed in WV concentration are not due to planetary wave activity.

The percentage difference in temperature for the year 2020 has also been obtained from MLS observations for these three zones and is shown in Fig. 7. The percentage changes in temperature in the UTLS region are higher in Central India and IGP regions compared to the South India. A cooling of ~1–2% has been observed near the tropopause over Central India (Fig. 7b) but not in the South and IGP regions immediately after
Fig. 6. Same as Fig. 5 but for the difference between 8 March and 14 April 2020 and climatology obtained during the same days averaged during 2010–2019 from NCEP/NCAR reanalysis in zonal wind (a-c), meridional wind (d-f) and vertical wind (g-i) over different regions.

Fig. 7. Same as Fig. 6 but shows the percentage difference in temperature from 8 March to 14 April 2020 obtained from MLS observations and climatology.
the lockdown.

5. Discussion

Lockdown during COVID-19 should lead to the significant reduction in the anthropogenic emissions due to the forced shut down of the industries, which is expected a reduction in CO near the surface or in the boundary layer. However, no obvious decrease in the CO was observed (Figs. 1a, 2a and S1a) and increase in CO was even seen over many regions. It should also be noted that surface observations provide limited insight into upper-layer variations because the upper-layer variations are not necessarily consistent with surface variations. For the WV, the influence of regional weather conditions and long-range transport should be more important than the lockdown. Compared with the CO and WV, the O₃ variations should be driven by more complex and various factors. Near-surface, O₃ is an important secondary pollutant and is mainly produced in polluted air by photochemical oxidation of nitrogen oxides (NOₓ) and volatile organic compounds (VOCs) in the presence of sunlight. Also note that the relationships between O₃ and its precursors are complicated and nonlinear. In addition, long-range O₃ transport and exchange between the stratosphere and troposphere (such as deep stratospheric intrusion and deep convection) can also influence regional O₃ pollution. Some studies have also indicated that the decrease in aerosol concentrations can also enhance the surface ozone concentration (Kalluri et al., 2021).

A decrease in CO and WV concentrations in boundary layer has been noticed over South India and IGP regions but not in the Central India where an increase has been observed (Table 1). The reduction in anthropogenic emissions would have resulted in lowering of CO concentrations over these regions. The surface level measurements reported by Singh et al. (2020) have shown a decrease in O₃ concentrations over South India, Central India and a slight increase in IGP region. In urban environments like IGP regions (VOC-limited regions), preference of OH to NO₂ over VOC’s retard the O₃ formation. However, during the lockdown, the NOₓ concentrations are lowered due to the forced shut down of Industries, power plants and cessation of vehicular transport. This resulted in the lowering of the major sink reaction of O₃ which might have resulted in the accumulation of O₃ concentration in the urban environments (Jain et al., 2021; Wayne, 2000). In contrast to surface measurements, satellite measurements had shown a decrease in O₃ concentration in boundary layer during the lockdown over all the regions. This discrepancy observed in the satellite observations could be due to the spatial averaging of the measurements which include both polluted urban and un-polluted rural hotspots unlike the in-situ measurements conducted in their study which are restricted to urban environments only.

An increase in CO concentrations has been observed in the mid-troposphere over Central India and IGP regions during the lockdown (Table 1). This could be due to the long-range transport from the biomass affected regions of Central Africa and South East Asia or local

Table 1
Observed concentration changes in CO, O₃ and WV over South India, Central India and IGP in PBL, MT and UT during the pre-lockdown and lockdown period of 2020 in comparison with 2010–2019. Red colors show the decrease in the concentrations, green colored value represents the increase in concentration.

| Chemical Species | Pressure level hPa | Zones | % change in 2020 when compared to 2010-2019 |
|------------------|-------------------|-------|------------------------------------------|
|                  |                   |       | Pre-lockdown (08-21 March) | Lockdown (25 March-14 April) |
| CO               | 1000-850 (PBL)    | SI    | -3.13 | -5.3 |
|                  |                   | CI    | -3.18 | 0.02 |
|                  |                   | IGP   | -0.261 | -1.92 |
|                  | 700-300 (MT)      | SI    | 4.67 | -1.30 |
|                  |                   | CI    | 1.90 | 4.93 |
|                  |                   | IGP   | -0.90 | 1.81 |
|                  | 250-100 (UT)      | SI    | 4.21 | 4.63 |
|                  |                   | CI    | 3.18 | 8.76 |
|                  |                   | IGP   | -2.92 | 4.13 |
| O₃               | 1000-850 (PBL)    | SI    | -12.90 | -14.08 |
|                  |                   | CI    | -8.66 | -13.06 |
|                  |                   | IGP   | -12.32 | -18.35 |
|                  | 700-300 (MT)      | SI    | -19.88 | -22.43 |
|                  |                   | CI    | -14.65 | -19.54 |
|                  |                   | IGP   | -9.20 | -20.09 |
|                  | 250-100 (UT)      | SI    | -10.71 | -8.17 |
|                  |                   | CI    | 15.13 | 2.01 |
|                  |                   | IGP   | 27.97 | 18.85 |
| WV               | 1000-850 (PBL)    | SI    | 5.20 | -2.21 |
|                  |                   | CI    | 13.35 | 14.35 |
|                  |                   | IGP   | 13.16 | -0.09 |
|                  | 700-300 (MT)      | SI    | -6.73 | 6.37 |
|                  |                   | CI    | 10.44 | 22.36 |
|                  |                   | IGP   | 0.250 | -9.40 |
|                  | 250-100 (UT)      | SI    | 3.20 | 9.47 |
|                  |                   | CI    | -1.19 | 26.46 |
|                  |                   | IGP   | -12.93 | 15.52 |
convective lifting (Chandra et al., 2016; Sheel et al., 2014) prevalent over Central and Northern parts of India during pre-monsoon season.

Similarly, an enhancement in WV concentrations has also been found over Central India which could be due to the vertical transport from the lower levels where high WV concentrations have been noticed (Fig. 2e). Though AIRS satellite observations had shown a decrease in $O_3$ concentration in the mid-troposphere over all the zones, the MLS $O_3$ observations at 316 hPa have shown a decrease over South India and increase over Central India and IGP regions just after the lockdown (AIRS also showed an increase at 300 hPa but the net effect has shown reduction when we have considered latitudinal average between the pressure level (700–300 hPa)).

The increase in mean CO and WV concentrations in the upper troposphere over all the regions is mainly attributed to the strong vertical transport and weakening of the horizontal wind during the lockdown (Fig. 6(a), (b) and (d), (e)). The industrialization of eastern Asia has influenced the chemical climate through the transport of boundary layer pollutants lifted episodically upward by tropical convective events and horizontal advection (Barret et al., 2008; Krishnamurti et al., 2009; Phadnis et al., 2002). A decrease and increase in $O_3$ concentrations have been noticed over South India and Central India and IGP regions. The temperatures play a major role in $O_3$ scavenging by NO because the reaction ($O_3 = NO\rightarrow NO_2 + O_2$) at 225 K is ~4 times slower than the reaction rate at 300 K (Atkinson et al., 2004). This might have favored the increased life time of $O_3$ at higher altitudes over IGP and Central India.

Atmospheric dynamics (Fig. 6) and the pollutant concentration (Fig. 4) in the lower atmosphere during pre-lockdown and lockdown might have partially influenced the observed differences in the vertical distribution of chemical constituents at the higher altitudes. The main difference during the period 8 March–14 April between the climatology (2010–2019) and 2020 is the lockdown. In spite of similar background conditions, significant differences have been noticed in the chemical species during 2020 which can be at least partially due to the lockdown impact. Other factors like long range transport and in-situ chemical transformations may also have significant roles in these changes. It would be difficult to give a conclusive evidence of the causative mechanisms for the observed changes in vertical distribution of chemical constituents considered in this study during the year 2020 when compared to climatology. This may ask for a completely different investigative approach which is out of scope of this study.

6. Summary and conclusions

The vertical distribution of the chemical constituents with special emphasis on the composition of upper troposphere and lower stratosphere (UTLS) region over India during the COVID-19 lockdown has been investigated using (AIRS and MLS) satellite measurements. The satellite measurements during the phase 1 of the pandemic lockdown only has been considered in the present study as it is during this period almost 95% of the industries, power plants, road transportation are shut down in the country. The surface observations are not necessarily consistent with the upper layer observations and they provide a limited insight into upper-layer variation as the chemical constituents in the atmosphere are driven by several other factors and more complex chemical processes. To investigate the upper layer variability of the chemical constituents, the satellite measurements of 14 days before (pre-lockdown) and during the lockdown have been separated and averaged to understand the influence of the lockdown compared to pre-lockdown. The lockdown 2020 influence when compared with the long-term average obtained from the similar time domain during the period 2010–2019 has also been outlined and summarized below.

1. 5–10% increase in the carbon monoxide (CO) is observed near surface (~925 hPa) during the COVID-19 lockdown particularly over Central India. Similarly, a significant increase of ~30–40% in water vapor (WV) is also noticed over the same region during the lockdown. However, nearly 5–10% decrease is noticed near surface in both CO and WV over south and IGP regions.

2. The decrease in CO concentration observed in the mid troposphere (~316 hPa) during the lockdown over all the three zones (South India, Central India and IGP) is mainly attributed to the reduction in the anthropogenic emissions due to the forced shut down of the industries, power plants and cessation of vehicular transportation. Similar to CO, the WV concentrations also showed a decrease in the mid troposphere levels. A maximum reduction in CO (~40–60%) has been observed over South India followed by Central India and IGP. A maximum decrease of ~50–60% is observed in WV concentrations in these levels over all the zones. The $O_3$ showed a decrease (~15–25%) over South India in this region and increase (~15–20%) over central and IGP regions.

3. The maximum increase in CO (~25–40%) and WV (~50–60%) concentrations are observed over Central India at ~147 hPa and ~215 hPa, respectively, during lockdown.

4. The stronger updrafts before the lockdown and the prolonged weakening of the zonal wind over Central India confines these species which resulted in the higher concentrations in the UTLS region.

Thus, the available emissions in the pre-lockdown period and the background dynamics during the lockdown played a major role in the observed increase in the chemical composition particularly in the CO and WV in the upper troposphere which can have impact on regional climate.

Author contributions

Alladi Hemanth Kumar designed the study, conducted research, curated the data, performed the Initial Data analysis and wrote the first manuscript draft. M. Venkat Ratnam supervised, reviewed and edited the first manuscript. Chaithanya D Jain reviewed and edited the manuscript.

Data availability

The data used in the present study are freely available. The MLS and AIRS trace gases (CO, WV and $O_3$) data are obtained from the Earth Science Data website (http://mirador.gsfc.nasa.gov/). The dynamical products (Zonal wind (U), Meridional wind (V), Pressure vertical velocity ($\omega$)) are downloaded from https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2021.105876,
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