International Journal of Geology, Earth and Environmental Sciences ISSN: 2277-2081 (Online)
An Online International Journal Available at http://www.cibtech.org/jgee.htm
2012 Vol. 2 (2) May-August, pp.173-192 /Kant et al.
Research Article

DIURNAL AND SEASONAL AEROSOL OPTICAL DEPTH AND BLACK CARBON IN THE SHIWALIK HILLS OF THE NORTH WESTERN HIMALAYAS: A CASE STUDY OF THE DOON VALLEY, INDIA

***Yogesh Kant[1], Piyush Patel[1], A.K. Mishra[1], U.C. Dumka[2] and V.K. Dadhwal[1]**
[1]*Indian Institute of Remote Sensing (IIRS), ISRO, Dept. of Space, Govt. of India*
4 Kalidas Road, Dehradun
[2]*Aryabhatta Research Institute of Observational Sciences, Nainital*
**Author for Correspondence*

ABSTRACT
Ground based measurement of aerosol optical depth (AOD) and black carbon (BC) aerosols were carried out over Dehradun during January to December 2007. The AOD values during winter (December-February) are low and found to be in the range of (0.08-0.38) than during summer (March-June) periods (0.32-0.62). The aerosol loading was observed to be high during summer period due to the long-range transportation of aerosol particles by air mass from the Thar Desert region to the observing site besides the biomass burning and frequent incidents of forest fire at local levels. The annual average BC concentration observed was found to be 4.3 $\pm$ 0.62 μgm^{-3}. Diurnal variation of BC shows a gradual build up in the morning hours between 0600 to 0900 local time and in evening from 1900 to 2200 hrs local time while low concentration is observed during day and night time. The analysis of traffic density measured in the city shows that it has direct influence on the BC concentration. BC concentration increases more than three times during morning and evening compared to afternoon and night hours. Seasonal variations of BC shows high concentration during winter dry season associated with the air masses predominantly coming from Indo-Gangetic plain rich in carbonaceous aerosols and minimum during monsoon season due to wash out. The BC concentration is found to have relationship with anthropogenic activities, boundary layer dynamics and biomass burning which has been observed by the MODIS fire data in and around the region. BC concentration were positive correlated with diurnal temperature range and negative correlated with rainfall and humidity. The values of aerosol optical depth and black carbon concentration over Dehradun have been compared with those reported from selected locations in India.

Key Words: *Aerosol Optical Depth, Black Carbon, Air Mass Back Trajectory, Traffic Density, Mass Mixing Ratio, Modis*

INTRODUCTION
Aerosols are important components of earth–atmosphere–ocean system. They affect climate through three primary mechanisms- direct radiative forcing (absorption and scattering of sun radiation), indirect radiative forcing (modifying the cloud properties thereby affecting albedo of clouds) and have indirect effect in the atmospheric chemistry by modifying the concentration of climate-influencing constituents (Schwartz *et al.*, 1995) (such as GHG's). Aerosols enhances the back scattering of solar radiation and leading to negative radiative forcing while the absorbing black carbon (BC) aerosols leads to the positive effect. Black carbon aerosol, the optically absorbing part of the carbonaceous aerosols is the major anthropogenic component of atmospheric aerosol system. Black carbon is one of the important constituents of ambient particulate matter, which is emitted into the atmosphere as a by-product of combustion processes such as fossil fuels, vegetation burning, industrial effluents, motor vehicle and aircraft exhausts and are generally in the sub-micron region and considered as tracers of anthropogenic impact on environment. The increase in anthropogenic emission would increase in aerosol loading thereby reducing the incoming solar radiation reaching the ground surface. These effects influence regional aerosol radiative forcing (Haywood and Shine, 1997). It has been reported that one of the

principal contributor in the atmospheric radiative forcing and climate change is black carbon (Chung *et al*., 2005; Jones *et al*., 2005). The role of BC and organic aerosols is getting increase recognized in the atmospheric chemistry and radiative forcing model (IPCC, 2007). It has been reported that the global mean clear sky radiative forcing at the top of the atmosphere due to BC ranges from + 0.27 to + 0.54 Wm^{-2} (Jacobson, 2001). The measurement and understanding of altitudinal variation of BC is important in estimating the radiative and environmental impact in a particular ecosystem. The lifetime of BC is of few days to weeks depending on the meteorological conditions in an area. The average atmospheric residence time of BC is high during dry season compared to wet periods (Babu and Moorthy, 2001). The sink for BC is through wet and dry deposition (not degraded in the atmosphere) (Orgen and Charlson, 1983). BC may have influence on the regional climate and on the regional hydrological cycle. Studies have shown there is heating of lower troposphere and cooling of surface due to the fact that aerosol BC absorb and reflect incoming solar radiation thereby enhancing the temperature gradient with stronger pre-monsoon rainfall and reducing monsoon rainfall over India (Chung *et al.*, 2002; Lau and Kim., 2006; Menon *et al.*, 2002; Ramanathan *et al.*, 2005). Meehl *et al.*, (2000) opined that if only the effects of the observed increase of greenhouse gases were affecting the Indian monsoon, the monsoon season rainfall should have been increasing which is contrary to the findings. This suggests that the aerosol black carbon have been playing a role in regulating the regional climate. There have been many studies over India showing the seasonal and diurnal variation of BC concentration at different types of environments (Babu *et al.,* 2002, Latha and Badarinth, 2003; Badarinth *et al.,* 2007; Tripathi *et al.,* 2005; Safai *et al.,* 2007). These measurements help us in understanding the temporal changes in BC characteristics associated with atmospheric patterns. Such information is essential for estimating and quantifying radiative forcing over Indian region. The present study aimed at aerosol loading and BC measurements carried out for one whole year over Dehradun, a valley in the shiwalik hills. The diurnal and seasonal behaviors of BC and AOD were studied and their relations to the meteorological parameters were examined. Traffic density at nearby places, local boundary layer and the air mass back trajectory for possible transport has also been studied.

Study Area

Dehradun ($30^{0}00'$ N to $30^{0}30'$ N and $78^{0}18'$ E to $78^{0}36'$ E) is the capital of Uttarakhand state, as well as the district headquarters. It is a valley situated in the Shiwalik range of the Himalayas at a mean altitude of 670 m.s.l, it extends 80 km in length and ~20 km in average width (Figure 1).

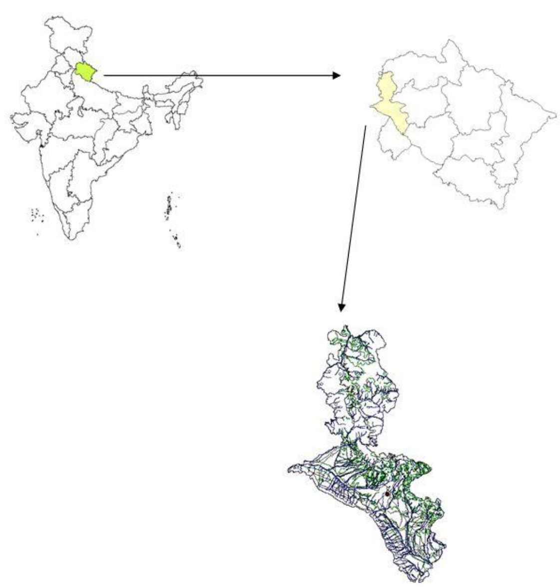

Figure 1: Location map of the study area

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It has prominent influence of Indo Gangetic flood plain and high altitude character of Sub-Himalayan region. To the north and east are hills of high altitude (2000 m). There are small-scale industries in Dehradun and some of the major ones are located to the east and south of Dehradun (30-40 km). Farther to the south lie densely populated regions, including New Delhi (250 km), and to the southeast lies the Indo-Gangetic plain. Since it is a valley, it attracts inversion during considerable period of year.

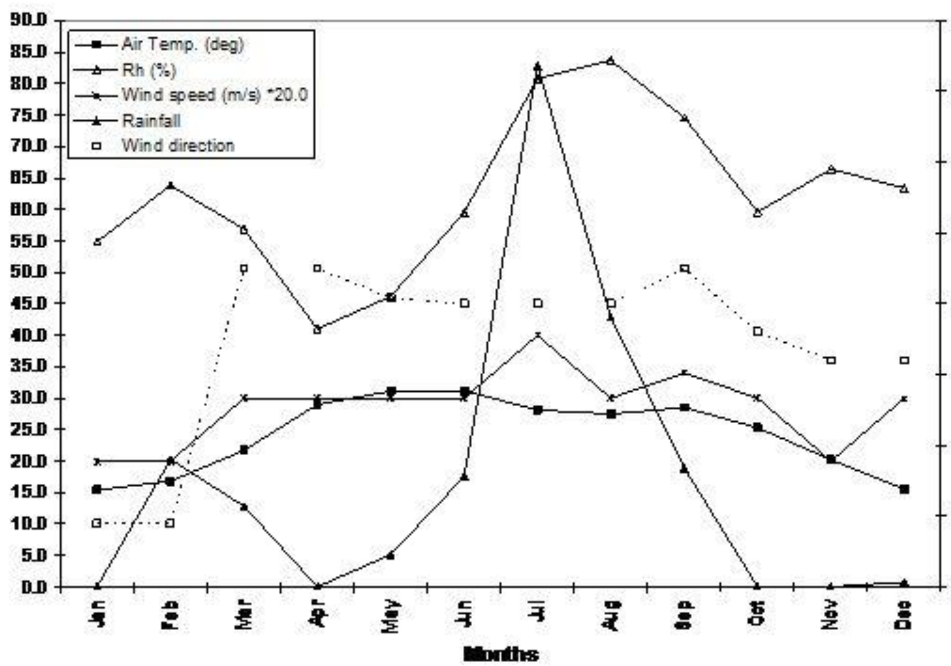

Figure 2: Monthly mean of meteorological parameters at Dehradun for the year 2007 (Source: IMD, Dehradun)

Significant amount of rainfall occurs between 15 June to September which accounts around 70-80% of the total annual rainfall. The annual rainfall over the area is around 2000 mm and the year 2007 experienced a deficit of around 50% and experienced significant pre-monsoon rains. The relative humidity is generally less than 55% during summer, around 60-65% during winter and 80-85% during monsoon (Figure 2). Around the year, the average wind speed over the area is generally low and is less than 4.0 m/s and the winds during summers (March-June) are predominantly from westerly-northwesterly, in monsoon (June-September) are south-southwesterly, during post-monsoon (October-November) are westerly-southeasterly and during winter (December-February) predominantly are southeasterly.

MATERIALS AND METHODS

Instrumentation and Data Analysis

AOD Measurement:

Measurement of aerosol columnar optical depth was carried out using Multi-Wavelength Radiometer (MWR), a passive ground-based instrument designed for studying the spatial variation in aerosol characteristics at 10 narrow wavelength bands viz., 380, 400, 450, 500, 600, 650, 750, 850, 935 and 1025 nm (Moorthy *et al.*, 1989). Being a passive system using the sun as the source, MWR can be operated only during clear days or on partly clear days when no visible clouds are present. Continuous measurement on the AOD was carried out at Dehradun during January to December 2007 using the MWR. A total of 78 days observations in the year have been taken to study the aerosol optical depth over the area.

The MWR collects the ground-reaching solar flux as a function of solar zenith angles. The well-known Lambert-Beer-Bouguer Law allows the estimation of aerosol optical depth (AOD)

$$I_\lambda = Io_\lambda \exp[-\tau_\lambda m_r] \quad (1)$$

Where Io_λ= extra-atmospheric solar irradiance,
m_r = relative air mass, I_λ is the direct solar irradiance at the earth's surface at wavelength λ, τ_λ= total optical thickness and m is the absolute air mass.
The total optical depth τ_λ is estimated by means of the calibration Langley procedure and considering τ_λ as the sum of the contribution of the different atmospheric components,

$$\tau_\lambda = \tau_{R\lambda} + \tau_{g\lambda} + \tau_{w\lambda} + \tau_{a\lambda} \quad (2)$$

$\tau_{R\lambda}$ = Rayleigh optical thickness, $\tau_{g\lambda}$ = absorption optical depth due to atmospheric gases,
$\tau_{w\lambda}$ = water vapor optical depth, $\tau_{a\lambda}$ = Aerosol optical depth.
The raw data was edited and AOD values are estimated as the slope of the regression line by solving a linear square fit between the natural logarithm of voltage at particular wavelength and the corresponding relative air mass following the Langley technique.

BC Measurement:

Continuous measurements of aerosol BC were made using Aethalometer model AE-42 of Magee Scientific, USA. The instrument was operated continuously daily on a 24 hours cycle at a flow rate of 3 Liter per minute at sampling rate of 5 min interval and aspirates ambient air using an inlet tube from ~15 m above the ground. The instrument was factory calibrated and errors in the measurements are around $\pm$ 2%. The atmospheric air is pumped through an inlet at the desired flow rate that impinges on a quartz filter strip. A LED lamp transmitted light beam at a wavelength of 880 nm is transmitted through the sample deposited on the filter strip. The measurement of the attenuation of light beam is linearly proportional to the amount of BC deposited on filter strip.

Details of the Aethalometer are discussed elsewhere (Hansen *et al.*, 1984). MWR and Aethalometer are located in the premises of Indian Institute of Remote Sensing (IIRS) campus (located within 1 km radius of urban city centre) and placed at a height of 15 m from the ground level. Continuous one year data from January to December, 2007 on AOD and mass concentration of aerosol BC was used for analysis.

In the study, experiments were also conducted on traffic density in addition to continuous measurement of BC and AOD during the dry periods of December-February as lifetime of BC is higher in the dry periods. The meteorological data of wind speed, wind direction, relative humidity, air temperature, rainfall were obtained from India Meteorological Department (IMD).

RESULTS AND DISCUSSION

Spectral Variation of Aod

Monthly mean AOD variation during the year 2007 is shown in figure 3. The spectral variation of AOD shows relatively strong wavelength dependence of optical depth at shorter wavelengths that gradually decreases towards longer wavelengths attributing to the dominance of accumulation mode particles. During summer a slight increase in AOD is observed at longer wavelengths suggesting presence of high concentration of coarse mode particles. The afternoon AOD values are observed to be high attributing to convective mixing and cloudy sky conditions.

The AOD values during winter (December-February) are low and found to be in the range of (0.08-0.38) than during summer (March-June) periods (0.32-0.62). Low AOD values during winters is due to weak generation and gas-to-particle conversion processes, while high AOD during summer is due to increase surface heating resulting in vertical mixing and the dust winds.

The high concentration of coarse mode particles during summer is due to the dust winds coming from the far western direction of Thar Desert region besides the biomass burning and frequent incidents of forest fire at local levels (Sapna *et al.*, 2009). Due to noticeable rains (pre-monsoon rains) observed in March the mean AOD values are observed to be low. AOD at 500 nm (AOD_{500}) value during summer is found in the range of 0.23-0.63 (figure 4) while for winter it is 0.1-0.39 except 0.54 observed on one day.

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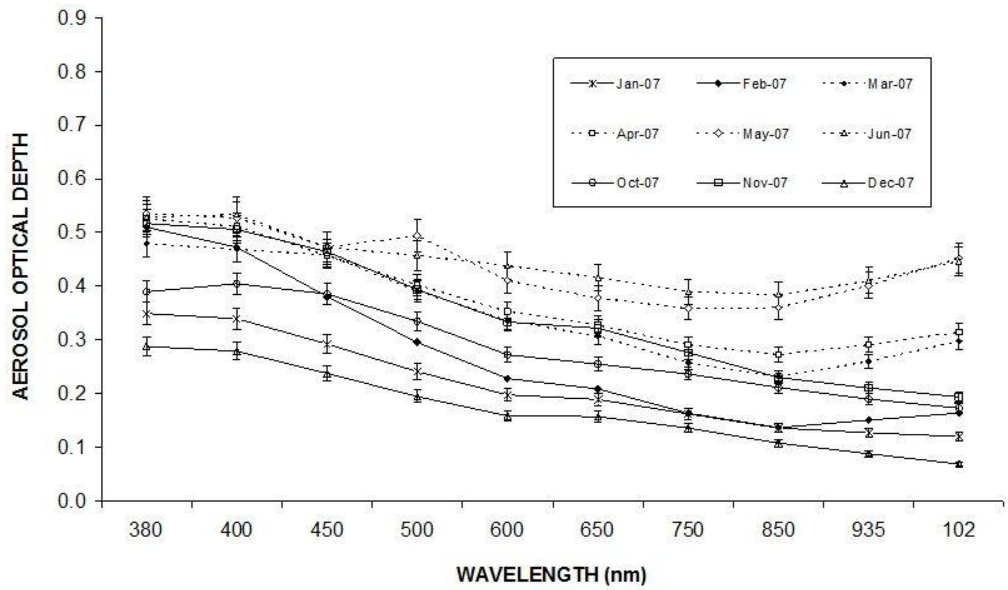

Figure 3: Mean monthly spectral variation of AOD over Dehradun (Vertical bars are S.D ± 1.0)

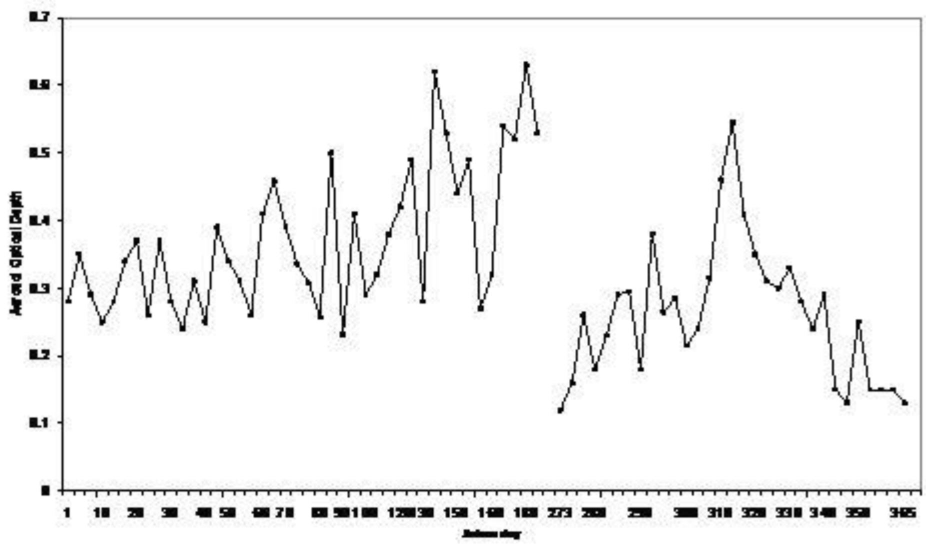

Figure 4: Variation of AOD at 500 nm over Dehradun for the year 2007

The observed values are found to be in the range with those reported at 500 nm for summer season (~0.16-0.45) over Nanital (29^0 22' N, 79^0 27' E, ~1950 m msl) (Dumka *et al.*, 2008); over Mohal (39^0 54' N, 77^0 7' E, 1154 m msl) in Kullu valley (0.24-0.27) (Kuniyal *et al.*, 2009); over Patiala (30^0 21.5' N, 76^0 27'E, 249 m msl) (0.26-0.58) (Singh *et al.*, 2008); over Dibrugarh ($27^0$18'N, 74^0 30'E) (0.2-0.5) (Bhuyan et al., 2005); over Rajkot (22^0 18' N, 70^0 44'E, 142 m msl) (0.20-0.30) (Ranjan *et al.*, 2007); mean monthly AOD_{500} over Pune (18^0 32'N, 73^0 51'E, 559 m msl) (0.42) (Pandithurai *et al.*, 2007); over Hyderabad (17^0 28'N, 78^0 26'E, ~530 m msl) (0.45-0.62) (Badarinath *et al.*, 2007); over Anantapur (14^0 37'N, 77^0 39'E) in the range of (0.437-0.496) (Raghavendra *et al.*, 2009); mean monthly AOD_{500} value 0.40 over Trivandrum (8^0 30'N, 76^0 55'E, 2 m msl) during inter monsoon season (April-May) (*Babu et al.*, 2007). However, the winter values are found to be high than observed for Nanital (a station in the Himalayan region) (~0.03-0.12) for the reason of high topography (1958 m a.m.s.l) of the station (free

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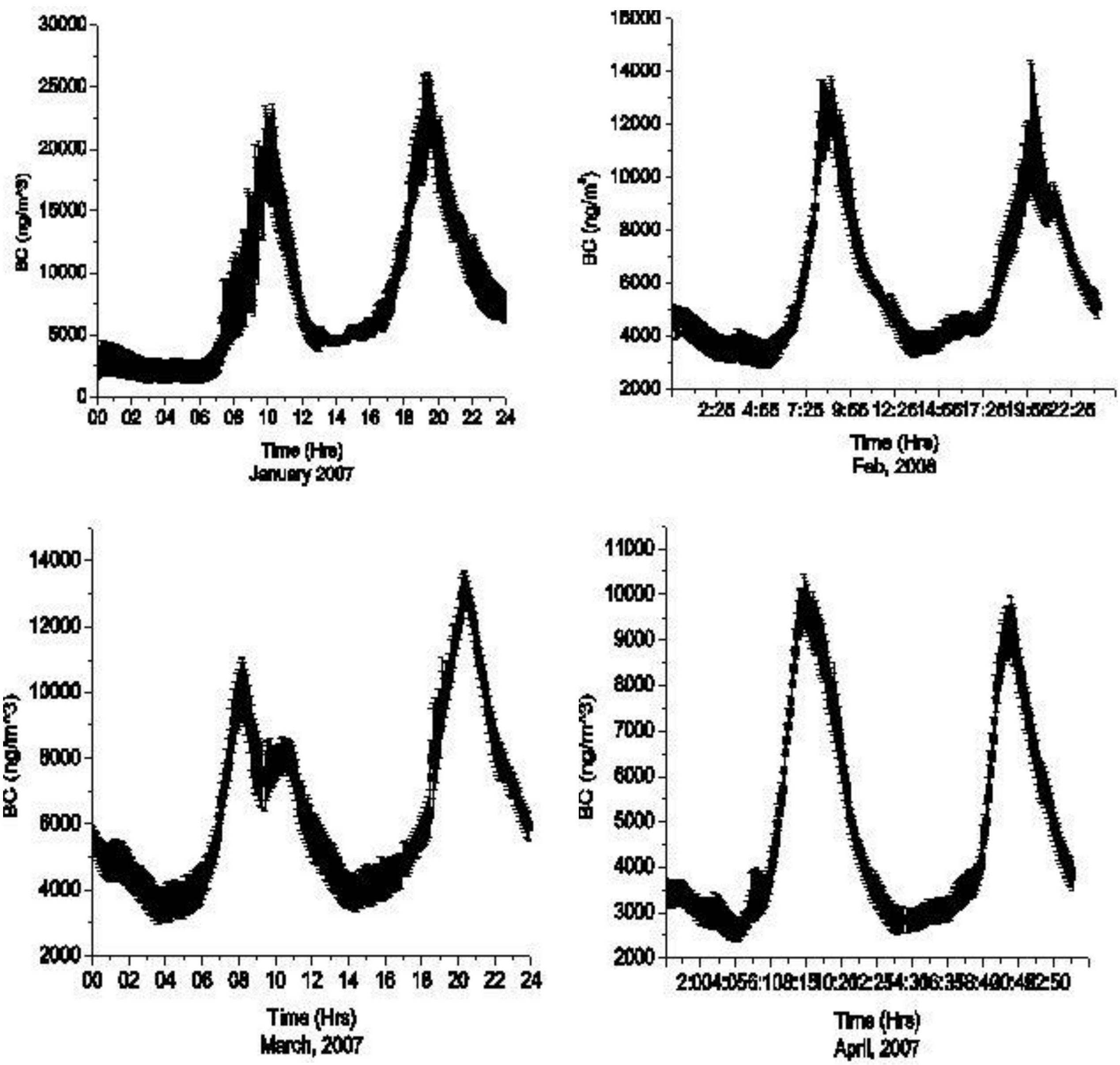
troposphere condition) affecting the boundary layer dynamics associated with the changes in solar heating. The mean AOD_{500} values over Dehradun are found to be low than observed during winters over Delhi (0.4-1.1) (Gupta *et al.*, 2005); Allahabad (25^0 28'N, 81^0 52'E) during December, 2004 (0.45-1.6) (Latha and Badrinath., 2005); mean monthly AOD_{500} value of 0.38 for clear days as reported at Kharagpur during December, 2004 (Niranjan *et al.*, 2007); mean monthly AOD_{500} value of 0.38 over Pune (Pandithurai *et al.*, 2007); over Hyderabad (0.32-0.45) (Badarinath *et al.*, 2007); over Anantapur (0.42-0.52) (Raghavendra *et al.*, 2009) and mean monthly AOD_{500} value of 0.43 over Trivandrum during (December-March) (Babu *et al.*, 2007). The AOD_{500} over Dehradun are also found to be comparable over Rajkot (semi-arid suburban region near Arabian sea) during winters (0.17-0.19) (Ranjan *et al.*, 2007); over Dibrugarh (0.17-0.38) (Bhuyan *et al.*, 2005).

Diurnal Variation in BC Concentration



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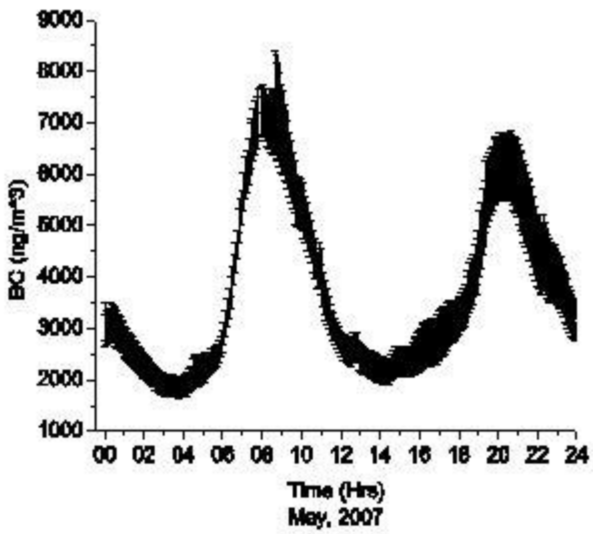

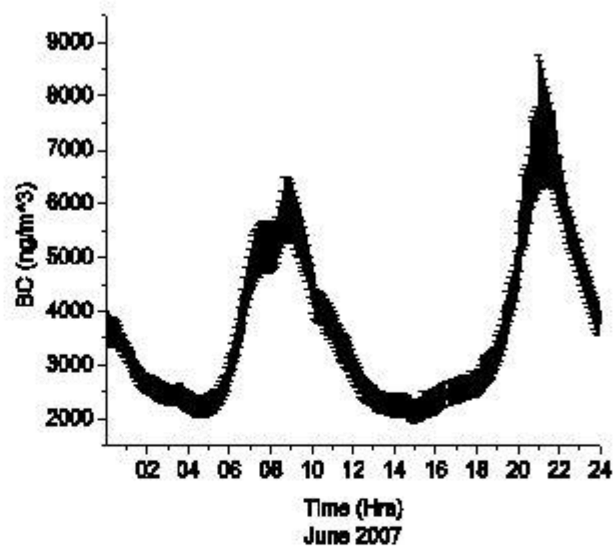

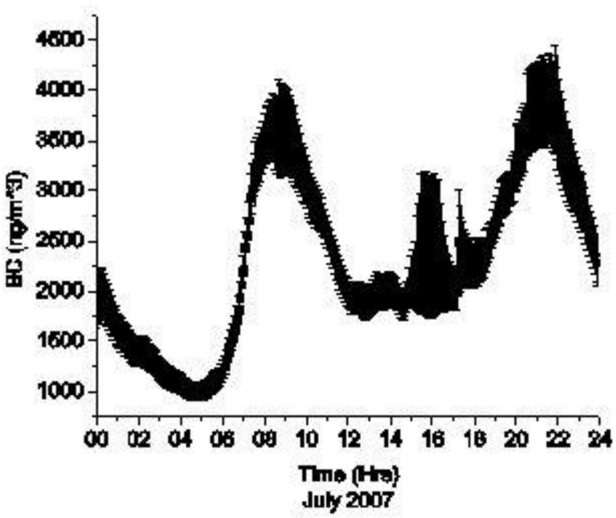

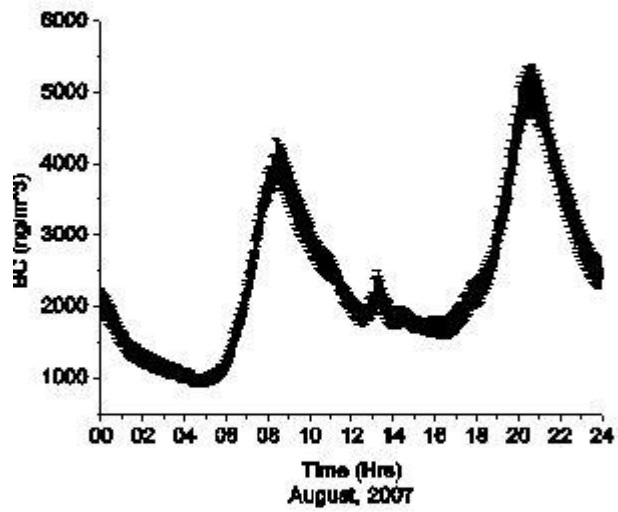

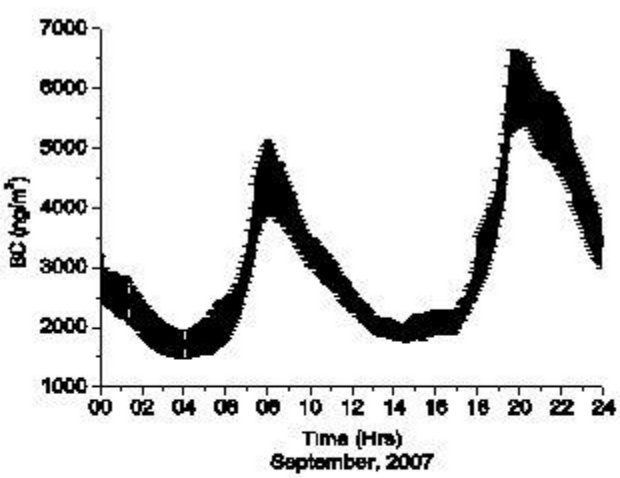

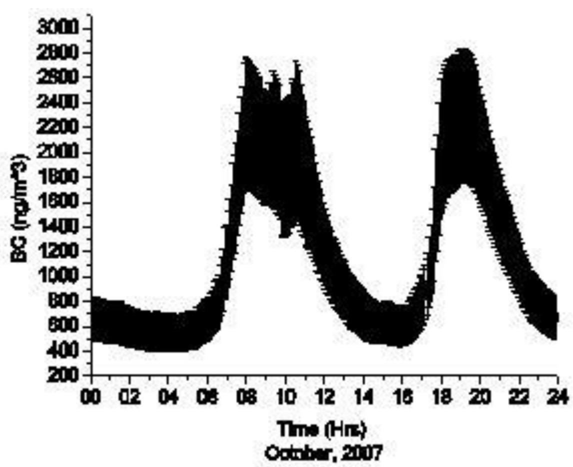

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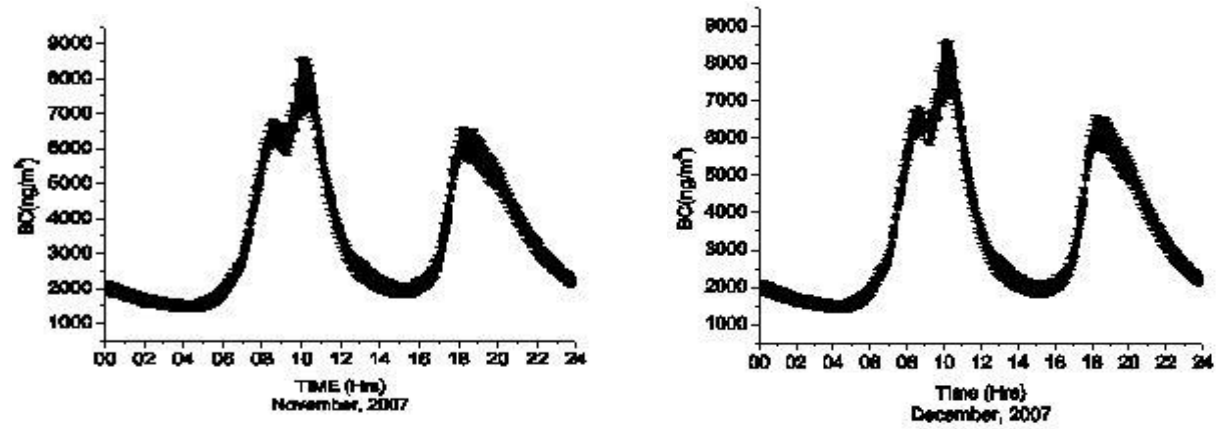

Figure 5: Average hourly variation of BC mass concentration during January to December 2007 at Dehradun

The monthly diurnal variation of BC aerosols for the year 2007 is shown in figure 5. The diurnal variation shows that the BC concentrations are observed to be low during the day time and night while peak is observed during morning and evening hours. From the graph it is evident that for all months, a sharp peak is observed during the morning (0600- 0900 Hrs) and evening hours (1900-2200 Hrs). After sunrise, the turbulence set-in by the solar heating breaks the night time stable layer and the nocturnal boundary layer breaks thereby lifting up the particles which may be responsible for sharp peak in the morning hours. Also due to the increased anthropogenic activities (particularly during 0600-0900 Hrs) the peak is observed and then the concentrations decreases gradually. There is increase in solar radiation in day time which results in an elevated boundary layer and also low traffic density thereby reducing the BC concentrations. The concentration decreases till 1700 Hrs and then gradually increases due to increase in local anthropogenic activities and of the decrease in boundary layer and BC concentration peaks during 1900-2200 Hrs during the all months. There is a slight variation in peaks during the months which corresponds to the local variation in boundary layer conditions and has been reported by Latha and Badarinath, 2003, Tripathi *et al.*, 2005, Safai *et al.*, 2007. The BC concentration is influenced by the transportation from the winds, by diurnal variation in the local boundary layer dynamics while rest would be from the local activities. The atmospheric forcing efficiency of aerosols is strongly dependent on the mass mixing ratio (F_{BC}) (which is the ratio of mass concentration of BC to that of composite aerosol). The observation at Trivandrum shows that during winters BC contributes to ~12% of the aerosol mass while during monsoon season the BC fraction is reduced to 3 - 4% (Babu and Moorthy, 2002) while at Bangalore and Kanpur the BC contribution was found to be ~11% and 7-15% respectively (Tripathi *et al.*, 2005). The observation at Manora peak, Nanital (a station in Himalayas at an altitude of 1958 m a.m.s.l) showed that mean BC concentration of 1.4 ± 0.99 µg m^{-3} contributed to ~5% to the composite aerosols mass (Pant *et al.*, 2006). These lage BC concentration is found to have relationship with the anthropogenic activities, biomass burning and to the boundary layer dynamics.

Effect of Traffic Intensity on BC Concentration

The important contributes of BC are from the vehicles and biomass burning and an analysis on traffic with respect to the types of vehicles over the area was studied. The traffic data was analyzed within 3 km radius of the sampling site in North, South, East and West direction. The data was collected during morning (900-1200 Hrs), Noon (1200-1500 Hrs), evening (1500-1800 Hrs) and night (1800-2100 Hrs). The traffic data was collected during the dry period when the lifetime of BC is high. In the area, city buses, school buses, Govt. Semi-Govt buses, ambulance, recovery and utility van (four wheeler light); three wheeler like public transport, commercial carriage; four wheeler heavy vehicles like trucks, tractor,

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trolley and many cars, taxis and jeep operating with diesel fuel are the major source of BC than petrol vehicles.

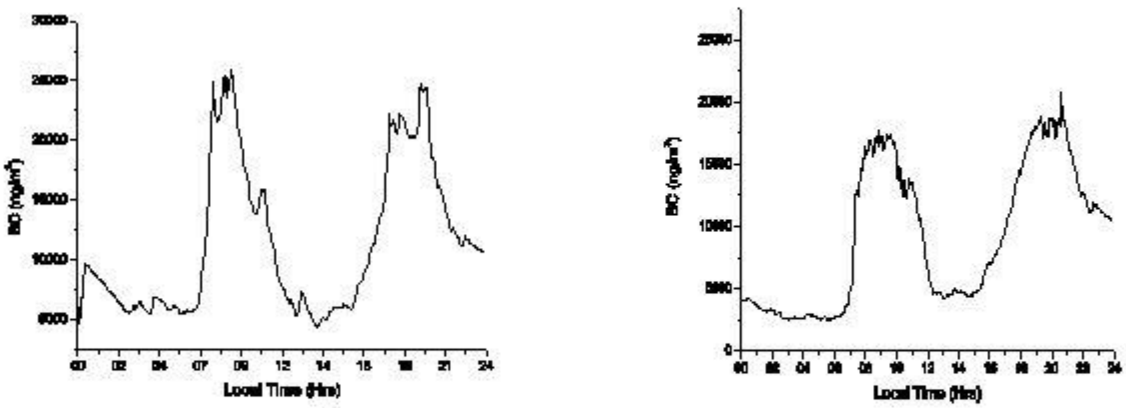

Figure 7: Diurnal variation of BC concentration measured on 12 and 21 January, 2007

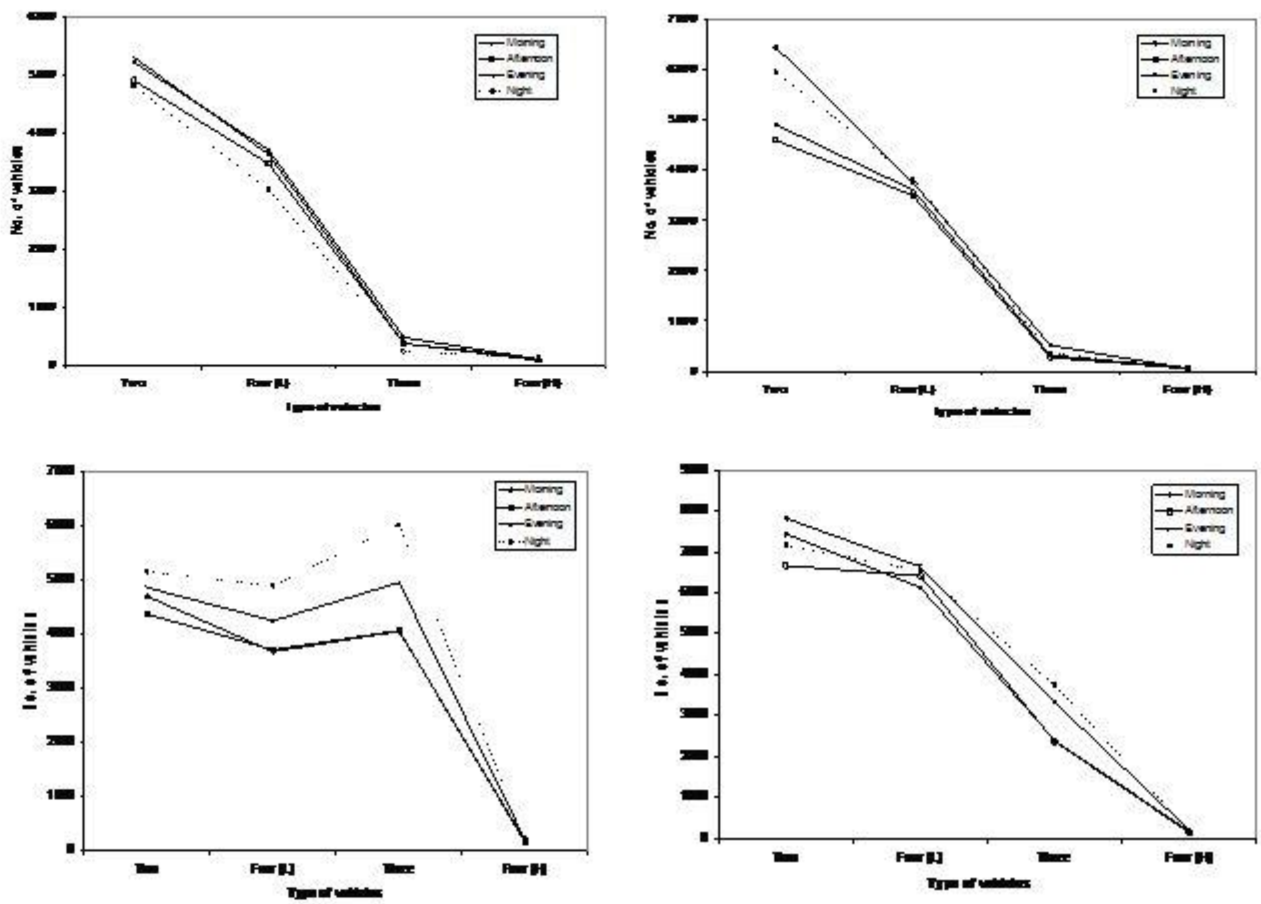

Figure 6: Variation of traffic density over the study area

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Two wheelers like scooter and motorcycles have petrol engine. Figure 6 Depicts the vehicular density collected during morning, afternoon, evening and night in four different locations in the area which is within three km radius of IIRS campus. The study suggests that BC concentration increases more than three times during morning (600-900 Hrs) and evening (1900-2200 Hrs) compared to afternoon and night hours. From all data collected from the four sites, it is inferred that the traffic is high during morning due to schools, offices and commercial activities; during evening due to offices, rush in markets and night due to ply of more trucks and heavy vehicles. The vehicular movement with diesel engines is high during morning and evening as compared to afternoon hours which is observed in the BC concentration measured with Aethalometer. High concentration of BC during morning and evening hours in the Aethalometer is attributed to the boundary layer conditions as explained above. The analysis was conducted within 3 km radius south of the measurement site where most of the daily traffic (at least 50%) is encountered and hence the BC concentrations are expected to reflect the impact of the traffic. Figure 7 shows diurnal BC concentration variation on selected weekday (Friday: January 12, 2007) and on weekend (Sunday:21 January, 2007). From the figure it is evident that diurnal variations in BC concentrations are found to be in the range of 4100-25000 ng/m^3 (weekday) while 3700-18000 ng/m^3 for weekend. Moreover, the daytime concentrations are similar to that of night time. The relationship between BC concentration and traffic density (figure 8) shows that the BC atmospheric concentrations are related to the traffic density with correlation coefficients of 0.71 for two wheeler vehicles, 0.629 for three wheeler, 0.614 for four wheeler light and 0.672 for four wheeler heavy vehicles.
The vertical bars denote the standard deviation from the mean. The annual average BC concentration is found to be 4.3 μg m^{-3}. The seasonal variation of BC (figure 9) reveals that the average monthly concentration is maximum during January (10.5 μg m^{-3}) that gradually decreases to minimum in August (2.382 μg m^{-3}) and then increases thereafter. From the relationship of the mean monthly BC with total monthly rainfall, it is evident that during the months (particularly monsoon period June to August) of heavy rainfall, the BC concentration decreases and increases during the dry months. The monthly average BC concentration are found to be maximum (5.0 μg m^{-3}) during December, January followed by summer period (4.9 μg m^{-3}) (March, April, May) post-monsoon period (3.04 μg m^{-3}) (October, November) and minimum during monsoon period (2.8 μg m^{-3}) (July, August, September). This is mainly attributed to the prevailing meteorological conditions during the seasons.

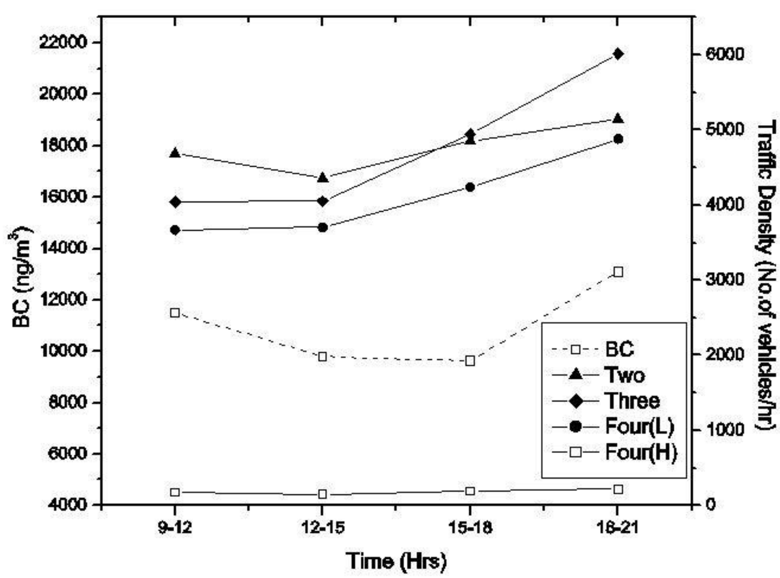

Figure 8: Relationship of BC concentration and traffic density during January, 2007 at Dehraudn

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The annual average BC concentration at Dehradun was found to be 4.3 μg m^{-3} which is found to be in agreement with those reported over urban locations of Bangalore, Anantpur and Pune (table 1). The BC values are found to be on lower side in comparison to the locations in Kanpur, Delhi, Mumbai and Hyderabad while the values were found to be higher than that reported over Trivandrum and Nanital (table 1).

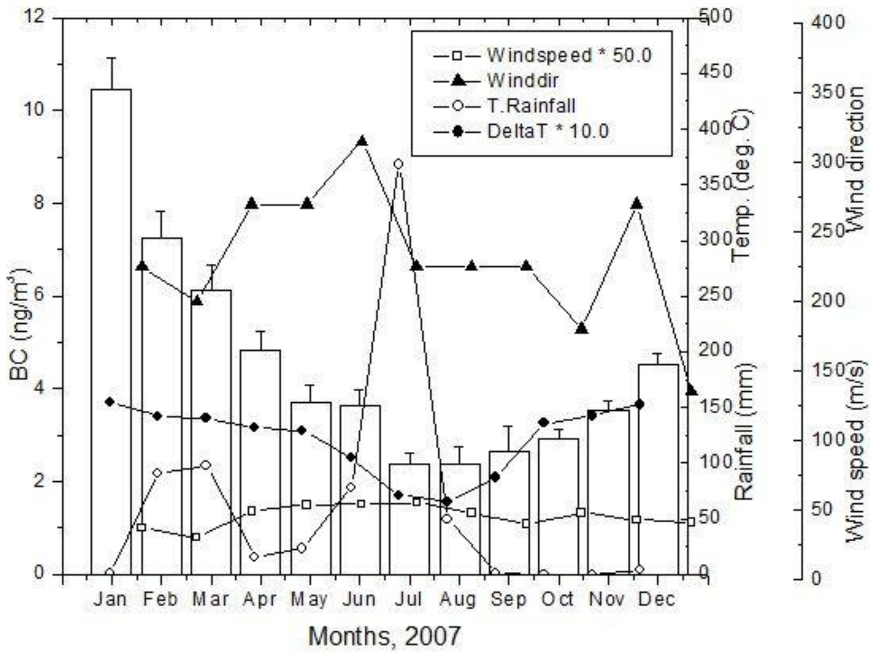

Figure 9: Mean monthly BC concentration and its relation with total monthly rainfall, mean monthly wind speed, wind director and temperature range

Seasonal Changes in BC Concentration

The average mean monthly BC concentration for the year 2007 is shown in Figure 9.

Table 1: Average BC concentration at various locations in India

Location	Type	Period	BC concentration (μg m^{-3}	Reference
Bangalore	Urban	November 2001	4.2	Babu *et al*., 2002
Anantpur	Urban	January-December 2007 and 2008	4.2	Source: Dr. Ramakrishna Reddy
Pune	Urban	January-December, 2005	4.1	Safai *et al*, 2007
Kanpur	Urban	December, 2004 to April, 2005	8.5	Nair *et al*., 2007
Delhi	Urban industrial	May 2001 to April 2002	17.9	Rai *et al*, 2002
Mumbai	Urban industrial	January to March, 1999	12.5	Venkataraman *et al*., 2005
Hyderabad	Urban	January-December, 2003	7.0	Latha and Badrinath, 2005
Trivandrum	Urban coastal	January-December, 2004	3.6	Abish *et al*., 2007
Nainital	Rural (high altitude)	December 2004	1.4	Pant *et al*., 2006

Figure 10 shows the frequency distribution of BC concentration during different seasons. For studying the distribution, the samples were segregated into 7 categories with <1, 1-4, 4-8, 8-12, 12-16, 16-20 and > 20 μg m^{-3}. From the distribution it is inferred that during summer, there is a gradual decrease of number of days having BC concentration from low to high concentration levels and were not greater than 12 - 16 μg m^{-3} which is also noticed in the post-monsoon period with the exception that number of days in 4-8 and 8-12 μg m^{-3} is slightly lower than that in summer season. During monsoon season, for more than 84% samples the BC concentration were <1 μg m^{-3} and in the range 1- 4 μg m^{-3} whereas in winter, number of days having all categories of BC concentration is distributed to entire spectrum except <1 μg m^{-3} range.

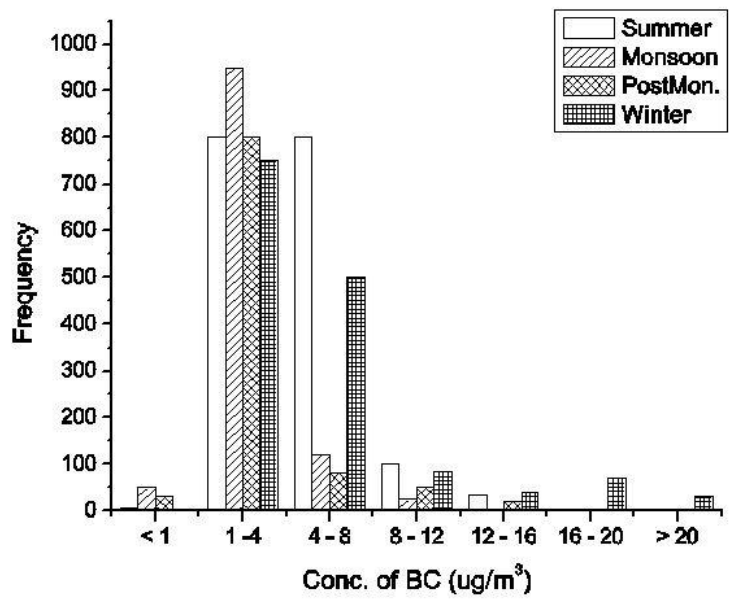

Figure 10: Frequency distribution of BC concentration for different seasons at Dehradun during year 2007

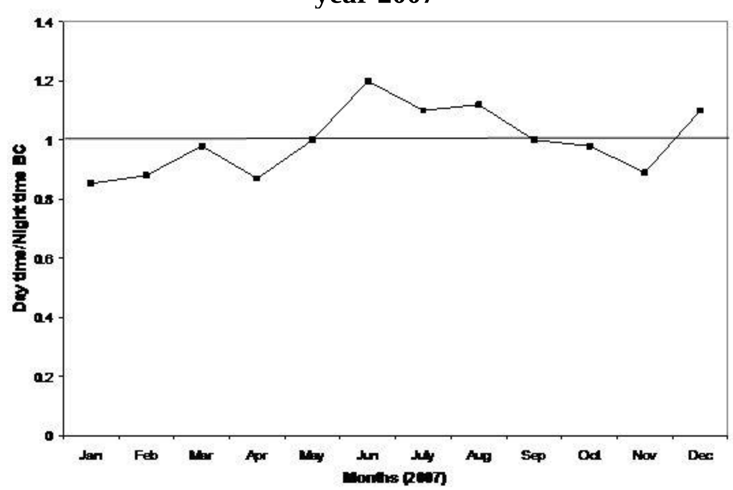

Figure 11: Ratio of Day time and night time BC concentration during 2007

Also, days showing the BC concentration range 16 – 20 and >20 μg m^{-3} is only noticed in during the winter season which indicates that maximum BC concentration is noticed during the winter period and low concentration during monsoon period. From the monthly variation of the ratio of day time and night time BC concentration (figure 11), it is inferred that during March to May and during November the BC concentration are high during night time hours which could be attributed to the biomass burning activities in the region. The burning activities have been observed by the MODIS fire maps over a 10-day period

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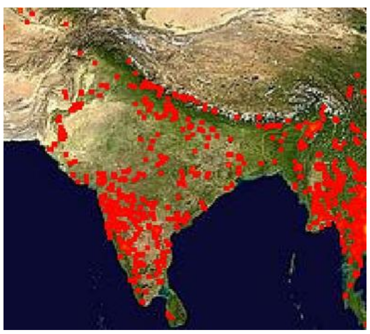
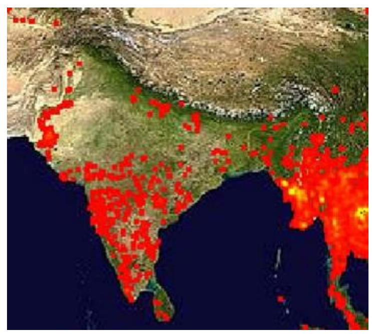
(figure 12). From the maps, it is observed that during March to May biomass burning is seen in and around the region. Also during April-May and October-November, agriculture residue burning is practiced in Punjab and northern region (Gurdeep *et al.,* 2009) which is evident from the MODIS fire map and this influences in increase of BC concentration. It has been reported by Srivastava *et al.,* 2006 that over Nanital, the occurrence of high AOD values were attributed to the air mass arriving from densely populated North Indian plain. The general meteorological conditions of Nanital (Dumka *et al.*, 2008) are similar to that of Dehradun. It has been reported that the aerosol atmospheric forcing estimated at Nanital was + 4.9 Wm^{-2} but the forcing efficiency (forcing per unit optical depth) was ~88 Wm^{-2} that is attributed to high BC mass fraction (Pant *et al.*, 2006). This forcing efficiency was found to be comparable to that over several polluted regions suggesting that type of aerosols over Manora Peak, Nanital have a large efficiency for forcing. Over Kanpur and Bangalore the atmospheric forcing due to aerosols is + 7.1 Wm^{-2} and + 2.8 Wm^{-2} respectively.

Relationship of Meteorological Parameters with BC Concentration

The wind direction of air mass data collected over Dehradun (Figure 9) signifies that during summer the winds are predominantly from west;


January, 2007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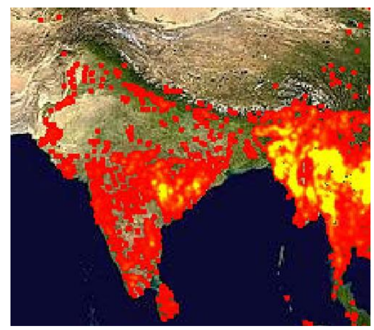
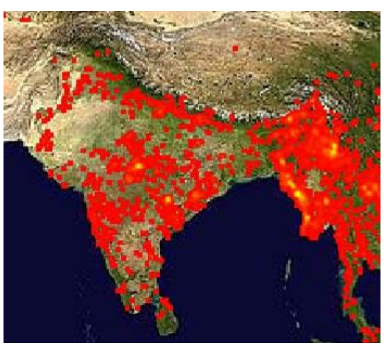
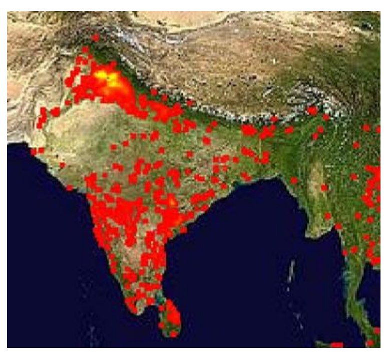
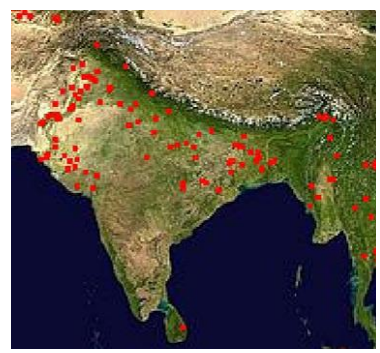
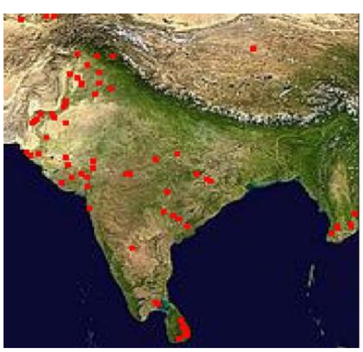
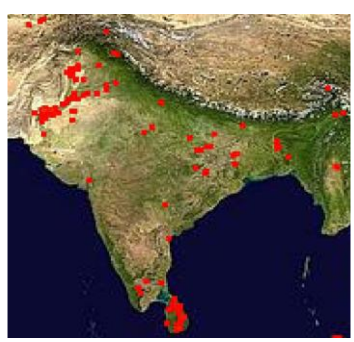

March, 2007

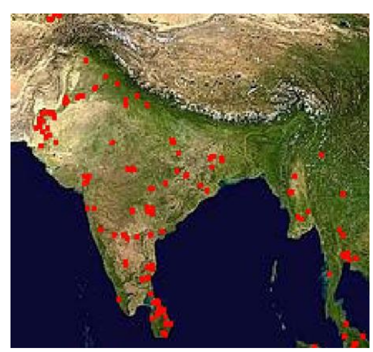

April, 2007

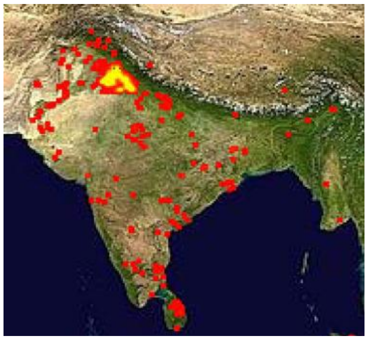

May, 2007

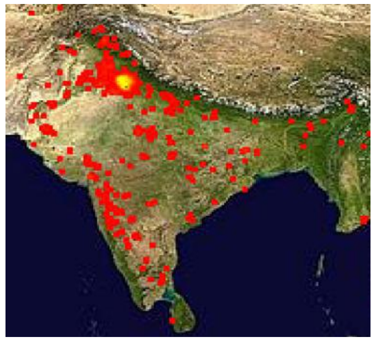

June, 2007


July, 2007


August, 2007


September, 2007


October, 2007


November, 2007


December, 2007

Figure 12: Fire maps as observed by MODIS during 2007

from south-south westerly during monsoon and changes to north-easterly and southerly during winters. The relationship of mean monthly BC concentration, wind speed and wind direction is also analyzed (figure 9). BC concentration is low during monsoon when the transition occurs from continental to marine air mass and high during winter due to the influence from IG plains and low wind speed during this time may help to confine the local urban air in the region. The variation of mean monthly BC concentration with monthly mean values of diurnal temperature is also shown in figure 9. There is appreciable increase in BC concentration whenever the ambient temperature increases. In the relationship the diurnal temperature range ΔT (difference of daily maximum and minimum temperature) which is considered as indicator of ambient heating is studied with BC concentration. The relationship shows that BC concentration increases with high ΔT during winters and low BC concentration with low ΔT during monsoon period. Correlation analysis shows that the monthly average BC mass concentration is negatively correlated with monthly total rainfall and positively correlated with ΔT. The diurnal pattern of BC concentration reveals that local wind significantly control the diurnal variation.

Air Mass Back Trajectory Analysis

In addition to the local sources of the BC particles, it has been studied that significant BC concentration could be carried over long distances downward wind from the potential source (Moorthy *et al.*, 2004). In order to account from the sources, back trajectories using the HYSPLIT data was studied for each month to study the possible transport of BC masses over Dehradun. Daily back trajectories estimated over a 7-day backward trajectory was analyzed at 1000 m a.g.l for all the months during 2007. The analysis from the monthly back trajectories (figure 13) shows that during March to May the winds are coming from far west, north-westerly direction bringing continental air masses from these regions. During mid June-September the winds sources are south-westerly having mixture of maritime and continental air masses while during October-February the air masses are predominantly from Indo-Gangetic plain rich in carbonaceous aerosols.

During summer the winds are coming from west, north westerly direction (relative humidity is around 48% and air temperature is between 29-32^{0}C) with air mass coming from far central Asia desert regions bringing continental air masses increasing the BC concentration. During monsoon, the winds are south westerly bringing mixture of continental and marine air masses (relative humidity is around 80% and air temperature is around 26^{0}C). Also scavenging due to precipitation helps in reducing the BC concentration during this period whereas the winds are easterly and northly during post-monsoon and winter period (relative humidity is around 62-66% and air temperature is around 18^0 C) and the winds are coming from Indo-Gangetic (IG) plain that bring continental air masses experiencing maximum BC concentration. The BC concentration is maximum during winter season when the winds are coming from northeast region (IG plain) carrying more carbonaceous aerosols and comparatively low during summer when the winds are from far west desert region.

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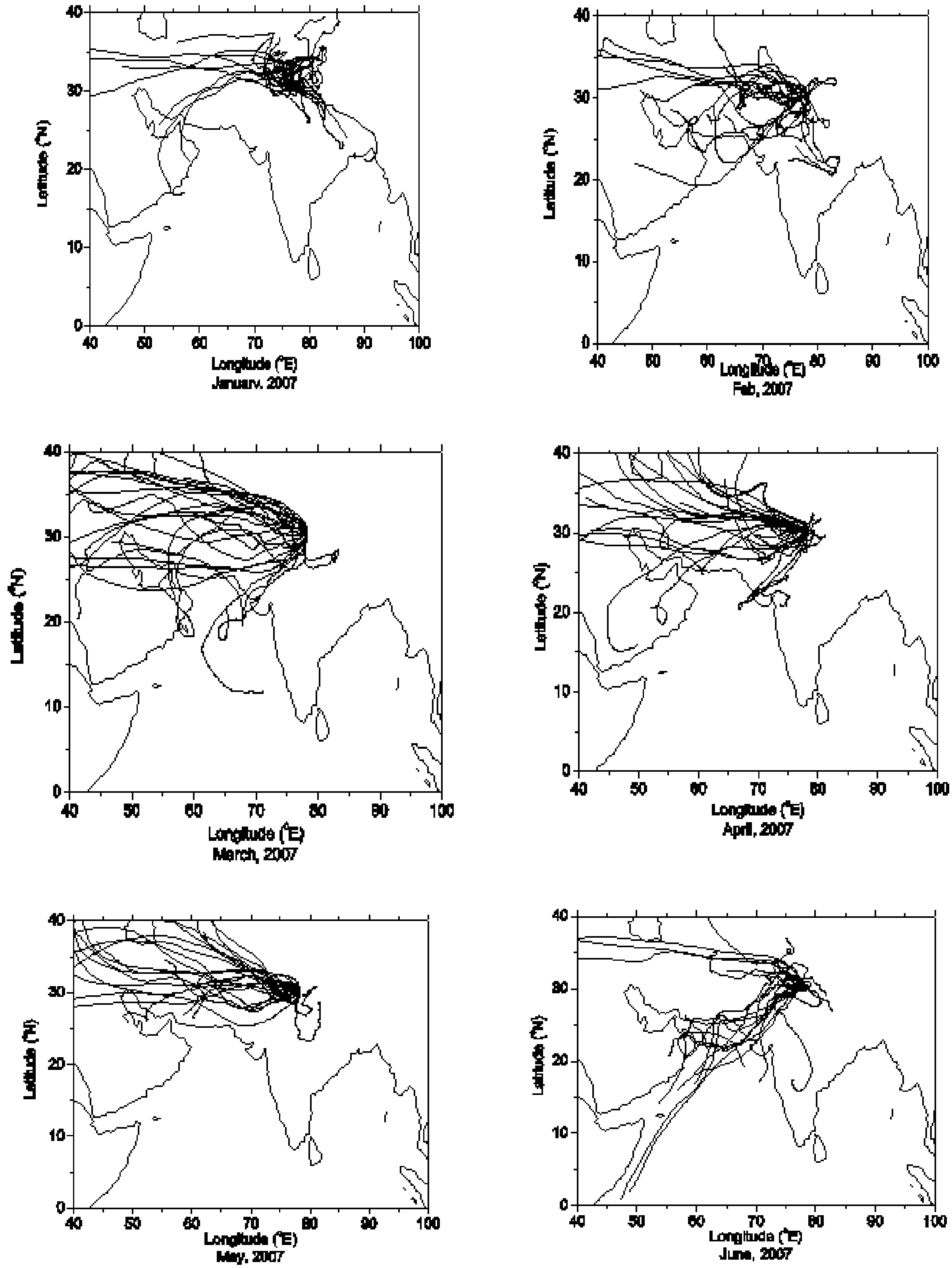

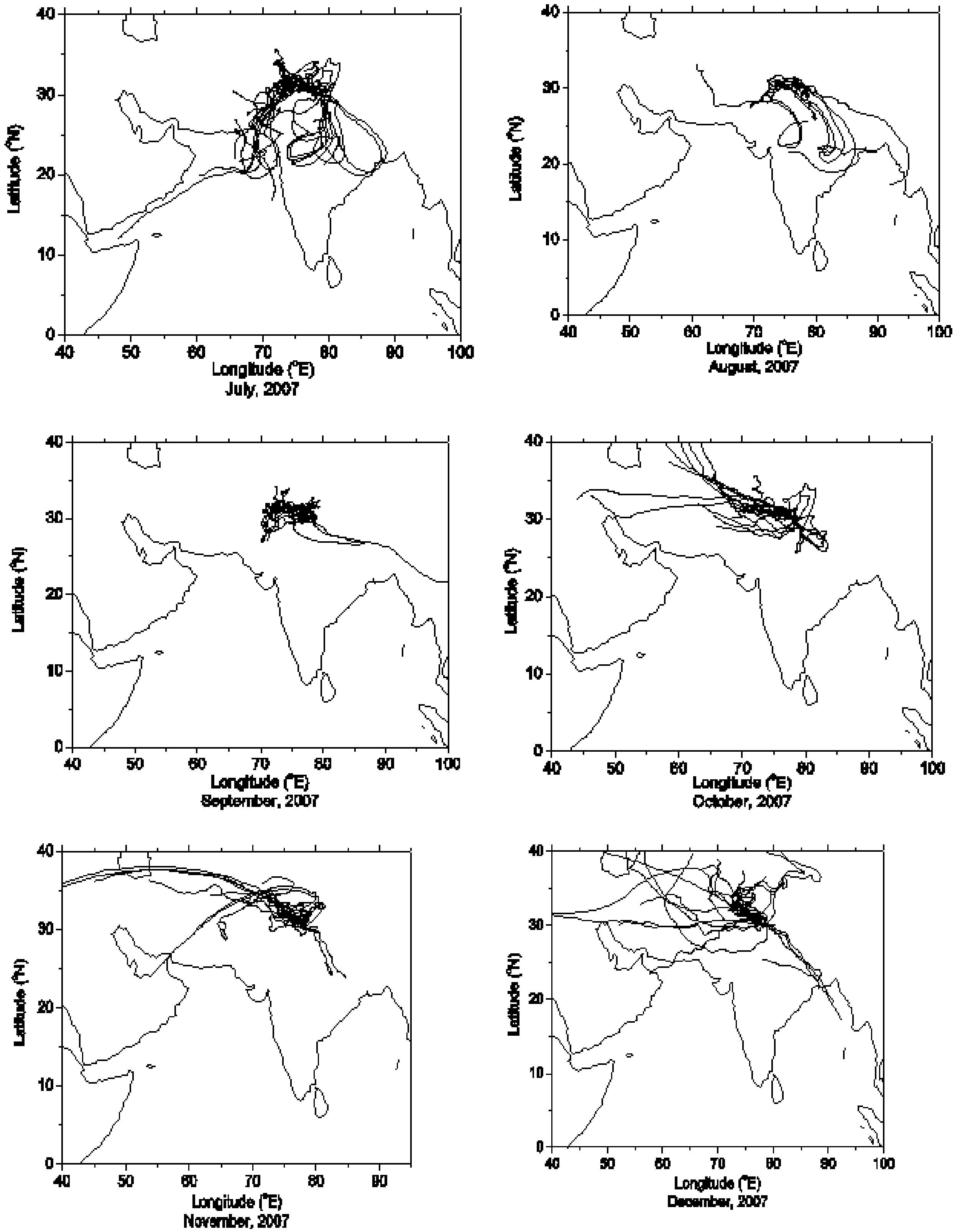

Figure 13: Air mass plots of trajectories (arriving at 1500 m a.g.l) at Dehradun for each month

CONCLUSIONS

Measurements of aerosol optical depth and aerosol black carbon have been carried out for all the months in the year 2007 and their seasonal variation is studied. The data on traffic density has been used to analyze it effect on the variation of BC concentration. The results obtained in the present analysis of aerosol and BC concentration shows that the behavior is largely influenced by anthropogenic aerosols at local level, local boundary layer condition, long-range transported airmass from outside region and on the season. The analyses indicate that:

The columnar AODs at 500nm were low (mean value of 0.35 $\pm$ 0.06) during winter and high (mean of 0.43 $\pm$ 0.08) during summer.

The aerosol optical properties show their dependence on meteorological parameters and on local topography.

The concentration of aerosol loading is high during summer period due to the winds bringing air mass with significant loading originating from far western direction.

The BC concentration showed significant diurnal variations with low values during day and night time while peak is observed during morning and evening hours and the amplitude of variation was of the order of 4. There is a gradual built up of BC in the morning hours between 0600 and 0900 Hrs and evening hours from 1900 to 2200 Hrs.

The analysis of traffic density measured at various sites in the city suggests that the emissions from the traffic have direct influence on the BC concentration and increases more than 3 times during morning and evening hours as compared to day and night hours.

Seasonal variations of BC shows high concentration during winter dry season and minimum during monsoon season. Mean monthly average BC concentration values gradually decreases from January to August and increases from September.

BC concentration shows positive correlation with diurnal temperature change and negative correlation with rainfall and humidity.

High BC concentration during the winter season over the area is attributed the air masses predominantly coming from Indo-Gangetic plain rich in carbonaceous aerosols.

ACKNOWLEDGEMENTS

The research work is funded by ISRO-GBP project on Aerosol Radiative forcing over India. Authors are grateful to Dr. K Krishnamoorthy, Director, VSSC and Dr. Suresh Babu, Project Manager ARFI and ICARB, VSSC for guidance and for providing encouragement and timely availability of funds. Authors acknowledge Mr. Puesh Dubey and Dr. C. Jeganathan for their study in collecting and providing the traffic data over Dehradun during their research work. The meteorological data provided by Dr. Anand kumar Sharma, Director, IMD, Dehradun during the research work is gratefully acknowledged.

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