CHAPTER – 5

STUDY OF VERTICAL DISTRIBUTION OF TOPOSPHERIC AEROSOL NUMBER DENSITY

5.1. INTRODUCTION

Twilight scattering method (TSM) is extensively used by several workers in all over the world to study the vertical distribution of aerosol particles which is a strong function of their sources, sinks and their residence times. All this study is reviewed by Jadhav et al. [1] which is mainly on the stratospheric aerosols. The tropospheric aerosols are least studied. In the present work aerosol measurements have been carried out at Kolhapur (16°42′N, 74°14′E) by using newly designed Semiautomatic Twilight Photometer during the period 1 January 2009 to 30 December 2011 to study the vertical distribution of the tropospheric aerosol number density per cm$^3$ (AND) (Here after aerosol number density per cm$^3$ is called as AND). The day to day variability of the vertical distribution of AND, monthly and seasonal variations of tropospheric AND have been discussed in the present study. This is being a passive technique; clear sky conditions are preferable for obtaining the vertical profile of aerosols. The days on which low, middle and high level clouds were observed also noted down during the period of observations. The aerosol-loading factor (Q), in terms of aerosol number density per cm$^3$ (AND) was determined for the heights between 6 to 7 Km, 8 to 12 Km and its changes attributed to variations in the weather conditions were also studied in the present work.

The troposphere aerosols absorbs the radiation from sun reaching the observer, this depends upon the wavelength we are used for observations [2]. During observations the scattered radiations only pass through the tropospheric layer at point of observations. Only rate of change of intensity with respect to height is considered for calculations. Thus the technique used gives the signature of aerosols above tropospheric aerosol layer only [3].
5.2. THE DAY-TO-DAY, MONTHLY AND SEASONAL VARIABILITY OF ‘AND’ IN LOWER MIDDLE TROPOSPHERE

Various types of variability of AND in between the heights 6 to 7km (lower middle troposphere) are shown in Figure-5.1.

Figure-5.1: Varies types of variability of AND in between the heights 6 to 7km
Figure-5.1 shows day-to-day variability in lower middle tropospheric AND from 27 October 2009 to 6 May 2010 for morning observations. In this figure Y-axis represents aerosol loading (Q, calculated by equ.15 in Chapter-3) and X-axis represents day numbers (i.e. date for each month). The TSM data collection at Kolhapur is generally not possible during ~mid-May to ~mid-October in any year because of the prevailing monsoon conditions (rains and extensive cloud cover). This being a passive technique, clear sky conditions are preferable for obtaining the vertical profiles of aerosols. Thus data coverage is for the period ~mid-October of any year to ~mid-May of the succeeding year.

For studying the seasonal variations, the year is divided into four seasons as follows, [4, 5, and 6]

- **Monsoon or rainy season:**

  Kolhapur city receives abundant rainfall (southwest summer monsoon) from June to September due to its proximity to the Western Ghats. Temperatures are low in the rainy season and range between 19°C to 30°C.

- **Post-monsoon season:**

  This is lasting from October to November. These two months are usually cloudless and experience the dry northeast monsoon.

- **Winter season:**

  Kolhapur experiences winter from December to February. The winter temperatures are a bit higher compared to other cities in Maharashtra such as Pune and Nasik. Lows range from 9°C to 16°C while highs are in the range of 26°C to 32°C due to its high elevation and being adjacent to the Western Ghats. Humidity is low in this season making weather much more pleasant.

- **Summer or pre-monsoon season:**

  Kolhapur experiences summer from March to May. Summer in Kolhapur is comparatively cooler, but much more humid, compared to neighboring
inland cities. Maximum temperatures rarely exceed 38°C and typically range between 33° to 35°C. Lows during this season are around 24°C to 26°C.

The lower middle troposphere (heights between 6 Km to 7 Km) showed day-to-day variability from October to May with highest aerosol loading in the month of May and lowest in the middle of March. (The lower middle tropospheric aerosol loading is abbreviated as $Q_1$). In the post-monsoon season the $Q_1$ started increasing form mid-October to end of November. In winter the $Q_1$ started decreasing from early December to the mid-January (11 January 2010). This was the relatively cold period in the winter having a lower temperature ~14°C. From 11$^{th}$ January $Q_1$ values increased up to mid-February (13 February 2010). The atmosphere started warming in this period. From mid-February $Q_1$ values started decreasing with lowest values of the year at mid-March (in between 10$^{th}$ March to 22$^{nd}$ March). In the summer the $Q_1$ values started increasing from end of the March through April up to May with highest aerosol loading. Deviations from this trend in April were observed for clear days in between cloudy days. Cumulous clouds were observed frequently in between 12$^{th}$ to 19$^{th}$ April 2010. There was no TSM data available after 6 May 2010 due to extensive cloud cover formed by the active phase of the south-west monsoon. The monthly variations were in good agreements with Hindu lunar months. (Kartika starts at ~mid-October and every succeeding Hindu lunar month starts at middle of every succeeding Gregorian month). The monthly and seasonal variability of AND ($Q_1$) obtained for very clear days in the present study are very well sound with the aerosol optical depth variations obtained at Mysore by Raju et al. [7].

Considering the seasonal variation of natural factors like temperature and rains Raju et al. [7], explained the experimentally observed features of aerosol characteristics as follows. The average temperature patterns for winter and summer months show significant differences. The relatively higher temperature in summer would result in enhanced aerosol generation due to primary production (bulk-to-particle conversion) and photochemical processes (secondary production) as compared to that in winter with low temperatures. During monsoon, the wet removal (scavenging) of atmospheric aerosols would be more efficient due to heavy and prolonged monsoon rains than in winter or summer
seasons. The combined effect of significant wet removal of atmospheric aerosols in monsoon season, which precede the winter months, and the decreased production of small aerosols by secondary production in winter months result in an overall reduction of aerosols. In summer, there would be remarkable enhancement in the total aerosol load due to increased small particle concentration from secondary processes and large particles from primary production. In addition, the presence of substantial but infrequent rains in summer and almost total absence of rains in winter months would influence the generation, growth and loss processes of the aerosols. Further, the usual dry conditions with reduced humidity in winter months and comparatively high humidity in summer months would affect the coagulation and growth processes of aerosols in winter and summer months. Thus the observed seasonal variations in the AND (in the present study) are as a result of the natural variations in the production and removal of aerosols in summer and winter. The experimental results obtained by the present study are well agreement with theory.

5.3. THE DAY-TO-DAY, MONTHLY AND SEASONAL VARIABILITY OF ‘AND’ IN MIDDLE AND UPPER TROPOSPHERE

Different types of variability of AND in middle and upper troposphere are shown in the following Figure-5.2. The black and red lines show day-to-day variability in middle and upper tropospheric AND from 27 October 2009 to 6 May 2010 for morning observations respectively. The middle troposphere (heights between 8Km to 11Km) showed day-to-day variability from October to May with highest aerosol loading in the month of October and lowest in the middle of March. (The middle tropospheric aerosol loading is abbreviated as Q$_2$). The upper troposphere (heights between 12Km to 16Km) showed day-to-day variability from October to May with highest aerosol loading in the month of October and lowest in the middle of March. (The upper tropospheric aerosol loading is abbreviated as Q$_3$).
Figure-5.2: Varies types of variability of AND in middle and upper troposphere
In the post-monsoon season the $Q_2$ started increasing highly in the month of October with highest on 3 November 2009. The values of $Q_2$ decreased slowly up to 24$^{th}$ November and then highly decreased up to 22$^{nd}$ December in winter. There was in phase relation in between the values of $Q_2$ and $Q_3$ for all above mentioned period. Many fluctuations were observed in the values of $Q_2$ and $Q_3$ from 22 December 2009 to 11 January 2010. In this period cumulus and cirrus clouds were observed frequently in between the clear sky days. There was opposite phase relation in between the values of $Q_2$ and $Q_3$ for this period. In winter having lowest temperature ~14°C, the values of $Q_2$ and $Q_3$ increased slowly up to 23$^{rd}$ January with in phase relation between them. Again many fluctuations were observed in the values of $Q_2$ and $Q_3$ from 23 January 2010 to 12 February 2010. In this period also cumulus and cirrus clouds were observed frequently in between the clear days. In the face of summer season values of $Q_2$ decreased having lowest in the month of March. After that the values of $Q_2$ stared increasing at the face of arrival of south-west summer monsoon season. In summer season the opposite phase relation was observed in between the values of $Q_2$ and $Q_3$.

5.4. COMPARISON BETWEEN TWO YEAR’S TROPOSPHERIC ‘AND’

Figure-5.3 shows comparison between two year’s tropospheric aerosols loading for morning observations. The black line represents annual variation from 1 January 2010 to 31 December 2010 and red line from 1 January 2011 to 31 December 2011. In this figure Y-axis represents aerosol loading factor ($Q$) and X-axis represents day numbers for each year. In the month of October lower middle tropospheric aerosol loading (‘$Q_1$’) showed (comparison between the years 2009 and 2010 is not shown in the figure) higher values (~50% increase) for 2010 than 2009, whereas higher aerosol loading showed no change for the both years. In both the months (November and December) there observed no change in tropospheric aerosol loading ‘$Q$’ for all the three layers ($Q_1$, $Q_2$, and $Q_3$) for both years (2009 and 2010). The values of ‘$Q_1$’ in the month of January and February, 2010 were nearly two times the values of ‘$Q_1$’ for year 2011 in the same months. In the months of March and April the values of ‘$Q_1$’ were ~50% higher for 2010 than 2011. The values of aerosol loading showed many fluctuations for all the three layers in the year 2010.
Figure-5.3: comparison between two year’s tropospheric aerosols loading for morning observations
Figure 5.4: comparison between morning and evening tropospheric aerosol loading

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5.5. COMPARISON BETWEEN MORNING AND EVENING TROPOSPHERIC ‘AND’

Figure-5.4 shows comparison between morning and evening tropospheric aerosol loading from 25 October 2009 to 10 May 2010 observations. In this figure Y-axis represents aerosol loading (Q) and X-axis represents day numbers (Day numbers 25 to 222 represent the dates from 25 October 2009 to 10 May 2010). Good agreement was observed between morning and evening aerosol loading for all the three tropospheric levels. The considerable difference in morning and evening aerosol loading was observed when there were cloudy days frequently in between clear days. The Lower middle tropospheric aerosol loading was ~10 times and ~15 times higher than that of middle and higher tropospheric aerosol loading respectively.

5.6. TO EXAMINE THE ASSOCIATION BETWEEN VARIATIONS IN AEROSOL NUMBER DENSITY AND WEATHER CONDITIONS

Weather is a set of all the phenomena occurring in a given atmosphere at a given time. Weather phenomena lie in the troposphere [8]. Weather refers, generally, to day-to-day temperature and precipitation activity. Cloud formation is dependent on aerosols. If no aerosols are present, large super-saturation (relative humidity over 100%) can be observed without droplet formation. But aerosols, in different concentrations, are present everywhere in the atmosphere. Cloud droplets condense on the aerosols, the giant particles (Coarse mode- >1μm). Stratospheric as well as tropospheric aerosols contribute to cloud formation [9].

The aerosol-loading factor (Q), in terms of aerosol number density per cm$^3$ (AND) was determined for the heights between 6 to 7 Km, 8 to 12 Km and its changes attributed to variations in the weather conditions were studied in the present work. The clouds are generally divided into three types, viz. High, medium and low level clouds as explained in section 3.15-3.17 (Chapter-3) [10].
High-level clouds

High-level clouds form above 6 Km [11]. Relation between AND vertical profiles at 6-7 Km obtained at clear sky days preceding the high level cloudy sky days were studied for the observational period and got the results. The results acquired reveal that one hump was detected three days prior to the high level cloudy sky days. This hump was at ~6.8 to 6.9 Km, having AND ~125 to 185 particles per cm$^3$. This hump was found to be moving downward with an average speed of the order of ~0.2 to 0.3km per day for the two subsequent days after perceiving it. The AND at 6km was increased up to ~1000 particles per cm$^3$ at prior to the high level cloudy sky conditions. Two of the examples are given in the following Figure-5.5.

Example-I:

5/11/2009 is a very high level cirrus cloud day (Figure-5.5-A). On 2/11/2009, a prominent hump having AND 128 particles/cm$^3$ was noticed at 6.88 Km. On the next day i.e. on 3/11/2009, bump was moved downwards with the height difference of 0.22 Km. Thus on this day a lump have AND 458 particles/cm$^3$ was perceived at 6.66 Km. On succeeding day i.e. on 4/11/2009 hump was detected at 6.44 Km with 984 particles/cm$^3$. Thus it was observed that, the hump was moving downwards with the speed at about ~0.22 Km per day with increasing AND. Above the major swelling additional two weak humps also identified. These two minor humps also moved downwards with major swelling. Thus whole pattern showed moving downwards before cloudy sky day (in case of high level clouds).

Example-II:

High level cirrus clouds were observed on 11/02/2011 (Figure-5.5-B). The lump noticed at 6.85 Km on 8/02/2011 having AND 187 particles/cm$^3$ was moved downwards with the speed of 0.27 Km per day for two subsequent days and aerosol loading also increased per day.
Figure 5.5: The variations in the AND vertical profiles at 6-7 km obtained at clear sky days preceding the high level cloudy sky days.
From the curve it was expected that the aerosol layer would come down to a lower height to create favorable conditions for high level cloud development on the following day. The observational evidence supported this fact. On the other days following cloudy sky conditions, the values of AND at ~6Km was found lower (~260 to 300 particles/cm$^3$) in most of the cases. Khemani et al. [12] and Momin [13] reported that at cloud heights, the cloud condensation nuclei (CCN) concentration was around 478 cm$^{-3}$ on cloudy sky days whereas it was around 265 cm$^{-3}$ on clear sky days. This shows an increase in aerosols at mean cloud height (above ~ 6 Km) during cloudy conditions. The findings of the present paper corroborate these results.

**Middle and low level clouds**

Middle and low level clouds were frequently observed following with high level clouds. It implies that the CCN particles perturb downwards. In very rare cases middle level cloudy days were noticed separately after any clear sky day. The bases of mid-level clouds typically appear between 2 to 6 Km [14]. An attempt was also made to study the variations in the aerosol loading, ‘Q’ at 6-7 km in terms of AND obtained on clear sky days preceding the middle level cloudy sky days. The results pointed out that the sudden increase in the values of ‘Q’ at any day followed by sudden decrease at subsequent day was precursor of middle level cloudy days. For example, 25 January, 6 February, 13 April 2010 and 9 March, 24 March, 16 November 2011 are middle level cloudy days. As shown in Figure-5.6, it was expected that the aerosol layer would come down to a lower height to create favorable conditions for middle level cloud development on the following day. The observational evidence supported this fact. In the following Figure-5.6, the black line represents the variations in the aerosol-loading factor (Q), in terms of AND for the heights between 6 to7 Km obtained on clear sky days preceding the middle level cloudy sky days. The red dots represent cloudy sky days.
Figure-5.6: The variations in the aerosol-loading factor (Q), in terms of AND for the heights between 6 to 7 Km obtained at clear sky days preceding the middle level cloudy sky days.
Figure-5.7: The variations in the AND vertical profiles at 8 to 12 km obtained at clear sky days preceding the contrail.
Contrails

Contrails usually occur between about 8 and 12 km altitude [15]. Contrails form through the injection of water vapor into the atmosphere by exhaust fumes from a jet engine. If the surrounding air is cold enough (only if the temperature there is below –40 °C), a state of saturation is attained and ice crystals develop, producing a contrail. Relation between AND vertical profiles at 8 to 12 km obtained at clear sky days preceding the contrail happening days were studied for the observational period and got the results. The results acquired reveal that one or two broad aerosol layers were detected at previous day to the contrail occurring days. For example- 1 February, 21 March, 1 April 2011 and 5 March 2010 were the contrail occurring days. The extensive aerosol layers noticed at previous days of the above mentioned days as shown in the above Figure-5.7. It was expected that these aerosol layers were responsible to create favorable conditions for contrail development on the following day. The observational evidence supported this fact.

Invisible cirrus clouds

Invisible cirrus clouds, i.e. optically thin cirrus layers frequently observed just below the tropopause. The thin cirrus layers extend several hundred to more than a thousand kilometers horizontally [16] and persist for time periods of several hours to several days before dissipating. Though they play a less significant role in the earth’s radiation budget than thick cirrus, their impact on the upper tropospheric thermal structure and vertical velocity, on the lower stratospheric water vapor mixing ratio, and on remote sensing applications are not negligible [17]. These clouds are invisible for normal eyes. Using twilight technique existence of thin invisible cirrus cloud in the field of view of the twilight photometer can be discovered. One more attempt was also made to study the variations in the aerosol loading, ‘Q’ at 8 to11Km in terms of AND obtained at clear sky days preceding the existence of invisible cirrus cloud days. The results pointed out that the aerosol loading at this level increased considerably prior to existence of this type of cloudy days. It was expected that increased aerosol loading was responsible to create favorable conditions for invisible cirrus clouds.
development on the following day. The observational evidence supported this fact.

Many of the consequences of this study are in good agreement with the conclusions made by Jadhav and Londhe [18]. They were unable to distinguish between different types of clouds and their association with aerosol loading. This is achieved in the present work with the help of semiautomatic twilight photometer. One of the main advantages of the semiautomatic twilight photometer is improvement in height resolution. This is obtained due to high rate of sampling, as data is stored for every 10secs, as compared to 30secs in earlier system. Due to this improvement in height resolution, the small fine-scale features, which are not visible in the profiles derived by earlier workers, are visible in the profiles derived in the present study.

5.7. SUMMARY AND CONCLUSIONS

The measurements using the twilight scattering method presented in this section suggest the following:

I. An in-phase relation has been observed between middle and upper tropospheric AND from October to January where as out of phase relation from February to May. The deviation from this trend was observed at the clear sky days in between cloudy days (i.e. when cirrus and cumulus clouds were observed frequently). More sets of observations are essential to arrive at definite conclusion.

II. An in-phase relation has been observed between middle and upper tropospheric AND in post monsoon and early winter seasons, whereas out of phase relation in late winter and summer seasons. More sets of observations are essential to arrive at definite conclusion.

III. Lower middle troposphere showed well agreement between morning and evening AND, (exceptions of cloudy period) where as no considerable difference observed in morning and evening AND for middle and higher tropospheric levels.
IV. The Lower middle tropospheric aerosol loading was ~10 times and ~15 times higher than that of middle and higher tropospheric aerosol loading respectively.

V. In the month of October lower and middle tropospheric aerosol loading showed higher values (~50%) for 2010 than 2009 and there was about double increase in the values of ‘Q’ for the year 2010 than 2011 in the month of January and February.

VI. The monthly variations were in good agreements with Hindu lunar months. More sets of observations are essential to arrive at definite conclusion.

VII. Detail study of AND vertical profiles in between 6 and 7 km gives pre-information about occurrences of high level cloudy days.

VIII. The sudden increase in the values of ‘Q’ at any day followed by sudden decrease at subsequent day could be a precursor of middle level cloudy days.

IX. One or two broad aerosol layers noticed in between 8 to 12 km on the AND vertical profiles at any day could be a forerunner of the contrail occurring at following day.

X. The increased aerosol loading in between 8 to 11 km at any day is responsible to create favorable conditions for invisible cirrus clouds development on the following day.

XI. However, at present the definite relation between variations in tropospheric aerosol number density (AND) and weather conditions could not be established with so few data events. But it is possible if a greater number of events are available.
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Figure-5.3: comparison between two year’s tropospheric aerosols loading for morning observations
Figure-5.4: comparison between morning and evening tropospheric aerosol loading