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Analysis of total column ozone, water vapour and aerosol optical thickness over Ahmedabad, India

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ABSTRACT: A preliminary study was performed to investigate the quality of total column ozone (TCO), water vapour (WV) and aerosol optical thickness (AOT) available from satellite and reanalysis from atmospheric models along with *in situ* observations over Ahmedabad (23.03° N, 72.5° E, 55 m above mean sea level), India. Ground-based measurements from a MICROTOPS II ozonometer as well as space-based satellite retrieved products from the moderate resolution imaging spectroradiometer (MODIS) and an ozone monitoring instrument were analysed during December 2014 to March 2015. The European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim) created TCO and WV were also used to assess the skill of global model reanalysis over the western part of India. An increasing trend was found in the TCO and WV parameters from the winter to summer period. Investigations showed that MODIS satellite retrieved and ERA-Interim reanalysis WV are able to capture the trends compared with ground-based hand-held MICROTOPS II observations. Higher TCO was found in the MODIS data, whereas the ERA-Interim and ozone monitoring instrument TCO matched well with ground-based observations. Larger differences were found with the MODIS AOT in comparison to MICROTOPS II AOT observations. Further, analysis showed that ERA-Interim has sufficient potential to be used for various meteorological applications over the western Indian region. Furthermore, the variations of TCO, WV and AOT were studied over the orographic region of Mount Abu (~110 km aerial distance from Ahmedabad), located in the Aravali range of mountains. Ground-based measurements at different altitudes (0.3, 1.1 and 1.67 km above mean sea level) revealed significant variations in WV and AOT. The WV varies 17.1% (30.3%) and the AOT varies 53.8% (57.5%) in 1.1 km (1.67 km), whereas no noteworthy variations are observed in the TCO in this field campaign.

KEY WORDS ERA-Interim; Microtops-II; MODIS; OMI

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1. Introduction

The total column ozone (TCO), water vapour (WV) and aerosol optical thickness (AOT) are some of the important atmospheric parameters that govern the radiation and hydrological balance and play an important role in the Earth's weather and climate system. The TCO, an important trace gas present in the atmosphere, receives a major contribution from the stratosphere, and WV and AOT receive a major contribution from the tropospheric height. Ozone exists in the form of a layer in the stratosphere, which plays a vital role in the existence and survival of all the living beings present on the Earth's surface. It has a shielding effect that reduces the impact of ultraviolet (UV) radiation on the Earth's surface (Ramanathan *et al.*, 1989). Because of these important characteristics, it is an important atmospheric parameter. Apart from ozone, the AOT and WV are two essential parameters in the lower atmosphere which play a key role in global warming and cloud formation respectively (Lindzen, 1990). Due to large variability of these parameters on the Earth's atmosphere, it is the area of concern and research. Stratospheric WV fluctuations affect the fluxes of long wave and solar radiation, which affect the Earth's radiation balance by modulating the temperature in the troposphere and stratosphere (e.g. Kiehl and Trenberth, 1997; Solomon *et al.*, 2010). Aerosols (i.e. the scattering and absorbing type) are responsible for atmospheric cooling and warming (Wild *et al.*, 2007; Wild, 2009). Previous studies from various locations using ground-based instruments (e.g. Kerr *et al.*, 1988; Van Roozendael *et al.*, 1998; Gao *et al.*, 2001; Balis *et al.*, 2007; Srivastava *et al.*, 2008) showed significant variability in TCO concentrations. Moreover, Balis *et al.* (2007) compared ozone monitoring instrument differential optical absorption spectroscopy (OMI-DOAS) satellite data with Brewer observations and specified that, at larger solar zenith angles, OMI-DOAS showed 3–5% higher values of TCO. Initially, the Dobson and Brewer spectrometer was used for ozone measurements and the retrieval method for ozone was very robust and expensive (Köhler, 1999). The MICROTOPS II ozonometer replaces this instrument due to its suitability, i.e. small size, easily operated and less expensive (Gómez-Amo *et al.*, 2012). Holdren *et al.* (2001) found a significant correlation between MICROTOPS II and Dobson spectrometer observations.

Srivastava *et al.* (2008) studied the daily variation in TCO, WV and AOT using MICROTOPS II observations and found a good agreement with the total ozone mapping spectrometer (TOMS) satellite data. Gómez-Amo *et al.* (2013) found a good comparison and correlation between three MICROTOPS II and TOMS, the ozone monitoring instrument (OMI) and global ozone measurements experiment (GOME) satellites. Kalapureddy *et al.* (2008) showed variations of TCO, WV and

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AOT during the pre-monsoon season using ship-borne Sun photometric observations over the oceanic (Bay of Bengal, Arabian Sea and northern Indian Ocean) regions around the Indian subcontinent and found that the variation in ozone during the afternoon is higher than in the morning and evening. Their study concluded that higher values of ozone over the head of the Bay of Bengal may be due to the influence of human activity, such as fossil fuel and biomass burning. Muyimbwa *et al.* (2015) found a seasonal variation in AOT and the perceptible water vapour column (PWVC) using a Cimel Sun photometer and showed that a significant increment in these parameters is more dominant during summer than winter. Srivastava *et al.* (2006) found good agreement between measured UV irradiances using MICROTOPS II and the tropospheric ultraviolet visible radiation model. Hadjimitsis (2009) compared AOT values from the Landsat TM band 1 image of Cyprus and the MICROTOPS II ozonometer and found acceptable validation of AOT values with an uncertainty of ±0.01 at a wavelength of 440 nm. Wang *et al.* (2003) studied the diurnal variation of the AOT using geostationary satellites and showed a higher value of AOT near the coast of East Asia and a lower value over the ocean.

In the present study TCO, WV and AOT measurements retrieved from the MICROTOPS II ozonometer were investigated over Ahmedabad (23.03° N, 72.58° E, 55 m above mean sea level (amsl)) and Mount Abu (24.5° N, 72.71° E, 1.1 km amsl), a mountainous site near Ahmedabad, in the western part of India (Figure 1(a)). The main aim of selecting the Mount Abu region was to study the TCO, WV and AOT at different altitudes and to assess the contribution of different altitude regions. Moreover, moderate resolution imaging spectroradiometer (MODIS) and OMI-Aura satellite data and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim) data are also compared with MICROTOPS II observations for the first time over the western Indian region to observe the variation in important atmospheric parameters (namely TCO, WV and AOT).

2. Observational site description and data

Ahmedabad is the fifth largest city and seventh largest metropolitan area in India. It lies in the western part of India along the banks of the river Sabarmati. It is almost a plain area and falls under seismic zone 3. Ahmedabad has a hot, semi-arid climate with marginally less rain during the summer monsoon over Ahmedabad. Mount Abu, near Ahmedabad is a tropical hill station which falls under the Aravali range of mountains in the Sirohi district of Rajasthan in western India. The highest peak on the mountains is Gurushikhar (∼1700 m amsl).

2.1. MICROTOPS II Sun photometer and ozonometer

The MICROTOPS II (Figure 1(b)) Sun photometer and ozonometer of Solar Light Company was used to measure TCO, WV and AOT. It is a low cost, portable and hand-held instrument for measuring atmospheric TCO, WV and AOT (Morys *et al.*, 2001). The multi-wavelength MICROTOPS II Sun photometer is used to measure the direct solar irradiance at five different wavelengths (i.e. 305.5, 312.5, 320, 936 and 1020 nm) (Morys *et al.*, 2001). These measured irradiances are used to derive integrated columnar atmospheric properties such as WV and AOT. The field of view of each channel is 2.5°. The Beer–Lambert–Bouguer law is used to determine the total

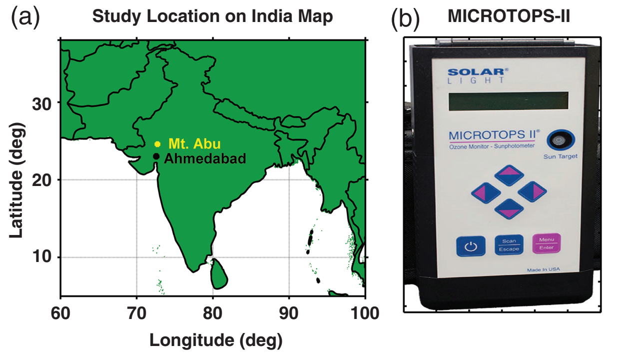

Figure 1. (a) Location of Ahmedabad and Mount Abu in India and (b) a photograph of the MICROTOPS II ozonometer instrument. [Colour figure can be viewed at wileyonlinelibrary.com].

optical depth at different wavelengths λ in a vertical air column (Srivastava *et al.*, 2008) using the expression:

$$I(\lambda) = I_0(\lambda) \exp\left\{-k\tau_t(\lambda)\right\}$$

where $I(\lambda)$ is the solar irradiance reaching the instrument detector, $I_0(\lambda)$ is the irradiance incident at the top of the atmosphere, k is the air mass and $\tau_t(\lambda)$ is the total optical depth, which includes the aerosol and gaseous optical depth. For taking observations, MICROTOPS II points towards the Sun. When the Sun is at the centre in the bull's-eye of the MICROTOPS II, all channels are oriented directly at the solar disc (Morys *et al.*, 2001) and data are recorded. MICROTOPS II data are only taken in clear sky conditions.

In order to retrieve the TCO using the MICROTOPS II ozonometer, total ozone portable spectroradiometer instruments provide measurements of solar irradiance in three channels of the UV spectrum (305.5, 312.5 and 320 nm) which is considered as the flux in that region (Flynn *et al.*, 1996). By using all these fluxes, the ozonometer measures the TCO in Dobson units (DU) of the atmosphere. To retrieve the columnar atmospheric WV concentration (which is also known as the perceptible water content), the differential optical absorption and scattering technique is used with high temporal resolution (Srivastava *et al.*, 2008). Detailed studies regarding the limitations and uncertainties of MICROTOPS II retrieved atmospheric parameters have been discussed by several researchers in the past, i.e. Flynn *et al.* (1996), Labow *et al.* (1996), Köhler (1999) and Holdren *et al.* (2001).

2.2. MODIS satellite

The MODIS works on the principle of radiometry and is the key instrument aboard the two satellites Terra and Aqua. Terra and Aqua were launched on 18 December 1999 and 4 May 2002 respectively. The MODIS measures sunlight reflected by the Earth's atmosphere and emitted thermal radiation at 36 wavelengths. MODIS satellite data are readily accessible and have a good coverage. The high radiometric sensitivity is observed by MODIS in 36 spectral bands ranging from 0.4 to 14.4 μm (e.g. Menzel *et al.*, 2008; Kühnlein *et al.*, 2013). All 36 spectral bands are categorized at different spatial resolutions: two are imaged at a spatial resolution of 250 m at nadir, five bands at 500 m and the remaining 29 bands at 1 km (Sun *et al.*, 2012). In the present study, the AOT at 550 nm was taken from the MODIS. A trend analysis of AOT variation at different wavelengths (340, 380, 440, 500, 675, 870 and 1020 nm) observed by the Aerosol

Robotic Network (AERONET) over a site near Ahmedabad was also done and a similar pattern of AOT was found at all wavelengths with a small magnitude difference. Therefore, the observed AOT at 1020 nm with MICROTOPS II was compared with the AOT at 550 nm from the MODIS04 product. The TCO and WV from the MODIS07 product were also used during the day time over Ahmedabad.

2.3. OMI-Aura

The OMI is one out of the four instruments on board the National Aeronautics and Space Administration Earth Observing System (NASA-EOS) Aura spacecraft which was launched on 15 July 2004. It is a nadir-viewing instrument for measuring backscattered solar radiances and irradiances in the wavelength range from 270 to 500 nm with two spectral UV–visible channels spectrometer, i.e. UV (270–370 nm) (again, the UV channels are divided into two parts, UV-1 270–311 nm and UV-2 307–383 nm) and visible (350–500 nm); detailed descriptions about the OMI are given in Dobber *et al.* (2006), Levelt *et al.* (2006) and Bak *et al.* (2015). It provides daily global coverage with a good spatial resolution of 13 km × 24 km. It measures the total ozone and air quality components such as NO_2, SO_2, AOT, aerosol effective cloud cover and cloud top pressure (Ziemke *et al.*, 2006). TCO data from the OMI-Aura satellite are received from the Tropospheric Emission Monitoring Internet Service, which is part of the Data User Programme of the European Space Agency.

2.4. Global model analysis

The ERA-Interim majorly opts from the ECMWF global model to produce reanalysis which uses an improved atmospheric model and a 4D variational data assimilation method, requiring huge computing power. The analysis step combines the observations with a previous estimate of the atmospheric state produced with a global forecast model in a statistically optimal manner. In ERA-Interim, two analyses *per* day are performed at 0000 and 1200 UTC and serve as initial conditions for the subsequent forecasts. Enhanced computing power also allowed the horizontal resolution to be increased (T255, nominally 0.703125°), and the latest cycle of the atmospheric model to be used, taking advantage of improved model physics. The ERA-Interim is also used for the assimilation of multiple types of observational data, including radiosonde observations. ERA-Interim reanalysis has 60 vertical levels which use hybrid co-ordinates that follow the terrain at the surface and gradually transition to pressure co-ordinates at the model top. The boundary layer is fairly well resolved with the lowest model levels at about 10, 30, 60, 100, 160 and 240 m above the model surface. The WV and TCO datasets from the ERA-Interim reanalysis were used in the present study.

3. Results and discussion

In the present study, a detailed comparison of the daily mean variations of the three most important atmospheric parameters, TCO, WV and AOT, over the Ahmedabad and Mount Abu region were performed from December 2014 to March 2015 by using retrieved MODIS and OMI-Aura satellite datasets and ERA-Interim reanalysis, in conjunction with MICROTOPS II ozonometer measurements. A comparative study was performed in order to examine the variations in TCO, WV and AOT obtained from ground-based hand-held MICROTOPS II ozonometers and a satellite over the observational site.

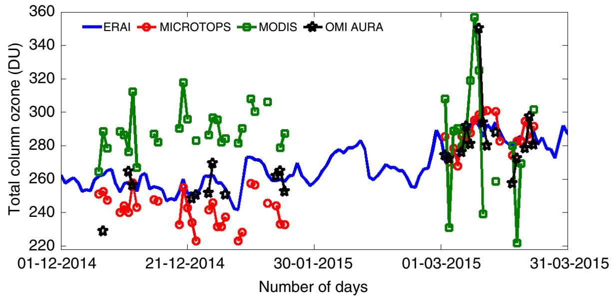

Figure 2. Daily mean variations in total column ozone (DU) from December 2014 to March 2015 observed by the MICROTOPS II, the moderate resolution imaging spectroradiometer (MODIS) and the ozone monitoring instrument on Aura (OMI-Aura) and ERA-Interim reanalysis over Ahmedabad, India. [Colour figure can be viewed at wileyonlinelibrary.com].

3.1. Total column ozone

The daily mean variation of TCO observed from the MODIS and OMI-Aura satellites and ERA-Interim reanalysis and the MICROTOPS II ozonometer is shown in Figure 2. When the TCO values from MODIS, OMI-Aura and ERA-Interim reanalysis were validated against MICROTOPS II TCO values, MODIS was found to overestimate the TCO values with the largest biases. The daily mean variation of TCO from ERA-Interim, OMI-Aura and MICROTOPS II shows that TCO increases from January to March 2015. MODIS retrieved TCO values are not able to capture this variation. The observed differences (underestimation/overestimation) between the MODIS and MICROTOPS II values could be due to the spatial grid and the difference in overpass time of the MODIS and the ground-based hand-held MICROTOPS II. In December, TCO measured with the MICROTOPS II ranged between 220 and 265 DU. A significant rise in the TCO values was observed as March was approached with values ranging from ~260 to 300 DU. It is clearly evident from the figure that the MODIS retrieved TCO is higher compared to OMI-Aura, MICROTOPS II and ERA-Interim reanalysis observations. Also, ERA-Interim reanalysis was able to reproduce the TCO correctly over the study region. Moreover, ERA-Interim reanalysis and OMI-Aura show a better comparison with MICROTOPS II during the pre-monsoon (March) season compared to the winter season. Root-mean-square (RMS) values of 44.08, 14.35 and 18.97 DU are found in TCO data from MODIS, ERA-Interim reanalysis and OMI-Aura respectively compared with the MICROTOPS II measured TCO (Table 1). Table 1 shows MODIS data with the largest bias value of about 29.3 DU followed by the ERA-Interim reanalysis with a bias value of about 8.6 DU and OMI-Aura with the smallest bias value of about 3.9 DU. A strong correlation (R = 0.94) was found between the ERA-Interim reanalysis and the MICROTOPS II TCO compared to the other satellite TCO datasets and this signifies that the use of the ERA-Interim reanalysis TCO is reliable for future meteorological applications in scientific studies over Ahmedabad.

3.2. Total water vapour

Figure 3 shows the daily mean variations of total WV available from the MODIS, ERA-Interim reanalysis and MICROTOPS II

Table 1. Statistics of TCO, WV and AOT available from MODIS and OMI-Aura satellite data and ERA-Interim reanalysis over Ahmedabad, India, when MICROTOPS II measurements are considered as truth.

Parameter	Source	RMS deviation	Bias	Correlation	Number of days
TCO (DU)	MODIS	44.08	29.26	0.02	41
	ERA-Interim	14.35	8.56	0.94	47
	Aura	18.97	3.86	0.74	26
WV (cm)	MODIS	0.81	0.58	0.41	44
	ERA-Interim	0.67	0.62	0.92	48
AOT	MODIS	0.29	0.22	0.67	23

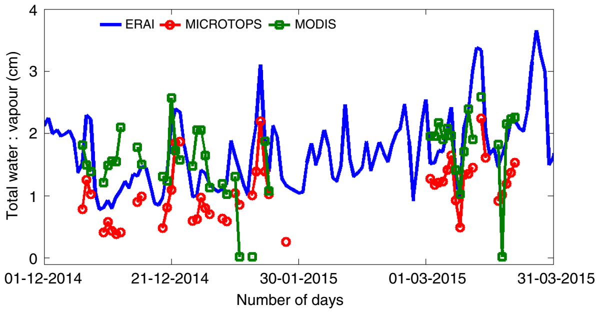

Figure 3. Daily mean variations in water vapour (cm) during December 2014 to March 2015 observed by the MICROTOPS II, the moderate resolution imaging spectroradiometer (MODIS) and ERA-Interim reanalysis. [Colour figure can be viewed at wileyonlinelibrary.com].

ozonometer. The MODIS overestimates the WV values compared to ERA-Interim reanalysis values when validated against MICROTOPS II measured WV values. The daily mean variation of WV from ERA-Interim and MICROTOPS II shows that WV increases from January to March 2015. The MODIS retrieved WV values did not capture this variation. The MICROTOPS II measured WV values range between 0.2 and 1.3 cm in December. A gradual increase in WV values was observed towards March with values ranging between 0.5 and 2.25 cm. The ERA-Interim WV values in March were observed to match the corresponding MICROTOPS II WV values for the winter. Table 1 shows RMS WV values of the MODIS and ERA-Interim compared to MICROTOPS II measured WV values. The highest RMS WV value of about 0.81 cm was found in the MODIS data and the lowest of about 0.67 cm was found in the ERA-Interim data. Table 1 also shows that the largest bias value of about 0.62 cm was found in the ERA-Interim WV data and the smallest value of about 0.58 cm was found in the MODIS WV data. The largest correlation value was found in the ERA-Interim WV data and the smallest was found when the MICROTOPS II measured

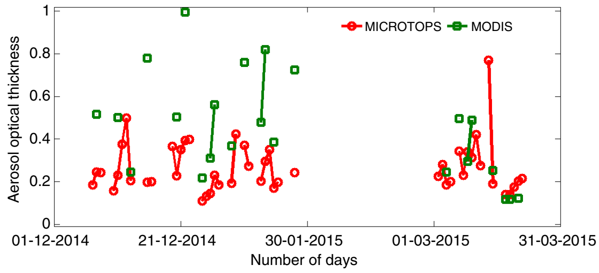

Figure 4. Daily mean variations in aerosol optical thickness during December 2014 to March 2015 observed by the MICROTOPS II and the moderate resolution imaging spectroradiometer (MODIS). [Colour figure can be viewed at wileyonlinelibrary.com].

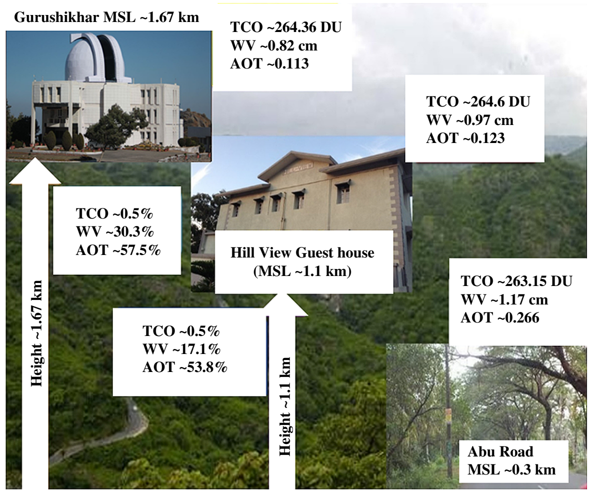

Figure 5. Variations in total column ozone (TCO), water vapour (WV) and aerosol optical thickness (AOT) observed by the MICROTOPS II at different altitudes over Mount Abu and Rajasthan regions. [Colour figure can be viewed at wileyonlinelibrary.com].

WV was compared to WV values retrieved from the MODIS satellite data.

3.3. Aerosol optical thickness

The daily mean variations of AOT retrieved from the MODIS at 550 nm and the MICROTOPS II ozonometer at 1020 nm are shown in Figure 4. An overestimation is observed in the MODIS AOT values in comparison to the MICROTOPS II AOT values. An increasing trend from January to March 2015 was observed in the daily mean variation of MICROTOPS II AOT. The trend followed by the MICROTOPS II AOT is also captured by the MODIS AOT. However, a magnitude difference

Table 2. Variations of TCO, WV and AOT at different altitudes.

Parameter	Variations					
	Abu Road (~0.3 km)	Hill View (~1.1 km)		Gurushikhar (~1.67 km)		
	Observed value	Observed value	Percent changes from Abu Road	Observed value	Percent changes from Abu Road	Percent changes from Hill View
TCO (DU)	263.150	264.600	0.5	264.360	0.5	−0.09
TWV (cm)	1.170	0.970	17.1	0.820	30.3	15.46
AOT	0.266	0.123	53.8	0.113	57.5	8.13

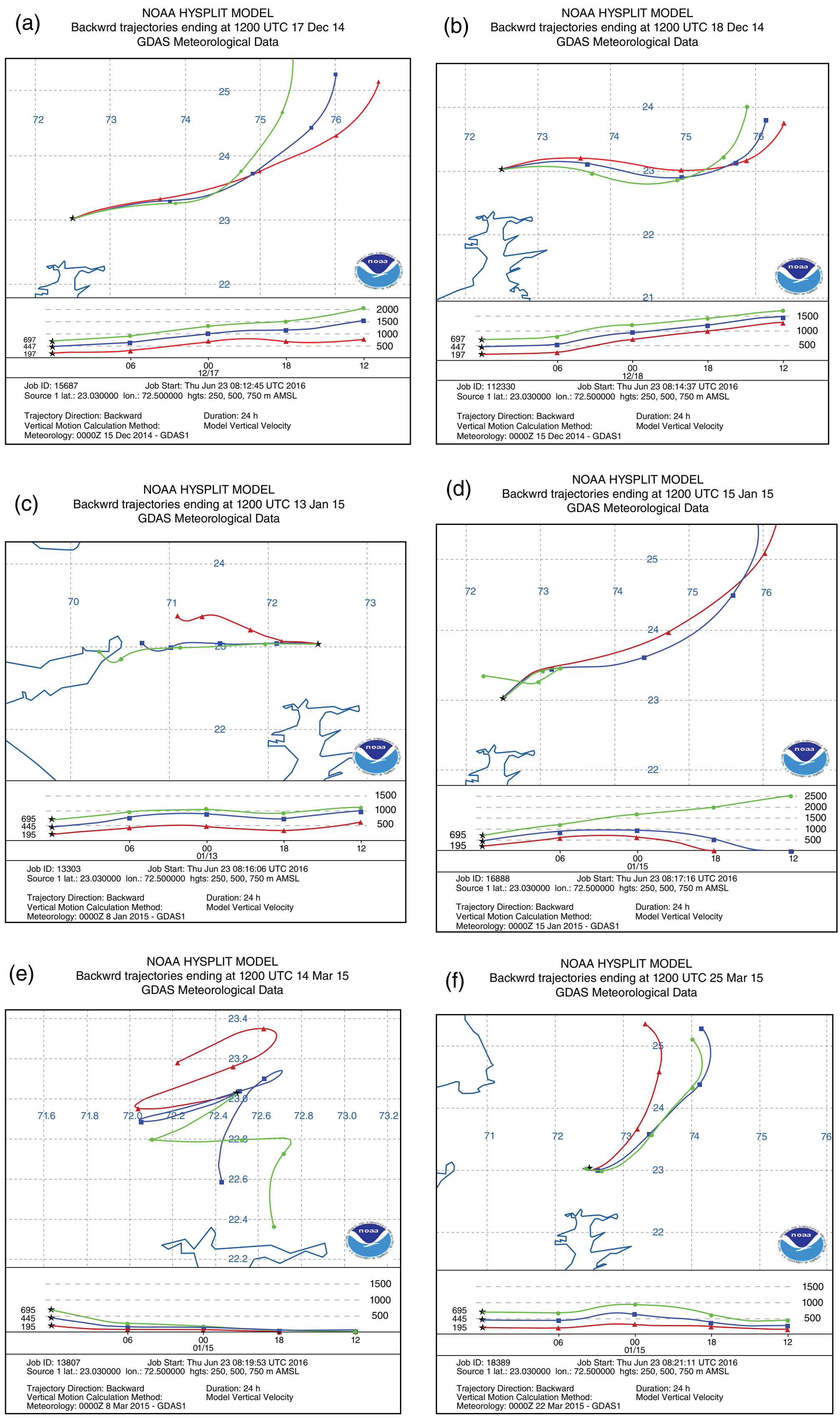

Figure 6. Seven day back air mass trajectory over Ahmedabad on a high aerosol optical depth observation day: (a) 17 December 2014, (b) 18 December 2014, (c) 13 January 2015, (d) 15 January 2015, (e) 13 March 2015 and (f) 25 March 2015. [Colour figure can be viewed at wileyonlinelibrary.com].

was observed in both ground-based and MODIS AOT which could be due to the spatial resolution and overpass time of the MODIS and also the wavelength difference. In December (March), the MICROTOPS II measured AOT ranged between 0.1 and 0.55 (0.19 to 0.8) respectively. Figure 4 shows that the MODIS retrieved AOT is higher than the MICROTOPS II observations. An RMS value of 0.29 is found in the AOT data from the MODIS compared with MICROTOPS II measured AOT (given in Table 1). A bias of ∼0.22 is found in the AOT retrieved by the MODIS. A reasonably good correlation (∼0.67) was found between MICROTOPS II measured AOT and MODIS retrieved AOT.

The increasing trend of the TCO, WV and AOT can be attributed to seasonal variation. During winter the weather is calm, but on approaching summer there are prevailing wind conditions and convection, leading to unstable atmospheric conditions which are a plausible reason behind such observed variability. Gómez-Amo *et al.* (2013) found good agreement and correlation between satellite observations and observations using three MICROTOPS. Srivastava *et al.* (2008) have also shown the variation in TCO, WV and AOT using MICROTOPS II and TOMS satellite data and found that the TCO from satellites is higher than the TCO measured with MICROTOPS II (Pant *et al.*, 2006). This difference in the magnitude of ozone resulting from ground-based and satellite-based instruments may be attributed to the observation process, a satellite passing through a particular location pointing downwards while ozonometer measurements are taken from the Earth's surface pointing upwards (e.g. Kalapureddy *et al.*, 2008; Srivastava *et al.*, 2008).

4. Spatial variation of TCO, WV and AOT over Mount Abu

Figure 5 shows a comparative study of TCO, WV and AOT at different altitudes. The present study aimed to find the variation of these parameters and also to investigate the effects of different altitudes on these parameters. The observations were taken from three different locations and altitudes at Abu Road (∼0.3 km amsl), Hill View Guest House (∼1.1 km amsl) and Gurushikhar (∼1.67 km amsl) which is considered as the highest peak in the Aravali range of mountains. The TCO shows almost negligible variation in the measurements taken at any of the altitudes, but WV and AOT vary significantly. The WV and AOT vary by 17.1 and 53.8% respectively in the first 1 km, and WV varies by 30.3% and AOT by 57.5% in ∼1.67 km (given in Table 2). Variations in WV and AOT are found over these sites while TCO remains almost constant as shown in Figure 5. Since WV and AOT are tropospheric constituents they show much variation within these ranges while the major contribution in TCO is the stratospheric constituent and hence it does not show much variation.

5. Influence of air masses over the observational site by using the HYSPLIT model

The National Oceanic and Atmospheric Administration (NOAA) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is an important tool that describes the transportation, dispersion and deposition of atmospheric pollutants in the atmosphere (Draxler and Rolph, 2003). Deshpande *et al.* (2015) studied the WV content transported over Ahmedabad during the monsoon season using the HYSPLIT model. They concluded that the Arabian Sea is a more dominant source of WV in comparison to the Bay of Bengal and other regions. In order to investigate the aerosol sources over the site on high AOT days during the study period, a 7 day air mass backward trajectory on 17 and 18 December 2014, 13 and 15 January 2015, and 14 and 25 March 2015 over Ahmedabad at 250 m, and 750 m amsl was performed to achieve a better understanding about the sources of the air masses arriving over the site (Figure 6). A Global Data Assimilation System analysis was used as the meteorological input parameter in the HYSPLIT model. The trajectory is plotted for 17 December 2014, 18 December 2014, 13 January 2015, 15 January 2015, 13 March 2015 and 25 March 2015 in Figures 6(a)–(f) respectively. The trajectories on 17–18 December 2014 and 25 March 2015 show the aerosol transport from the Thar desert of the Rajasthan region over the site. The high aerosol concentration over the site due to local sources of the Gujarat was observed on 13, 15 January 2015 and 13 March 2015. Ahmedabad is an urban city and has lots of industries around the site within a distance of a few kilometres (5–10 km). Local pollution sources such as dust, industry emissions, biomass burning and vehicular emissions have played an important role in the increase in AOT over the site. The wind pattern during winter (December–February) and the pre-monsoon season (March–May) over Ahmedabad is northerly to northeasterly and northeasterly respectively.

6. Conclusions

Significant daily and seasonal variations are found in total column ozone (TCO), water vapour (WV) and aerosol optical thickness (AOT) over the western India region. These atmospheric parameters show an increasing trend from the winter to the summer. The results show a reasonably good comparison between satellite data retrieved from the ozone monitoring instrument on Aura (OMI-Aura) and ERA-Interim reanalysis, in conjunction with MICROTOPS II ozonometer measurements. Higher concentrations of TCO and WV are noted from the satellites and ERA-Interim reanalysis similar to the MICROTOPS II measurements, although for a few occasions there is a good match between ground-based measurements and space-based satellite retrieval in the case of TCO, WV and AOT. Furthermore, a comparative study was performed at Mount Abu to find the concentration of TCO, WV and AOT at various altitudes. Variations in TCO recorded at different altitudes are negligible, but WV and AOT vary significantly. WV and AOT vary 17.1% and 53.8% respectively in the first 1 km change of altitude from the lowest altitude locations, and at 1.67 km points over the hill top WV varies by 30.3% and AOT by 57.5%. The HYSPLIT model represents the dominance of local sources of aerosols due to industrial and vehicular emissions and also transported from the nearby desert station Rajasthan. These ground-based measurements showed large variability of these two atmospheric constituents (WV and AOT), which are extremely important for a modelling exercise, which generally misses in numerical models which are required as an input parameter at higher spatial resolution. Moreover, high altitude observations are very sparse on the Indian subcontinent and it becomes an important input parameter to improve and understand numerical models over such complex orographic regions.

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