Environmental Science: Atmospheres

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Cite this: *Environ. Sci.: Atmos.*, 2021, **1**, 416

Characterization of black carbon aerosols over Indian Antarctic station, Maitri and identification of potential source areas†

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With the advent of industrialization, aerosol pollutants have gained global attention for being a formidable threat to the human health and climate change. These pollutants travel *via* long range transportation to the far reaches of the Earth, wreaking havoc. Black carbon (BC) depositories have repercussions in snow and ice profiles such as alterations in ablation and albedo processes leading to accelerated ice melting rates. In the present study, atmospheric BC aerosol concentrations were measured at 'Maitri', the Indian Polar research station situated in Schirmacher Hills, East Antarctica during the austral summer of December 2018 to February 2019 on behalf of the XXXVIII Indian Scientific Expedition to Antarctica (ISEA). For that, an AE42 Aethalometer was used and found a maximum concentration of 82 ng m^{-3} for BC aerosol between a timeline of 09.00 and 13.00 LT in the month of February, 2019 whereas a minimum concentration of 37 ng m^{-3} in the timeline of 21.00–22.00 LT, Dec 2018, with the mean of 60 ng m^{-3} being observed throughout the study period. The potential source areas (Patagonia, Australia, New Zealand and South Africa) were examined to study the source of long-range transport of BC to Maitri by backward and forward trajectory analyses. The trajectory analysis confirmed that Patagonia is a definitive BC origin in addition to the day-to-day station related activities. The influence of meteorological parameters on BC aerosols at Maitri was also studied and correlation analysis stated that BC has a negative alliance with RH, temperature and pressure except wind speed denoting meteorological conditions as a driver of spatio-temporal variation of BC.

Received 31st March 2021
Accepted 13th July 2021

DOI: 10.1039/d1ea00024a

rsc.li/esatmospheres

Environmental significance

This peer-reviewed literature includes black carbon studies and its health effects. This study discusses the atmospheric BC aerosol concentrations measured at 'Maitri', the Indian Polar research station in East Antarctica during the austral summer of December 2018 to February 2019 in the part of XXXVIII Indian Scientific Expedition to Antarctica. This study reveals a new path to identify the potential source areas for BC aerosols to the East Antarctica. The authors have not used any hazardous chemicals or substances to assessing air quality and their potential sources. Hence, in support of study on environment and pollution level due to BC aerosols at Antarctica, this work has significance and can contribute some knowledge to science.

1. Introduction

Over the past two decades, researchers have devoted great attention to black carbon (BC) with the ability to absorb solar radiation effectively due to its unique surface area having capabilities of large-scale global warming, secondary to carbon dioxide.[1–4] It is a carbonaceous material obtained from the incomplete combustion of biomass and fossil fuels *via* natural and anthropogenic activities and is an excellent marker for air quality and pollution level.[4] Moreover, the BC emissions can occur alongside noxious gases such as carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), and sulfur dioxide (SO_2)[5] with a negative impact on health,[6,7] modifications of cloud characters, ice or snow albedo,[8] visibility and the Earth's energy budget.[9] Moreover, meteorological parameters such as wind speed, wind direction, pressure, temperature and relative humidity govern variations in aerosol distribution and quantities of BC. For instance, visibility degradation is observed in remote regions operated at low temperatures due to submicron black carbon aerosol.[10] It has a short residence time in the stratosphere making it an ideal candidate for short-term reduction strategies to reduce future warming of the climate. Hence, the policy makers were focused on reducing BC emissions by reduction and mitigatory actions.[11,12]

Antarctica is a no-man's land with pristine environment, entirely encompassed by snow and ice. The nominal but

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1ea00024a

gradual pollution of Antarctica is attributed to the rapid increase in anthropogenic activities and tourism. Environmental protection of Antarctica is globally recognized and documented in the Antarctica Treaty.[13] The treaty and its corresponding annexure set the guidelines for international responsibilities to save and maintain the mint condition of Antarctica. The Madrid Protocol on Environmental Protection was held to enhance and clarify the treaty's environmental protection practices.[14]

In the recent past, researchers have reported the presence of BC within Antarctica's environmental matrices.[15] Bulk producers steering from long range transportation of BC to Antarctica are surrounding continents of South America, Africa and Australia.[16] Short and long-term climate variations could affect the local transport of BC from the biomass burning on Antarctica, within the southern hemisphere. Therefore, a scientific program was designed to study the environmental impact assessment through BC emissions and their sources at the Maitri station during the austral summer period of December 2018 to February 2019 to assess the BC variations and long-range transport predictions *via* the HYSPLIT trajectory analysis (backward/forward) under the influence of meteorological properties. This work presents the study on the long-term observations that predict the reliable sources of BC to East Antarctica.

2. Experimental section

2.1 Sampling site and meteorology

Black carbon (BC) measurements were conducted at the second Indian Polar research base, Maitri (70° 45′ 56.57″S and 11° 44′ 06.21″E), a part of Schirmacher Hills in East Antarctica with an elevation of 130 m, and 5 km away from the Russian station, Novolazarevskaya (Fig. 1). The observational period of this study was selected from 19th December, 2018 to 20th February, 2019 (austral summer in Antarctica). The station featured a 75 member team including both scientific and logistics. The station maintenance involved the regular use of electrical incinerators, power generators, vehicles and boilers.

Two diesel generators were continually operated at the station, which generated ~62–120 kVA (maximum) of electricity for maintenance and scientific activities.[17] The transportation of goods and personnel to airport and other stations was dependent on the use of diesel powered vehicles. Local activities may have contributed to the air pollution that may have travelled *via* advection to the Maitri station. Meteorological parameters at the Maitri station were recorded by the Indian Meteorological Department (IMD) using an Automatic Weather Station (AWS, Dynalab Weathertech-WL1002) at an interval of 1 min. This collected data points such as relative humidity (RH),

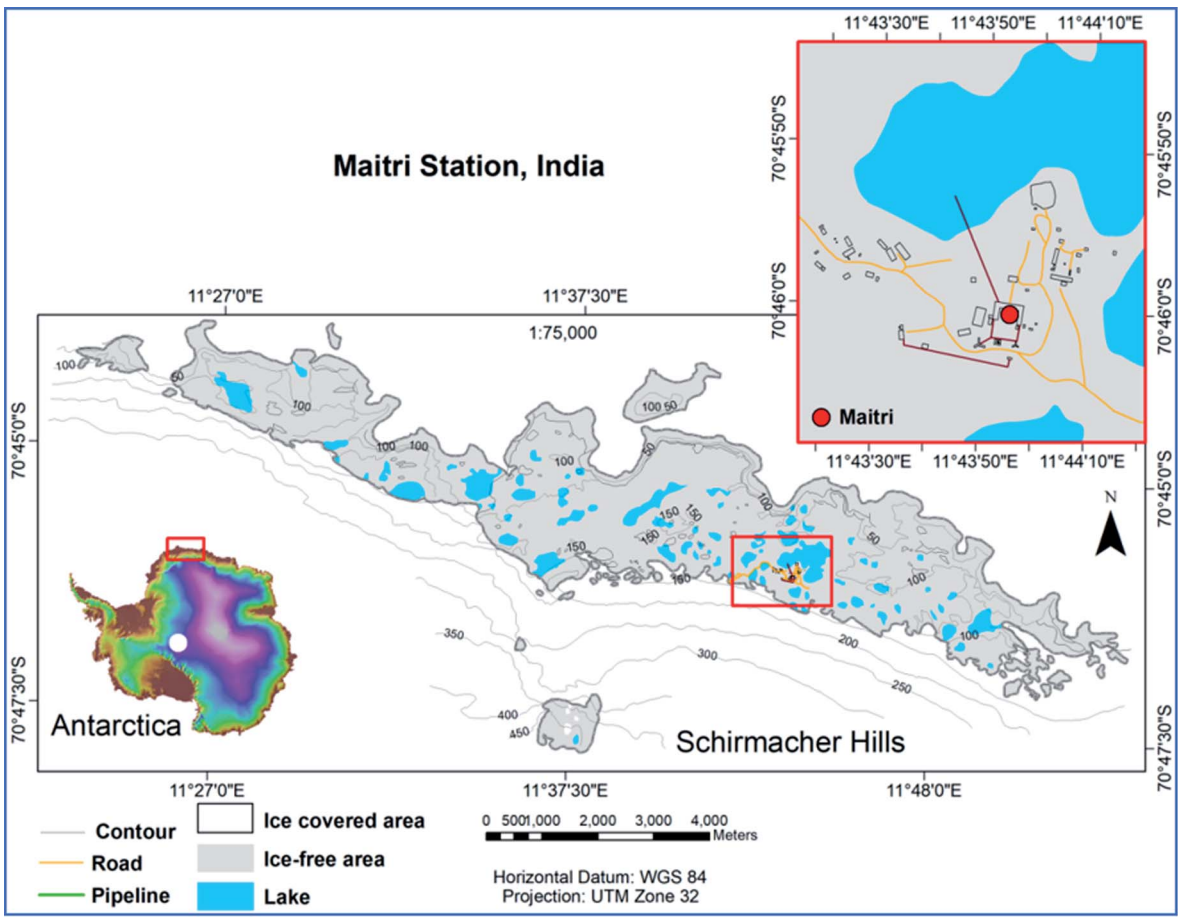

Fig. 1 Location of the study area, Maitri station, Antarctica.

air temperature (T), wind direction (WD), wind speed (WS) and pressure (P) at the Maitri station.

2.2 Monitoring of BC aerosols

A portable Aethalometer (AE42, Magee Scientific) was employed to measure the attenuation of light-absorbing aerosols on the filter fibre in real-time.[18] AE42 gathered air particulate matter (PM2.5) using a cut point cyclone on a quartz filter tape and measured the absorption of light at seven designated wavelengths (λ) of 370, 470, 520, 590, 660, 880 and 950 nm. In this study, the λ_{880} nm channel was specifically considered for measuring BC aerosol concentrations. BC concentration is derived from the relation between absorption coefficient (by measuring the attenuation of incident light transmitted through the sample spot on the filter tape), and the mass absorption cross-section (MAC),[18] which was provided by the manufacturer of the instrument and attenuation (ATN) in this study was done based on previous reports.[22] AE42 uses a fixed calibrated factory mass absorption efficiency value of 16.6 $m^2\ g^{-1}$ and the flow rate was set to 5 L min^{-1}. The sampling inlet height was almost a meter above the ground level at the sampling site. AE42 was employed to continuously record the BC aerosol concentrations at this site for every 15 min. The obtained data was attenuated and loading corrections were made in order to circumvent man-made errors. To determine the BC concentration, the specific MAC and absorption coefficient of BC was used.[18,19] Loading effects were compensated by increased attenuation, indicating that the attained BC concentrations were found to increase after, as sampling by the filter tape advanced.[19,20] The correction algorithm for this loading effect has been reported earlier.[21,22] The corrected ATN coefficient without the scattering coefficient is mentioned in eqn (1) and using that co-efficient, the corrected BC aerosol concentration can be obtained from eqn (2).

$$b_{ATN}\ (\text{corrected}) = (1 + k \times \text{ATN}) \times b_{ATN}\ (\text{Aethalometer}) \quad (1)$$

$$\text{BC (corrected)} = b_{ATN}\ (\text{corrected})/\sigma_{ATN} = (1 + k \times \text{ATN}) \times \text{BC (Aethalometer)} \quad (2)$$

Where 'k' is an empirically derived constant that depends on factors such as sampling location, season, aerosol composition, and age of the aerosols.[23] The measurement of uncertainty due to filter loading and multiple scattering effects is reported to be about ±10% by the manufacturer.

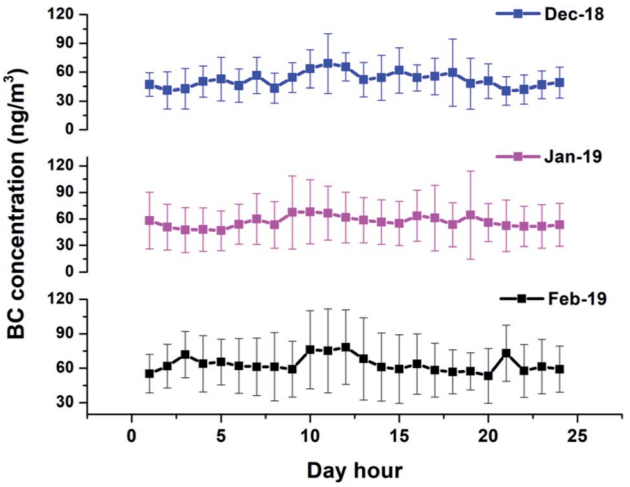

Fig. 2 Diurnal variation of BC aerosol concentration.

The potential distant sources were assessed from the backward/forward trajectory analysis with the help of HYSPLIT4 model developed by NOAA's Air Resource Laboratory. The location coordinates were set for 120 hour runs at 6 hour intervals for backward projection and 240 hour runs at 6 hour interval for the forward trajectory analysis. In HYSPLIT settings, the precipitation was enabled and a single trajectory protocol was run for trajectories at three different heights (100, 500 and 1000 m) over the observation period of 19th December 2018 to 20th February 2019 for the identification of trajectory patterns or dispersion variability. Trajectory analysis results were saved as a ".kmz" file format with end plot using coordinates of the location. The trajectories were overlaid in one coordinate file using ArcGIS 10.3.

3. Results and discussion

3. 1 Diurnal variation and mass concentrations of BC

The mean hourly variation of the BC mass concentration is shown in Fig. 2. 24 hours of daylight was observed at the Maitri station during the study period from 19th December 2018 to 20th February 2019, resulting in slight diurnal variation in the

Table 1 BC concentrations measured in air at various sites in Antarctica

Sampling Site	Lat/long	Elevation (m.s.l) or(a.s.l)	Study period (Year)	Approx. BC concentration (ng m^{-3})	References
McMurdo station	77°51′S, 166°41′E	—	1995–1996	300	24
Larsemann Hills of coastal Antarctic (Bharati)	69.73°S, 76.19°E	48 m (msl)	January–March 2009	13	17
Maitri	70.77°S, 11.73°E	123 m (msl)		75	
Halley station	75 35′S, 26 14′W	—	February 1992–1995	0.3–2 (mean)	29
Neumayer station	70°39′S, 8°15′W	—	1999–2009 2006–2022	2.6	30
Ferraz, King George Island	62°05′S, 58°23.5′W	—	1993, 1997, 1998	8.3	31
Maitri	70.77°S, 11.73°E	123 m (msl)	Dec 2018–Feb 2019	37–82 (mean 60)	Current study

surface temperature. Hence, daily diurnal patterns in BC concentrations at the Maitri station might be due to the variation in emissions from different local sources. The only noticeable source of pollution at Maitri is few local activities involving emission from the running vehicles (crane, Arctic truck, JCB, and Piston Bulley), electrical incinerators, power generators and boilers to conduct the scientific activities and station maintenance. The maximum concentrations of BC during the 24 hour day occurred between 09.00 LT and 13.00 LT (local time in hours) and were marked by vertical dash lines, and the minimum BC concentration was found to be 37 ng m^{-3}. In the morning session, the observed peak was contributed by the vehicular movement around the station, whereas afternoon (~13–14.00 LT) emissions occurred from the waste incineration. Aviation Turbine Fuel (ATF) is utilized for vehicles and power generators at the Maitri station. The operations that contributed to BC were also estimated from the mean hours BC, as shown in Fig. 2. The non-operations of incinerators and vehicles occurred during 22.00 LT to 09.00 LT, which corresponds to the BC emissions from fuel-use component and local sources.[24]

It can be found that the daily mean BC concentration varied from 37 to 82 ng m^{-3} with a mean of 60 ng m^{-3} during the observation period. Also, large intra-day variation in the BC concentration was noticed and confirmed by standard deviations, as shown by the vertical bars in Fi. S1 (ESI†). The sampling site was selected as Tirumala Hut, upwind from the station distanced around 300 meters away from the power generators and about 100 m from the electrical incinerators. The obtained BC concentrations exhibit variability as weak and strong based on a 100 ng m^{-3} benchmark, above which reflected a robust-local influence.[24] Remarkably, the observed concentrations were mostly weak (73%), suggesting that the regional impact is dominant. The mean BC concentration (<60 ng m^{-3}) fell under 59.8% of total BC. Although, the higher concentrations were recorded amidst high wind owing to ablation of snow and its BC scavenging ability acting as a long-range transport barrier of BC from the other continents.[17]

High mean BC concentration (82 ng m^{-3}) was observed throughout the monitoring period due to emissions; direct influence of local emissions from the local station combustion activities are associated with winds emanating from the direction of the station, which result in high mean value. The BC flux calculated as a product of wind speed and BC concentration showed a clear directionality.[24] BC emission from anthropogenic activities at each station is likely to be negligible or very low in BC source strength in other regions in Antarctic. It was hypothesized that the BC point sources originated from beyond the Antarctic Circle as no proximal source was strong enough to maintain ambient BC concentrations within the area of interest. In other words, BC can be used as a tracer of long-range transport of aerosols to Antarctic regions. Moreover, other sources of BC at any Antarctic station could be emissions from the nearby research stations.[17]

The average BC mass concentration measured at Maitri is different from various sites in Antarctica (Table 1), which is attributed to the accumulation of BC aerosols from regional, local anthropogenic activities at the station and distant repositories.[25,26] Table 1 represents the comparison of the BC concentration at the present site with other sites reported in Antarctica. In an earlier study, our group had reported Maitri station BC concentration to be 75 ng m^{-3}, which was now increased to 82 ng m^{-3} due to the variations of the movement of air parcels with time infused by local and global activities. However, day-average of the BC aerosols are highest in February (63.4 ± 11 ng m^{-3}), followed by January

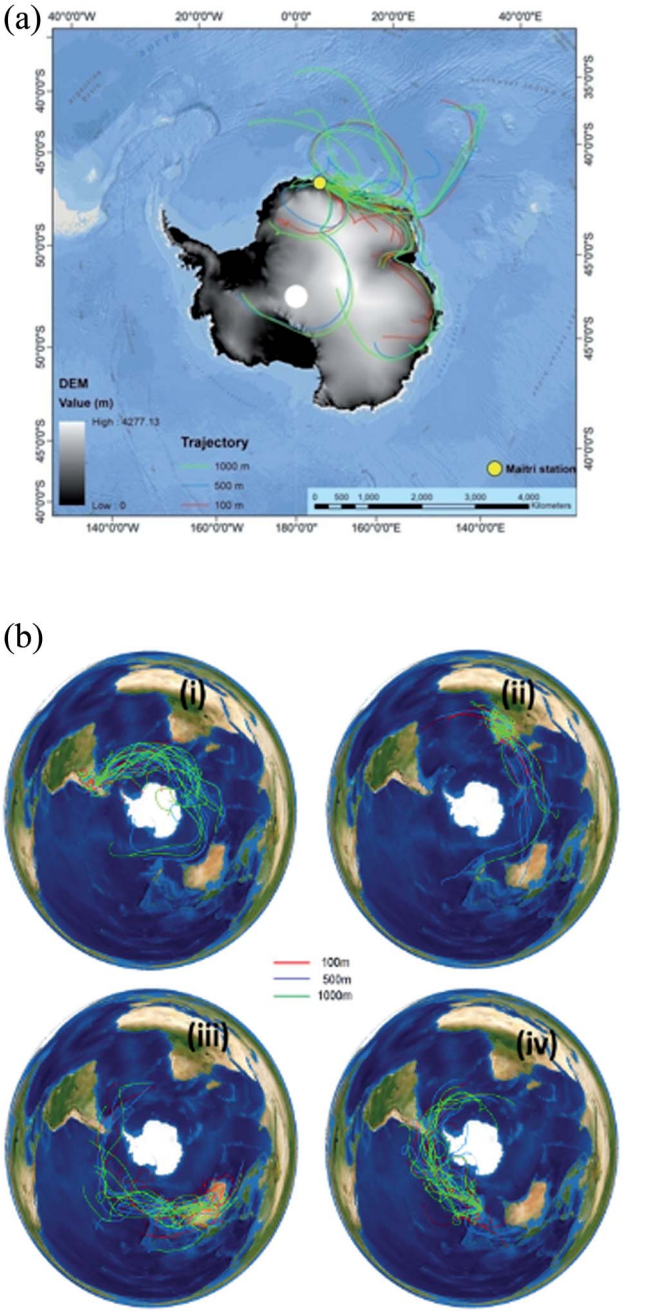

Fig. 3 (a) Back-trajectory analysis for the source of BC to the observatory site. (b) Forward trajectory analysis of PSA sources for BC sources.

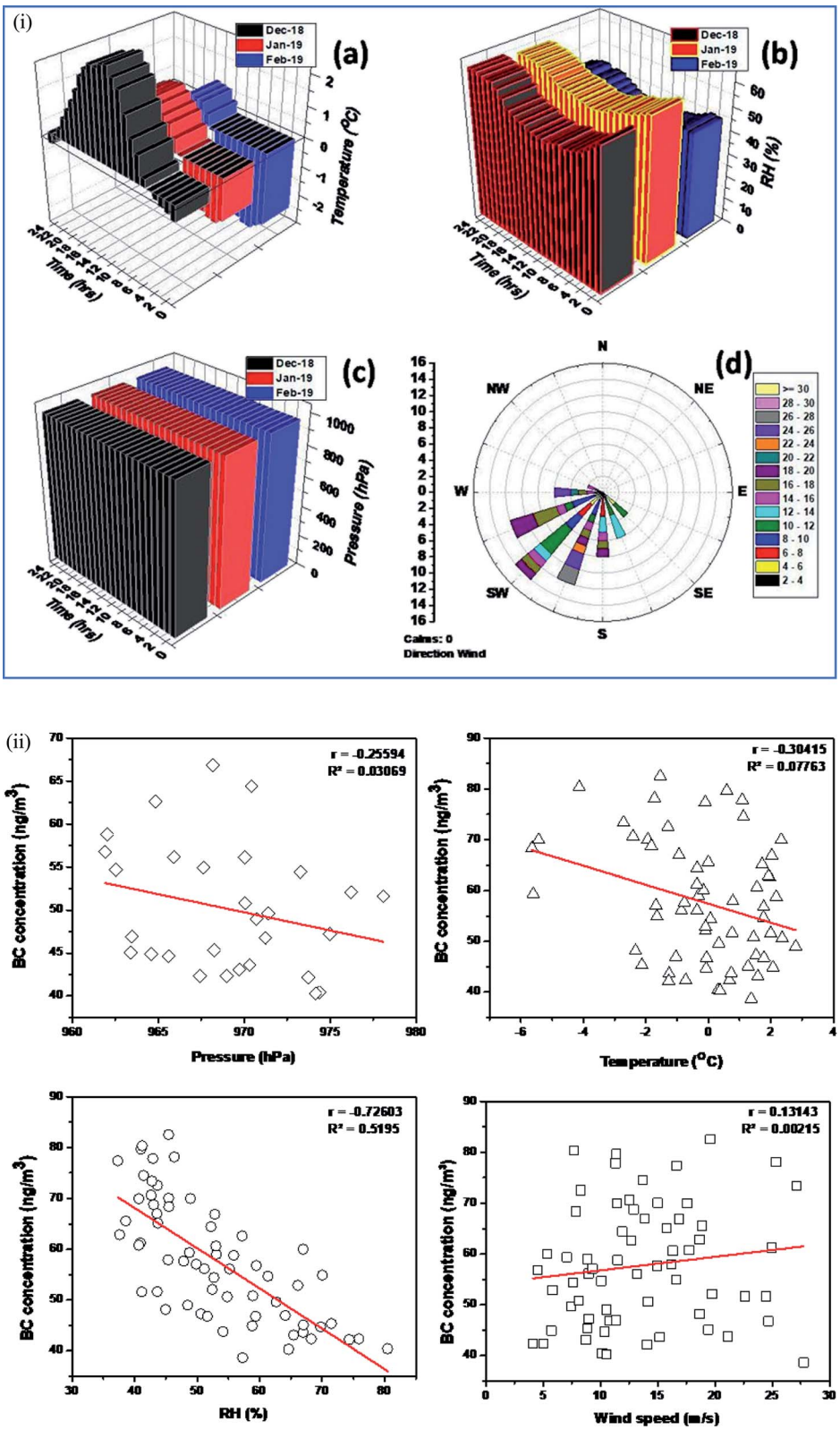

Fig. 4 (i) Diurnal variations of (a) temperature, (b) RH, (c) pressure and (d) wind speed at station. (ii) Correlation of the BC concentration with pressure, temperature, RH and wind speed.

$(56.6 \pm 12.4\ \text{ng m}^{-3})$ and December $(51.6 \pm 6.8\ \text{ng m}^{-3})$. Even though the scope of this comparison is narrow, it encapsulates the nature of contrast in the BC concentrations in diverse environments across Antarctica. Copious stations reported ambiguous BC concentrations due to the choice of fuel based tasks.[27,28]

3.2 Trajectory analysis

The study area is approximately 80 km away from the sea with no direct BC source from the sea. BC has a short life span (~1 week) and can be transported vertically or horizontally across long distances *via* atmospheric processes.[29] The sources are predicted to be far from the study location contributing to the BC aerosol concentration through long-range transport (LRT).[32] Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) and air-mass back projection were used to identify the BC LRT to the observation site. Local emission sources also contributed BC at 100 m above the ground level (agl), *i.e.* shorter trajectories, providing information on point sources in the vicinity of sampling site.

Fig. 3a shows the backward trajectory to determine the BC source range variation and signifies the degree of impact on the long range transport. BC transport is different with great variation in the source range of the air-mass particulate backward trajectory. The yellow circle represents the sampling location at the Maitri station. An ice-sheet in Antarctica occupies a large surface area with different multiple altitudes. In Antarctica, the elevation ranges from 3500 m (asl) to a few meters in coastal regions.[33] Accordingly, the selected initial point is calculated as air parcel heights from ground level. Hence, the studies on aerosol parcels crossing at 100 (red), 500 (blue) and 1000 m (green) of agl were conducted in this study and compared with the aerosol transport at the observatory site five days prior. The results revealed that the BC aerosol transportation is mainly of oceanic origin perhaps because of the high altitude and elevated precipitation levels, therefore resulting in variability in the BC concentrations during the summer time.[34]

On the other hand, a unique maximum BC aerosol concentration was observed during the window of 22–26 January 2019. This discrepancy was explained by the HYSPLIT forward analysis in which ten days forward trajectories were employed at the height of 100 m, 500 m and 1000 m agl. A primary input of Antarctic dust deposition was estimated from two dominant potential source areas (PSAs) namely Australia and southern South America.[35,36] Neff and Bertler (2015) have reported that four PSAs, which contributed more BC to Antarctica.

They are (i) Patagonia: 44° S, 67° W, (ii) Australia: 29° S, 137.5° E, (iii) New Zealand: 43.5° S, 172° E and (iv) South Africa: 28° S, 21° E. Fig. 3b displays the weighed ten-day forward trajectory for the above four PSAs and confirmed that the source of BC aerosols for the study area is Patagonia at 100 m agl for the observed maximum BC concentration period. Thereafter, ten days forward trajectories were initiated from Patagonia, which contributed 15.5% of BC to the station (Fig. S2 in ESI†) in two sets of days (6 Jan 2019 and 26 Jan 2019) during the observatory period (19th December 2018 to 20th February 2019) due to proximity and efficient transport. These air parcels ultimately get incorporated into the Antarctic Circumpolar Vortex (ACV) before mass compensation by the anticyclonic polar easterlies in the East Antarctic region.[37]

3.2.1 Influence of meteorological parameters on BC concentration. Meteorological parameters showed a significant impact on the BC concentrations. Fig. 4i displays the diurnal variation of the physical properties of meteorology such as temperature, relative humidity (RH), pressure, wind speed and wind direction. Interestingly, the minimum and maximum temperatures were recorded in February 2019 (06th February and 19th February 2019) at the study site and found to be −5.6 and 3.7 °C, respectively, with an average of −0.07 °C. The temperature showed negative correlation ($r = -0.3041$) with BC mass, as shown in Fig. 4ii. During December, the temperature rose gradually (at a rate of 1.2 °C) with moderate BC average concentration (53 ng m^{-3}) and then slowly decreased to −1.0 °C in February with an increase in the BC mass concentration (63 ng m^{-3}). *In situ* pressure was observed in the range of 949.5–984.5 hPa with an average of 968.5 ± 6.04 hPa. The pressure and BC concentration were in weak correlation with $r = -0.2559$ and the recorded pressure is maximum in December 2018 with an increase in the BC concentration. This may be compensating with the local temperature and wind direction.

Fig. 4i(b) illustrates the RH mean values for the observational period at Maitri, indicating that the minimum and maximum percentages of humidity were 37.3 and 80.4, respectively, with an average of 53.1 ± 10.7%. The BC aerosol concentration is also strongly influenced by wind speed and direction. The wind speed exhibits a better correlation with the BC mass, as depicted in Fig. 4ii. The sampling location was upwind, and the dominant wind direction over Maitri was Southwestern (SW), and the prevailing wind speed was 18–20 m s^{-1}, as shown in Fig. 4i(d). A lower wind speed (4.12 m s^{-1}) and low BC mass (42 ng m^{-3}) were observed on 14th January, 2019, whereas the highest wind speed (27.7 m s^{-1}) with an average concentration of 13.5 ± 5.9 (BC was 37 ng m^{-3}) was recorded on 10th February, 2019 and the reason could be due to the sample inlet placement in the upwind direction.

In context to experimental cross-contamination from local point sources, placement in the upwind direction was taken into consideration to prevent emissions from the station-related activities. Although during calm conditions or change in wind direction, the short term contamination stood far above the normal values. Fig. S3 in ESI† implies the comparison of BC with (a) wind speed, (b) temperature, (c) RH and (d) pressure; among all, good trend occurred with the wind speed.

4. Conclusion

In conclusion, the BC aerosol quantities at the Maitri station in the southern hemisphere during the austral summer period of 2018–19 have been studied using a filter-based technique. The summary of this study is that the highest mean mass concentration of BC is 82 ng m^{-3} in December 2018 due to more anthropogenic activities than usual at the Maitri station. HYSPLIT trajectory analyses (both forward and backward) predicted the long-range transport of BC aerosols to Maitri and observed that the Patagonia is the main BC contributor for the recorded maximum BC concentrations in two set of days, *i.e.*, 6 Jan 2019 and 26 Jan 2019, which contributed 15.5% to the station. It is proved that meteorological parameters have influenced the BC variation and BC was negatively correlated with them except with the wind speed. Daily routine manual activities carried out

at the Maitri station are secondary emission sources for BC. In future, this dataset can be extended by the long range study, which covers summer and winter periods for detailed study.

Author contributions

SM Botsa: data curation, methodology, interpretation, writing –original draft; NS Magesh: data curation, visualisation. AK Tiwari and Tara DLLM: editing & review-draft.

Conflicts of interest

Authors stated that no conflicts of interest.

Acknowledgements

We would like to thank Dr Muthalagu Ravichandran, the Director of National Centre for Polar and Ocean Research, Ministry of Earth Sciences for his support and permission to participate in XXXVIII-Indian Scientific Expedition to Antarctica during the austral summer period of 2018–19. This is the NCPOR contribution number J-28/2021-22.

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