

Unusual aerosol characteristics at Challakere in Karnataka

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During a series of measurements, simultaneous measurements were made of spectral aerosol optical depths (AOD), black carbon (BC) mass concentration, total and size segregated composite aerosol mass concentrations at the second campus of Indian Institute of Science (IISc), Challakere, Karnataka. Surprisingly, most of the aerosol mass is found in the submicron size range, which is unusual for a dry region. Unexpectedly large enhancement in BC aerosol concentration was observed during the morning hours (6–8 a.m.), both during summer and winter, which is mysterious and hence requires further study. However, BC mass fraction, which is one of the most important climate-relevant parameters was 3.3% of total aerosol mass, implying a significantly low aerosol-induced absorption of solar radiation and hence consequent atmospheric warming. Based on our initial measurements as well as 11 years of satellite data analysis, we conclude that this location is best suited for establishing a climate observatory.

Keywords: Aerosols, climate change, clouds, radiation.

AEROSOLS are one of the most important components of the earth's atmosphere due to their complex nature and consequent climate effects (see Satheesh and Moorthy¹ for a review of radiative effects of aerosols). Several studies have suggested that aerosols may be mitigating global warming by increasing the planetary albedo, although the sign and magnitude of aerosol effects on climate are still uncertain as outlined in the Intergovernmental Panel on Climate Change (IPCC) reports². The complexity of this problem is compounded by the interaction of aerosols with clouds. Aerosols change cloud properties, alter precipitation patterns and hence alter the hydrological balance of the earth–atmosphere system¹. Several field campaigns have been undertaken at the national level in recent years to improve the understanding of spatial and temporal variation of the optical, physical and chemical properties of aerosols and their radiative impacts^{3,4}. The major goals of these experiments have been the characterization of regional aerosol properties,

their controlling processes and estimation of their direct and indirect radiative forcing.

In India, systematic studies of the physico-chemical properties of aerosols, their temporal heterogeneities, spectral characteristics, size distribution and modulation of their properties by regional mesoscale and synoptic meteorological processes have been carried out extensively since the 1980s at different distinct geographical regions as part of the different national programmes such as the Indian Middle Atmosphere Programme (I-MAP), and the Indian Space Research Organisation's Geosphere Biosphere Programme (ISRO–GBP)⁵. During the I-MAP, a project was initiated to monitor the aerosol characteristics over the Indian region in the late eighties and has been continued after the I-MAP as a part of Aerosol Climatology and Effects (ACE) project of the ISRO–GBP^{5,6}. A national network of aerosol observatories was set up to facilitate long-term observations of aerosols following the establishment of a common protocol⁵. This has brought out the large heterogeneity of aerosol properties over India on one hand, and the need to develop a comprehensive and climatological database for modelling aerosol properties and assess their impact on the radiation budget on the other. Due to the large heterogeneity over the Indian region, large areas remained unobserved over the land whereas the vast ocean areas around the Indian peninsula remained unexplored. For the first time in India, systematic and long-term observations over the ocean were initiated from the tiny island location of Minicoy in the Arabian Sea, and the four years of data from this location are still the only database of its kind over the ocean^{7,8}. As a follow-up, an aerosol observatory was set up in Port Blair in the Bay of Bengal^{9,10}. In addition, several national campaigns were organized under ISRO–GBP to study the spatial distribution of aerosols and their impact on the radiation budget and climate^{11–17}.

One of the important objectives of the Aerosol Radiative Forcing over India (ARFI) has been to study and understand long-term changes in aerosol loading. The most important parameter to represent the impact of aerosols is aerosol optical depth (AOD), which is the vertical integral through the entire height of the atmosphere of the fraction of incident light at any wavelength, scattered

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and/or absorbed by aerosols. At Thiruvananthapuram, the increase in AOD was about 2.4% per year (compared to its value in 1985) at visible wavelengths^{18,19}. The airborne measurements of black carbon (BC) aerosols were made over Central India for the first time to examine the vertical distribution of aerosols²⁰. In addition, based on satellite measurements, Jethva *et al.*²¹ have reported that AOD values over the Indo-Gangetic belt are generally higher than those over other Indian regions for all seasons. Taking cue from all these experiments, a mega experiment, Integrated Campaign on Aerosol gases and Radiation Budget (ICARB) was conducted over the Indian region during March–May 2006 and December 2008–January 2009, which is the most exhaustive field experiment conducted over this region^{3,4,22}.

Long-term (11 years) satellite data from MODIS satellite sensor (2001–2011) indicate that AOD is the lowest over northern Karnataka (a region which includes Challakere; Figure 1). This is true for all months as seen from Figure 2, where the all-India average (8–35°N, 67–95°E) AOD is compared with AOD averaged for Challakere (14–15°N; 76–77°E). Also shown is AOD averaged over a polluted region (27–29°N; 78–80°E) of the Indo-Gangetic Plains (IGP) for reference. In view of the above, we have made initial observations in the second campus of the Indian Institute of Science (IISc) at Challakere (14.3°N, 76.6°E, 580 m amsl), Chitradurga district, Karnataka. The region is semi-arid and the terrain is flat (Figure 3). In this article, we discuss the preliminary results from initial observations and analysis using long-term satellite data.

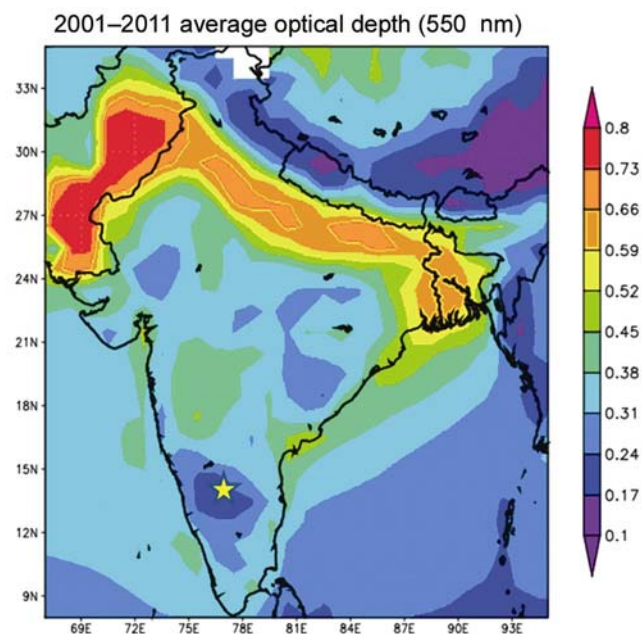


Figure 1. Long-term average (11 years of data) aerosol optical depth (550 nm) from MODIS satellite sensor. Location of Challakere IISc Campus is marked by yellow star.

Initial observations

The initial observations were conducted during summer and winter seasons (9–10 April, 6–7 and 28–29 November 2012) from one of the buildings in the area, during which a few important aerosol parameters were measured. The BC mass concentration measurements (ng m^{-3}) were

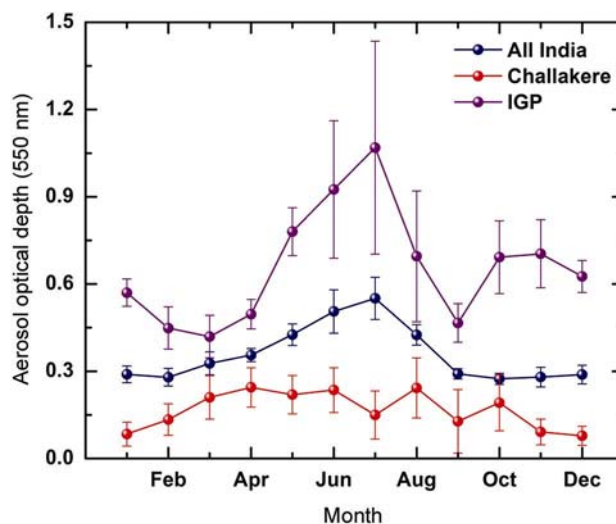


Figure 2. Monthly variation of long-term average (11 years of data from 2001 to 2011) aerosol optical depth (550 nm) from MODIS satellite sensor. *a*, Indo-Gangetic Plains (IGP) (pink); *b*, All-India average (blue); *c*, Challakere (red).

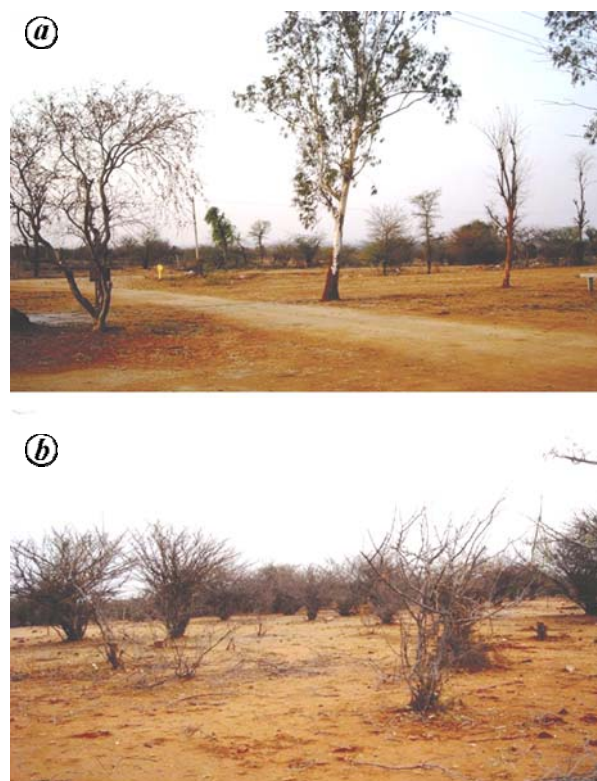


Figure 3. Photographs of the location which indicate a flat terrain.

made using an aethalometer (model AE-2, Magee Scientific). The instrument measures attenuation of light transmitted through aerosols accumulated on a quartz fibre filter with light-absorbing particles embedded in it. The optical attenuation measurements were subsequently converted to BC mass using a standard calibration factor. The instrument was operated at a flow rate of 3 l/min and a data-averaging time of 5 min. Uncertainties associated with the BC measurements are discussed in the literature^{23–25}.

Total and size-segregated mass concentration of composite aerosols has been measured using a portable instrument known as Dust Track, TSI Inc. (model 8533). This has the ability to measure size fractions of the sampled aerosol (PM1, PM2.5, PM10, TSP). Here, PM, PM1, PM2.5, PM10 and TSP represent particulate matter mass concentration, mass of particulate matter with size less than 1, 2.5 and 10 μm , and total suspended particulate matter in the atmosphere respectively. Aerosol spectral optical depths were measured using a Microtops-II Sun photometer, which is a 5-channel hand-held Sun photometer to measure the instantaneous AOD from individual measurements of direct solar flux, using a set of internal calibration constants. A Global Positioning System (GPS) receiver attached with the photometer provided information on the location, altitude and pressure. The wavelengths are centred about 340, 380, 500, 675 and 870 nm, with a full width half-maximum bandwidth of 2–10 nm and a field-of-view of 2.5°. More details are available in Ichoku *et al.*²⁶. In addition to the Microtops Sun photometer, we have utilized 11 years of AOD data from MODIS satellite sensor in order to study the regional distribution of aerosols compared to that at Challakere.

The location of IISc second campus is shown in Figure 1 as a yellow star. During the initial experiments, simultaneous measurements of aerosol spectral optical depths, BC mass concentration and total and size segregated composite aerosol mass concentration were made at Challakere. AOD at 500 nm, measured using the Microtops Sun photometer, was in the range 0.12–0.15, which is typical of a continental rural/background site. Such low optical depths are usually found over pristine oceanic regions^{27,28} or high-altitude locations such as Hanle or Nainital²⁹. On a long-term (2001–2011) also, AOD at Challakere is lower than the all-India average throughout the year (Figure 2). For comparison, Satheesh *et al.*³⁰ have reported AOD (at 500 nm) ranging from 0.3 to 0.6 at Bangalore, just 250 km southeast of Challakere.

The diurnal variation of TSP, PM1, PM2.5 and PM10 is shown in Figure 4. The curves show an increase in PM from a moderately high night-time value to a very high value around 8 a.m. Subsequently, the mass concentration decreases to lower values into the afternoon. A nocturnal peak occurs at ~23 h IST and thereafter the decrease is gradual. The diurnal variation can be attributed to the

combined effect of boundary layer dynamics and anthropogenic activity. It is known that over continents the nocturnal boundary layer or mixing height is shallower than its daytime value³¹. The shrinking and rising of the boundary layer tends to trap the aerosols closer to the surface during the night and disperses it to higher levels during the day. Figure 5a and b shows the scatterplot of PM2.5 versus PM10 and TSP respectively. Surprisingly, most of the aerosol mass is found in the submicron size range, with PM2.5 contributing 89% and 85% respectively, of PM10 and TSP, which is unusual for a dry region such as Challakere.

BC aerosols, produced primarily due to fossil fuel or biomass burning, are mainly absorbing in nature²⁷. Being in the submicron size regime and chemically inert, BC particles can get transported from the source region to long distances and can have large radiative effects regionally^{32,33}. Due to its environmental and climatic effects, as well as the anthropogenic nature of its origin,

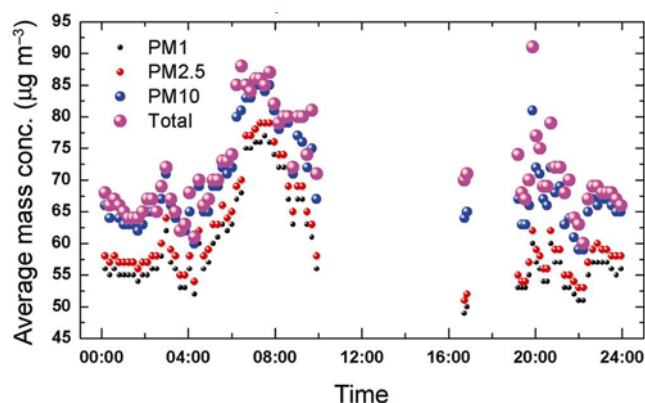


Figure 4. Diurnal variation of PM1 (black), PM2.5 (red), PM10 (blue) and total suspended particulate matter (TSP) (pink).

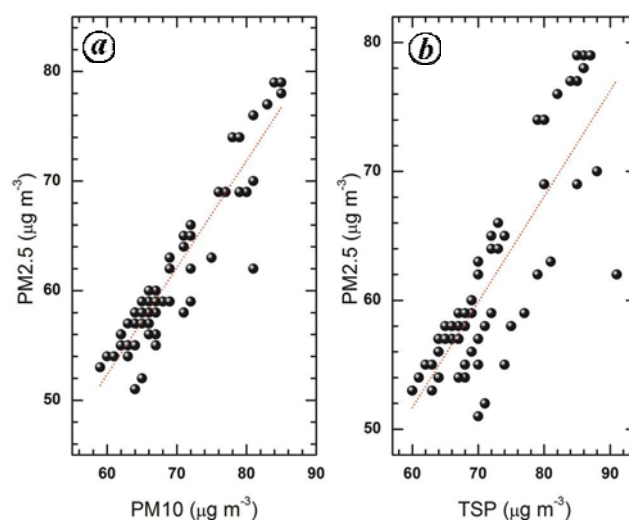


Figure 5. Scatter plot between (a) PM2.5 and PM10, and (b) PM2.5 and TSP.

the characterization of BC has been attracting considerable interest in recent years^{34–36}. The diurnal variation of BC mass concentration is shown in Figure 6, indicating unexpectedly large enhancement in BC mass concentration by around 8 a.m., which requires further study. Subsequently, BC mass decreases rapidly and a broad diurnal low is attained. This is the period when BC is lowest with values ranging from ~1 to 2 $\mu\text{g m}^{-3}$. A nocturnal peak occur ~23 h IST and thereafter the decrease is gradual. Similar measurements made during winter 2012 are shown in Figure 7, which again show unexpectedly large enhancement in BC mass concentration during morning hours. The particulate matter mass concentrations also show a similar pattern. The diurnal variation of BC (like that of TSP) arises due to the combined effects of boundary layer dynamics and anthropogenic activity (mainly vehicular traffic and domestic activities such as cooking in the case of BC). It has been shown earlier that over continents the nocturnal boundary layer or mixing height is shallower than its daytime values³¹. The shrinking

boundary layer traps BC close to the surface during the night. After sunrise, BC gets dispersed upwards. It has been reported that the BC mass fraction is more important than the actual mass in radiative forcing estimates³⁷. BC mass fraction determines the single scattering albedo (SSA) of aerosols, a measure of its absorption efficiency. We have estimated BC mass fraction by taking the ratio of BC mass concentration to the PM_{2.5} and PM₁₀ concentration. The BC mass fraction, which is one of the most important climate-relevant parameters was low; 3.3% of total aerosol mass and 3.9% of submicron mass, implying a significantly low aerosol-induced absorption of solar radiation and hence consequent atmospheric warming.

Based on the observed values of AOD and BC mass mixing ratio, it is evident that the aerosol properties over the study area resemble the continental clean model of Hess *et al.*³⁸. Incorporating the measured aerosol properties, SSA (which is the ratio of scattering to extinction) and phase function are estimated and the aerosol radiative forcing values are estimated using Discrete Ordinate Radiative Transfer model (Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model described in Ricchiuzzi *et al.*³⁹). Here, the surface reflectance values are taken from MODIS satellite data product and tropical atmospheric conditions are used for the computation of aerosol radiative forcing. The estimated SSA at 500 nm works out to be 0.96, which is comparable to those values usually observed over oceans or high-altitude sites. The resulting diurnally averaged aerosol forcing at the surface is -12 W m^{-2} and at the Top of the Atmosphere (TOA) is $+2 \text{ W m}^{-2}$ for an optical depth of 0.16 at 500 nm (Figure 8). The positive sign of the TOA forcing arises due to the absorption by BC and high surface reflectance. The difference between TOA and surface forcing, i.e. $+14 \text{ W m}^{-2}$, is absorbed in the atmosphere. This atmospheric absorption translates to an atmospheric heating of 0.2 K per day, which is quite low compared to other continental locations in India.

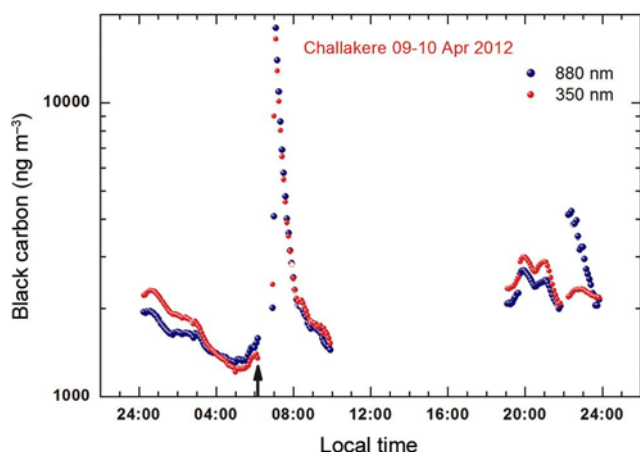


Figure 6. Diurnal variation of aerosol black carbon during 9–10 April 2012.

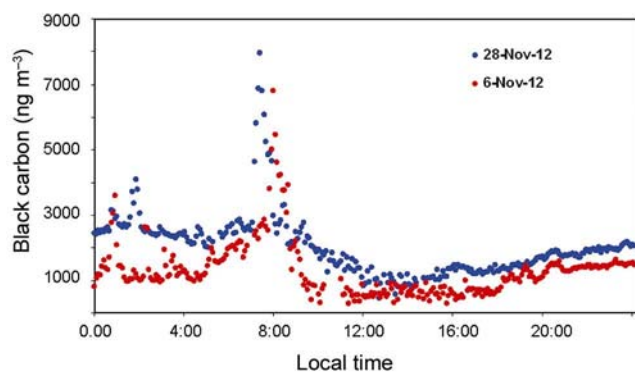


Figure 7. Diurnal variation of aerosol black carbon on 6 and 28 November 2012. For November the sunrise time is around 06:20 am (later than in April) and consequently the fumigation peak also occurs later than in April, showing the role of the ABL dynamics.

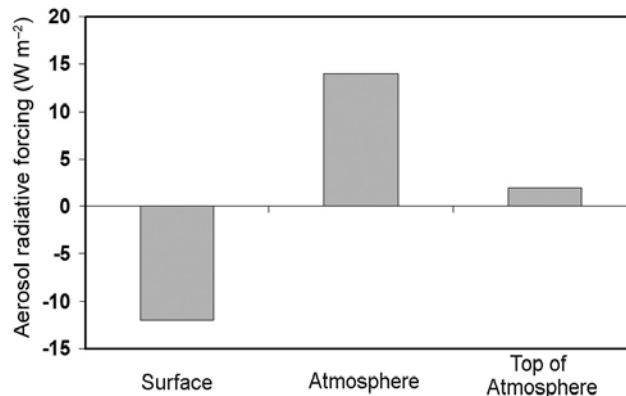


Figure 8. Aerosol radiative forcing at Challakere estimated using measured aerosol properties.

Proposed climate observatory at Challakere

There have been several national efforts to accurately characterize the optical, physical and chemical properties of aerosols over India in order to make an assessment of aerosol–climate impacts. More than 40 fixed aerosol sites as part of Aerosol Radiative Forcing over India (ARFI) network under the ISRO–GBP, known as ARFINET is an example. IPCC has particularly focused its assessment on climate impact of anthropogenic (man-made) aerosols. However, assessment of the climate impact of anthropogenic aerosols essentially requires accurate information about the background aerosols measured from a remote continental site and ARFINET has been in search of such a site to establish a climate observatory.

Preliminary results from Challakere indicate unusual results such as substantially large fraction of submicron aerosol mass and sharp increase in BC aerosol mass during morning hours, which require further study. Analysis using long-term satellite data indicates that Challakere is representative of a typical remote continental location suitable for measurements of continental background aerosols and surface radiation, which is the first step towards assessment of anthropogenic climate impact. We also conclude that this location is best suited for establishing a national radiometric calibration facility, which is essential for the surface radiometer networks in India. In this section, we further discuss the rationale and major science goals of the proposed climate observatory at the Challakere IISc campus.

Background aerosol

Large amount of data are being collected at the ARFINET observatories of ISRO. In order to make an assessment of anthropogenic impacts, it is essential to have accurate information about the background aerosols measured from remote continental sites. It is in fact a real challenge to get such a site, with reasonable amount of logistic support. Results from our initial experiment and analysis of long-term satellite data indicate that Challakere is representative of a typical remote continental location suitable for measurement of background aerosols.

Surface radiation budget

Well-calibrated measurements of surface solar (and infrared) radiation budget are sparse over the Indian region. Such measurements at a site with background aerosol conditions could serve as a base for regional radiation budget analysis. Measurements should be continued for long enough periods (say 5–10 years) to generate a climatological picture and also to examine trends. These measurements would also improve the mathematical description of radiative transfer processes simulated in global circula-

tion models used to predict climate change. For example, evaluations of the ‘excess absorption’ by clouds and radiative transfer models for clear skies are highly dependent on accurate surface measurements of downwelling solar radiation.

National radiometric calibration facility

A central calibration facility needs to be established for periodic calibration of radiometers. The radiometric calibration facility provides shortwave radiometer calibrations traceable to the World Radiometric Reference. Absolute cavity radiometers are usually used to calibrate pyrhemometers and pyranometers for measuring the direct normal and total hemispheric (or global) shortwave irradiances respectively. The calibration of longwave radiometers is based on exposures to temperature-controlled blackbodies and outdoor comparisons with standard pyrogeometers. High atmospheric transmittance (due to low optical depth) at Challakere provides an opportunity to establish a national radiometric calibration facility.

Aerosol–cloud interactions

The climatic impacts of atmospheric aerosols are generally grouped into two broad categories – direct (scattering and absorption) and indirect (effect on cloud microphysical properties effects). The latest report of the IPCC indicates that significant progress has been made in quantifying the direct effects of aerosols, but indirect effects are not understood well². The indirect effects are due to modification of cloud micro physical properties by aerosols. Thus understanding the indirect effects requires a thorough understanding of microphysics of aerosols and clouds. This is first step towards understanding aerosol–cloud interactions, an essential information to predict Indian monsoon. While most of the year in Challakere experiences clear-sky conditions, monsoon months witness low clouds. Cloud base height is often as low as 500–1000 m. This provides an opportunity to study aerosol–cloud interactions.

Atmospheric boundary layer studies

The dispersion of surface aerosol concentration mainly depends on three factors – the source, redistribution and removal processes. Redistribution is made effective by the advection by winds, both horizontally as well as vertically. In addition, the mixing depth or mixing height determines the extent of aerosol mixing in the vertical and plays an important role in their redistribution. A parameter combining both advection by wind and redistribution in the vertical by the boundary layer effect is known as ventilation coefficient (VC), defined as the product of

average wind speed in the well-mixed layer and mixing depth⁴⁰. The higher the VC, lower the pollutant concentration and vice versa. It was observed that BC and VC vary inversely⁴⁰. A tower-based measurement set up with sonic anemometers at different levels along with SODAR and a Radio Acoustic Sounding System (RASS) can provide detailed information about the atmospheric boundary layer and its role in dispersion of aerosols.

A conceptual sketch of the proposed climate observatory at the Challakere IISc campus is shown in Figure 9.

Summary and conclusions

Assessment of the climate impact of anthropogenic aerosols essentially requires accurate information about the background aerosols measured from a remote continental site. We have conducted initial experiments at Challakere during summer and winter seasons of 2012 and simultaneous measurements of aerosol spectral optical depths, BC mass concentration, and total and size-segregated composite aerosol mass concentration. Most of the aerosol mass is found in the submicron size range, with PM_{2.5} contributing 89% and 85% of PM₁₀ and TSP respectively, which is unusual for a dry site like Challakere. Sharp increase in BC aerosol mass concentration during the morning hours remains to be understood. Low amount of BC was observed with a daytime average value of $1.8 \mu\text{g m}^{-3}$. The BC mass fraction was low; 3.3% of total aerosol mass and 3.9% of submicron mass. The aerosol visible optical depth was in the range 0.12–0.18, typical of a background site. Solar dimming at the surface due to aerosols has been estimated as 12 W m^{-2} and aerosol-induced atmospheric warming rate as 0.2 K day^{-1} . Long-term (11 years) satellite data analysis covering the entire Indian region indicates that AOD is lowest over northern Karnataka (a region which includes Challakere). Our observations indicate that Challakere is suitable for measurements of continental background aerosols. We also

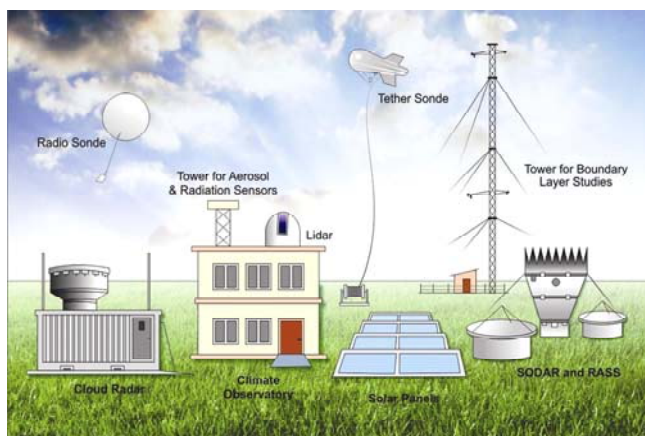


Figure 9. Conceptual sketch of the upcoming climate observatory at Challakere IISc second campus.

conclude that this location is best suited for establishing a national radiometric calibration facility, which is essential for calibrating the surface radiometers in network sites in India. The rationale and major science goals of the proposed climate observatory at the Challakere IISc second campus have been discussed here.

1. Satheesh, S. K. and Moorthy, K. K., Radiative effects of natural aerosols: a review. *Atmos. Environ.*, 2005, **39**, 2089–2110.
2. Intergovernmental Panel on Climate Change, *Climate Change 2007*, New York, Cambridge University Press, 2007.
3. Moorthy, K. K., Satheesh, S. K., Babu, S. S. and Dutt, C. B. S., Integrated campaign for aerosols, gases and radiation budget (ICARB): an overview. *J. Earth. Syst. Sci.*, 2008, **117**, 243–262.
4. Satheesh, S. K., Krishna Moorthy, K., Suresh Babu, S., Vinoj, V. and Dutt, C. B. S., Climate implications of large warming by elevated aerosol over India. *Geophys. Res. Lett.*, 2008, **35**, L19809, doi:10.1029/2008GL034944.
5. Moorthy, K. K. *et al.*, Aerosol climatology over India. 1 – ISRO–GBP MWR network and database. ISRO/GBP, SR-03-99, 1999.
6. Subbaraya, B. H., Jayaraman, A., Krishna Moorthy, K. and Mohan, M., Atmospheric aerosol studies under ISRO's Geosphere Biosphere Programme. *J. Indian Geophys. Union*, 2000, **4**, 77–90.
7. Moorthy, K. K. and Satheesh, S. K., Characteristics of aerosols over a remote island, Minicoy in the Arabian Sea: optical properties and retrieved size characteristics. *Q. J. R. Meteorol. Soc.*, 2000, **126**, 81–109.
8. Vinoj, V., Satheesh, S. K. and Moorthy, K. K., Optical, radiative and source characteristics of aerosols at Minicoy, a remote island in the southern Arabian Sea. *J. Geophys. Res.*, 2010, **115**, D01201.
9. Moorthy, K. K., Babu, S. S. and Satheesh, S. K., Aerosol spectral optical depths over the Bay of Bengal: role of transport. *Geophys. Res. Lett.*, 2003, **30**, 1249; doi: 10.1029/2002GL016520
10. Moorthy, K. K. and Babu, S. S., Aerosol black carbon over Bay of Bengal observed from an island location, Port Blair: temporal features and long-range transport. *J. Geophys. Res.*, 2006, **111**, D17205; doi: 10.1029/2005JD006855
11. Moorthy, K. K. *et al.*, Wintertime spatial characteristics of boundary layer aerosols over Peninsular India. *J. Geophys. Res.*, 2005, **110**, D08207; doi: 10.1029/2004JD005520
12. Moorthy, K. K., Babu, S. S. and Satheesh, S. K., Aerosol characteristics and radiative impacts over the Arabian Sea during the intermonsoon season: results from ARMEX field campaign. *J. Atmos. Sci.*, 2005, **62**, 192–206; doi:10.1175/JAS-3378.1
13. Moorthy, K. K., Babu, S. S., Satheesh, S. K., Srinivasan, J. and Dutt, C. B. S., Dust absorption over the Great Indian Desert inferred using ground-based and satellite remote sensing. *J. Geophys. Res.*, 2007, **112**, D09206; doi: 10.1029/2006JD007690
14. Ganguly, D., Jayaraman, A. and Gadhavi, H., *In situ* ship cruise measurements of mass concentration and size distribution of aerosols over Bay of Bengal and their radiative impacts. *J. Geophys. Res.*, 2005, **110**, D06205; doi: 10.1029/2004JD005325.029/2006JD007635
15. Niranjan, K., Sreekanth, V., Madhavan, B. L. and Moorthy, K. K., Wintertime aerosol characteristics at a North Indian site Kharapur in the Indo-Gangetic plains located at the outflow region into Bay of Bengal. *J. Geophys. Res.*, 2006, **111**, D24209.
16. Singh, S. *et al.*, A study of aerosol optical depth in the central Indian region (17.3–8.6°N) during ISRO–GBP field campaign. *Atmos. Environ.*, 2006, **40**, 6494–6503.
17. Nair, V. S., Babu, S. S. and Moorthy, K. K., Spatial distribution and spectral characteristics of aerosol single scattering albedo over the Bay of Bengal inferred from ship-borne measurements. *Geophys. Res. Lett.*, 2008, **35**, L10806; doi: 10.1029/2008GL033687

18. Moorthy, K. K., Babu, S. S., Satheesh, S. K., Lal, S., Sarin, M. M. and Ramachandran, S., Climate implications of atmospheric aerosols and trace gases: Indian scenario. In *Climate Sense*, World Meteorological Organisation, Tudor Rose, UK, 2009, pp. 157–160.
19. Moorthy, K. K. and Satheesh, S. K., Black carbon aerosols over India. *UNEP e-bulletin*, 2011, **3**, 1–3.
20. Moorthy, K. K., Babu, S. S., Sunilkumar, S. V., Gupta, P. K. and Gera, B. S., Altitude profiles of aerosol BC, derived from aircraft measurements over an inland urban location in India. *Geophys. Res. Lett.*, 2004, **31**, L22103; doi: 10.1029/2004GL021336
21. Jethva, H., Satheesh, S. K. and Srinivasan, J., Seasonal variability in aerosol properties over Indo-Gangetic basin. *J. Geophys. Res. D*, 2005, **110**, Art. No. D21204; doi: 10.1029/2005JD005938
22. Babu, S. S., Satheesh, S. K., Moorthy, K. K., Dutt, C. B. S., Nair, V. S., Alappattu, D. P. and Kunhikrishnan, P. K., Aircraft measurements of aerosol black carbon from a coastal location in the north-east part of peninsular India during ICARB. *J. Earth. Syst. Sci.*, 2008, **117**, 263–272.
23. Weingartner, E. *et al.*, Absorption of light by soot particles: determination of the absorption coefficient by means of aethalometers. *J. Aerosol Sci.*, 2003, **34**, 1445–1463.
24. Arnott, W. P. *et al.*, Towards aerosol light-absorption measurements with a 7-wavelength aethalometer: evaluation with a photoacoustic instrument and 3-wavelength nephelometer. *Aerosols Sci. Technol.*, 2005, **39**, 17–29.
25. Corrigan, C. E., Ramanathan, V. and Schauer, J. J., Impact of monsoon transitions on the physical and optical properties of aerosols. *J. Geophys. Res.*, 2006, **111**, D18208; doi: 10.1029/2005JD006370
26. Ichoku, C. *et al.*, Analysis of the performance characteristics of the five-channel Microtops II Sun photometer for measuring aerosol optical thickness and precipitable water vapour. *J. Geophys. Res. D*, 2002, **107**, 4179; doi: 10.1029/2001JD001302
27. Babu, S. S., Moorthy, K. K. and Satheesh, S. K., Vertical and horizontal gradients in aerosol black carbon and its mass fraction to composite aerosols over the east coast of Peninsular India from Aircraft measurements. *Adv. Meteorol.*, 2010, 1–7; doi: 10.1155/2010/812075
28. Vinoj, V., Babu, S. S., Satheesh, S. K., Moorthy, K. K. and Kaufman, Y. J., Radiative forcing by aerosols over the Bay of Bengal region derived from shipborne, island-based and satellite (moderate-resolution imaging spectroradiometer) observations. *J. Geophys. Res. D*, 2004, **109**, D05203; doi: 10.1029/2003JD004329
29. Sagar, R., Kumar, B., Dumka, U. C., Moorthy, K. K. and Pant, P., Characteristics of aerosol spectral optical depths over Manora Peak: a high-altitude station in the central Himalayas. *J. Geophys. Res.*, 2004, **109**, D06207; doi: 10.1029/2003JD003954
30. Satheesh, S. K., Vinoj, V. and Moorthy, K. K., Weekly periodicities of aerosol properties observed at an urban location in India. *Atmos. Res.*, **101**, 307–313; doi: 10.1016/j.atmosres.2011.03.003, 2011
31. Stull, R. B., *An Introduction to Boundary Layer Meteorology*, Kluwer, Dordrecht, 1988.
32. Satheesh, S. K. and Ramanathan, V., Large differences in the tropical aerosol forcing at the top of the atmosphere and earth's surface. *Nature*, 2000, **405**, 60–63.
33. Babu, S. S., Satheesh, S. K. and Moorthy, K. K., Aerosol radiative forcing due to enhanced black carbon at an urban site in India. *Geophys. Res. Lett.*, 2002, **29**, 1–4; doi: 10.1029/2002GL015826
34. Haywood, J. M. and Ramaswamy, V., Global sensitivity studies of the direct radiative forcing due to anthropogenic sulfate and black carbon aerosols. *J. Geophys. Res.*, 1998, **103**, 6043–6058.
35. Hansen, J. E., Sato, M., Reudy, R., Lacis, A. and Oinas, V., Global warming in the 21st century: an alternative scenario. *Proc. Natl. Acad. Sci. USA*, 2000, **97**, 9875–9880.
36. Jacobson, M. Z., Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature*, 2001, **409**, 695–697.
37. Babu, S. S., Moorthy, K. K. and Satheesh, S. K., Aerosol black carbon over Arabian Sea during inter monsoon and summer monsoon seasons. *Geophys. Res. Lett.*, 2004, **31**, 1–4; doi: 10.1029/2003GL018716
38. Hess, M., Koepke, P. and Schult, I., Optical properties of aerosols and clouds: the software package OPAC. *Bull. Am. Meteorol. Soc.*, 1998, **79**, 831–844.
39. Ricchiuzzi, P., Yang, S., Gautier, C. and Sowle, D., SBDART: a research and teaching software tool for plane-parallel radiative transfer in the Earth's atmosphere. *Bull. Am. Meteorol. Soc.*, 1998, **79**, 2101–2114.
40. Vinoj, V., Investigation of aerosol characteristics over inland, coastal and island locations in India. Ph D thesis, Indian Institute of Science, Bangalore, 2009.

ACKNOWLEDGEMENT. We thank Prof. P. Balaram, Prof. B. N. Raghunandan, Prof. M. S. Hegde and Shri Jagadeesh Haldipur for their encouragement and support to make observations of climate-relevant atmospheric parameters at Challakere IISc Campus.

Received 3 August 2012; revised accepted 16 January 2013