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Research Paper

Aerosol Studies on and Around Antarctica

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Antarctica provides an excellent environment to examine the natural and background aerosols in the atmosphere over snow and ice. The Indian efforts (metrological measurements) at Antarctica were initiated with the establishment of the first Antarctic station in Eastern Antarctica during the first Indian Scientific Expedition to Antarctica (ISEA) in 1981. The detailed and systematic characterization of physical and optical properties of coastal Antarctic aerosols over Indian Antarctic stations Maitri and Bharati were initiated during the International Polar Year (IPY) 2007 to 2009. Since then, several scientific publications were emerged from the Indian side on Antarctic aerosols. This article provides a brief review of the Indian efforts on Antarctic aerosols.

Keywords: Antarctic Aerosols; AOD; Black Carbon; Size Distribution; Snow Scavenging

Introduction

Antarctica provides an excellent environment to examine the natural and background aerosols in the atmosphere over snow and ice. Besides that, the large ice sheet of the Antarctic continent affects atmospheric circulation patterns over this region, which affects the transport and removal of the aerosol particles (Shaw, 1979). In the recent years, with the increase in human interventions (exploratory, scientific and tourism) in Antarctica, there is an increase in the emissions of anthropogenic species (including aerosols) (Shaw, 1979; Tomasi *et al*., 2007). Overall, aerosol over Antarctica consists mainly of the transported components either from the Oceans or from the surrounding continents. It mainly consists of aged aerosols. Large variations in the columnar aerosol loading over Antarctica are also reported during the periods of strong volcanic eruption of El Chichon (1982) and Mt. Pinatubo (1991), which also justifies the teleconnection of Antarctica with other regions of the world from transport at higher altitudes and their subsequent influence on the Antarctic aerosols system (Herber *et al*., 1993; Tomasi *et al*., 2007).

Antarctic aerosol system is studied by several investigators from different countries which include the aerosol properties such as their chemical nature (Savoie *et al*., 1993; Minikin *et al*., 1998; Wagenbach *et al*., 1998; Kerminen *et al*., 2000), their total number, mass concentrations and size distributions (Samson *et al*., 1990; Jaenicke *et al*., 1992; Mazzera *et al*., 2001; Koponen *et al*., 2003) their role as cloud condensation nuclei (De Felice *et al*., 1997); and their chemical mass size distributions (Harvey *et al*., 1991; Gras, 1993; Ito, 1993; Teinila *et al*., 2000; Rankin and Wolff, 2003). As far as the columnar aerosol optical depths (AODs) are concerned, Antarctica presents a pristine environment. The first measurements of AOD performed in Antarctica using a Sun photometer were in 1968/69 (Sakunov and Rusin, 1980), while regular measurements have been recorded at South Pole (USA) since 1976 (Bodhaine *et al*., 1986). AOD over Antarctica at 500 nm varies between 0.01 and 0.06 for the coastal and low-latitude sites and further lower values are reported at the high-latitude sites (Six *et al*., 2005). Aerosol concentrations varied from few particles cm^{-3} to few thousands particles cm^{-3} (Hogan, 1975). While fine particles of sulphate are most abundant over the Antarctic continent, coarse particles of sea-salt are major contributor to aerosols in the coastal Antarctic regions (Hall and Wolff, 1998;

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Wagenbach *et al*., 1998; Kerminen *et al*., 2000). The cyclonic storms revolving around the continent over the oceans bring the marine aerosol in to the Antarctic continent.

Concerning the global distribution and importance of black carbon (BC) aerosols, there is a major lack of observations of BC at Antarctica, especially in the Indian oceanic sector of eastern Antarctica (Hara *et al*., 2008). The first long term (from December 1986 to November 1987) measurements of BC over Antarctica was made by Hansen *et al*. (1988) which provided the background value of BC at South Pole. These measurements are important when we consider the recent increase in the ship borne Antarctic tourism activities during Austral summer (Graf *et al*., 2010). Impact of local pollution and growing combustion derived emissions from ship borne activities in the oceans surrounding Antarctica have strong relevance for BC concentrations (Weller *et al*., 2012).

All these studies have pointed out the importance of long term measurements of physical and optical properties of aerosols for complete characterization of the Antarctic aerosols on the spatial and temporal scales from different regions of Antarctica with the following objectives. They are: (1) Delineation of long term changes in the physical, chemical and optical properties of aerosols in Antarctic atmosphere, quantification of the effect of long range transport and estimation of radiative impact (2) Estimation of snow scavenging of aerosols and deposition of black carbon on ice and to characterise the physical, chemical and optical properties of aerosols in Snow and the corresponding changes in snow albedo and (3) Quantification of the anthropogenic influence in Antarctic atmosphere to delineate local and long-range transport.

Indian Efforts on Aerosol Studies Over Antarctica

The Indian efforts (meteorological measurements) at Antarctica were initiated with the establishment of the first Antarctic station (Dakshin Gangotri) in Eastern Antarctica during the first Indian Scientific Expedition to Antarctica (ISEA) in 1981. While the meteorological measurements are carried out continuously in each ISEA, the aerosol measurements are limited to few days of the expedition and are discontinuous. During January 1997 to February 1998, NPL team has carried out measurements of columnar ozone, water vapour and aerosol optical thickness at 1020 nm at Maitri (Tripathi *et al*., 2002). While limited measurements of number concentrations and size distributions (Lal and Kapoor, 1989; Pant *et al*., 2011), columnar aerosol optical depth (AOD) and mass concentrations (Gadhavi and Jayarman, 2004, Chaubey *et al*., 2010, 2011, 2013), aerosol conductivity (Kamra *et al*., 2009) are carried out during different years, a comprehensive multi parameter aerosol measurements were not available from Indian side till the International Polar Year (IPY) of 2007.

During the southern hemispheric summer of International Polar Year (IPY) 2007 to 2009, a detailed characterization of physical and optical properties of coastal Antarctic aerosols has been carried out over Indian Antarctic station Maitri, and for the first time over 3rd Indian Antarctic station Bharati, before the station has been established (Chaubey *et al*., 2010; 2011). During this study the first time measurements of black carbon (BC) and semi-quantitative effects of scavenging of aerosols by snow were carried out from Maitri and Bharati.

The mean AOD at 500 nm over Maitri (0.034 ± 0.005) and Bharati (0.032 ± 0.006) during IPY (2008) were found to be comparable, showing the spatial homogeneity in columnar aerosol properties over the Antarctic atmosphere (Chaubey *et al*., 2011). Spectral variations of AOD over Bharati differ significantly from those over Maitri. Estimated α_{AOD} (Angstrom wavelength exponent) showed an increased fine mode dominance at Maitri (α_{AOD} ~ 1.2) compared to Bharati (α_{AOD} ~ 0.7).Based on the measurements from Maitri during 2001, Gadhavi and Jayaraman (2004) have reported a mean AOD value of 0.036 ± 0.018 at 400 nm. Based on the measurement during December 2004 to February 2005, Devara *et al*. (2011) have reported a mean AOD value of 0.042 at 500 nm over Maitri with an Angstrom exponent of 0.24 indicating the abundance of coarse particles during the study period. On the other hand, AOD measured at these stations were significantly lower than that measured over the oceanic regions surrounding Antarctica (Chaubey *et al*., 2013). The AOD at 500 nm measured during different expeditions by the Space Physics Laboratory is shown in Fig. 1.

The distinct geographical features of Maitri and Bharati, despite being in the Antarctic Circle, might be, at least partly, responsible for the distinct

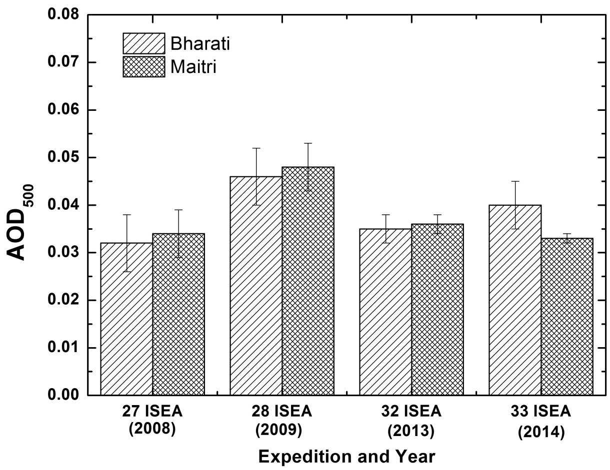

Fig. 1: Aerosol Optical Depth at 500 nm measured from Maitri and Bharati during different summer expeditions. The AOD is in general comparable over both stations except in 2014

differences seen in the aerosol characteristics. Maitri is a continental station under moderate anthropogenic influence while Bharati is rather pristine and is more under the influence of marine environments. The two main mechanisms which might be contributing to the variabilities in aerosol properties at Maitri are (i) marine particles (sea salt) and dust particles from the oasis both produced and transported by the winds, and (ii) those produced by the local activities at Maitri and nearby stations. Moreover, as the coarse mode sea salt particles get settled faster in comparison to the fractionated sea salt aerosols, the marine airmass reaching Maitri would be strongly deprived of the coarse mode component. On the other hand, Bharati being very near to and surrounded by the open Ocean (free from sea ice) and having a low elevation, is conducive for being influenced by the (local) wind generated sea salt particles much more than Maitri. This would also explain the difference in α_{AOD} between the two stations.

In comparison to AOD, most of the near surface aerosol parameters depicted larger day to day variations at Maitri and Bharati indicating the spatial heterogeneities associated with long range transport and local influences. Based on the measurements during the summer of 2007-2008, Chaubey *et al.* (2011) have reported that the total mass concentration of composite aerosols (M_T) depicted fairly large day-to-day variation at Maitri, from a minimum value of 4.4 μg m^{-3} to a maximum of 14.7 μg m^{-3}, with a mean value of 8.25 ± 2.87 μg m^{-3}. Comparatively lower values are found at Bharati where it varied from 4.58 μg m^{-3} to 8.53 μg m^{-3} with a mean value of 6.03 ± 1.33 μg m^{-3}, implying better pristine conditions (Chaubey *et al*., 2011). Based on the measurements over Maitri, Gadhavi and Jayaraman (2004) reported that the total aerosol mass concentration at surface level is of 7 μg m^{-3} for the PM10 particles with significant (day-to-day) variations. Based on the measurement during the 2009-2010, Budhavant *et al*. (2015) reported that the mean mass concentration for PM10 aerosols over southern ocean was found to be 13.4 μg m^{-3} and over coastal Antarctica near Bharati was found to be 5.13 μg m^{-3}. They further reported that the elements of anthropogenic origin (Eg. Zn, Cu, Pb …) were highly enriched with respect to crustal composition. Based on the observations during 11 January 2009 to 21 March 2009 and 09 December 2009 to 09 January 2010, Ali *et al*. (2015) have reported that the total suspended particulate matter (TSPM) over Larsemann hills (where the present-day Bharati station is established) reduced from 7.6 μg m^{-3}during Jan to Mar, 2009 to 2.4 μg m^{-3} during Dec 2009 to Jan 2010. The TSPM reported over Maitri during December 2009 to January 2010 was 9 μg m^{-3}. They also reported that the TSPM over both Maitri and Larsemann hills are acidic in nature with a PH value of 5.56 at Larsemann hills and 5.28 at Maitri. The acidic nature of TSPM is due to the absence of sufficient alkaline minerals. Based on the snow sample collected over coastal Antarctica near to Maitri and Larsemann Hills during December 2009 to March 2010, Budhavant *et al.* (2014) reported that the pH of surface and fresh snow were 6.03 and 5.64 respectively.

Based on the measurement over Maitri, Kamra *et al*. (2009) have shown that the ion concentrations of all categories and the air-earth current simultaneously decrease by approximately an order of magnitude as the wind speed increases from 5 to 10 m s^{-1}. This reduction is due to the scavenging of atmospheric ions and aerosols by the drifting snow particles. Based on the measurements over Maitri during January-February, 2005, Siingh *et al*. (2013) showed that the diurnal variations in positive ion concentrations and the surface temperature are almost parallel to each other on fair weather days and the rate of increase of positive ion concentrations is linked to the freezing point. However, the exact mechanism for the formation of intermediate ions, which is also responsible for the formation of new particles, is yet to be identified. Pant *et al*. (2010) have studied the number concentration and size distributions of aerosol particles during the passage of cyclonic storms (revolving around the Antarctic continent)close to the Maitri station during February 2005. They reported that as a storm approached Maitri, concentration of coarse particles increased by an order of magnitude and the number size distribution frequently showed a coarse mode at ~ 2 μm, a broad Aitken mode from 0.04 to 0.1 μm and, once in a while, a nucleation mode at 0.018 μm. All these modes exist with a slight change in the mode diameter while the storm is going away from the Maitri station. In addition to this, Pant *et al*. (2011) have also shown that at Maitri, total number concentrations of coarse and fine particles vary from 0.1 to 0.8 and from 100 to 2000 particles cm^{-3} respectively, during the southern summer months of January and February, 2005 at Maitri. Maitri is situated on an oasis and experiences a fair amount of local station activities during the summer period. Moreover, advection from the neighbouring stations lying upwind, movement of men and transport of goods (more frequent during Antarctic summer at all the stations) also contribute to the local (regional) aerosols and to the day-to-day variations in the near-surface aerosol characteristics.

Prior to IPY (2007-2009), direct measurements of BC mass concentrations did not exist over Maitri and Bharati. The BC values measured over Larsemann Hills (Bharati) and Maitri during the summer expedition in 2009 are shown in Fig. 2. The mean BC mass concentration at Maitri and Bharati observed during the IPY period were respectively 75 ± 33 ng m^{-3} (which is on the higher side of the background concentration and values reported at other coastal Antarctic locations) and 13 ± 4 ng m^{-3} (which is comparable to the values reported for the other few coastal Antarctic locations), respectively (Chaubey *et al*., 2010). The BC values reported in this study over Bharati were measured even before the establishment of the permanent Indian station at Larsemann hills (Bharati). BC contributed very little to the mass concentrations of composite aerosols over both stations during the study period; being 2 % at Maitri and 0.2 % at Bharati. The BC, produced by the activities over Antarctica, is found to contribute to the high concentration at Maitri. The Angstrom

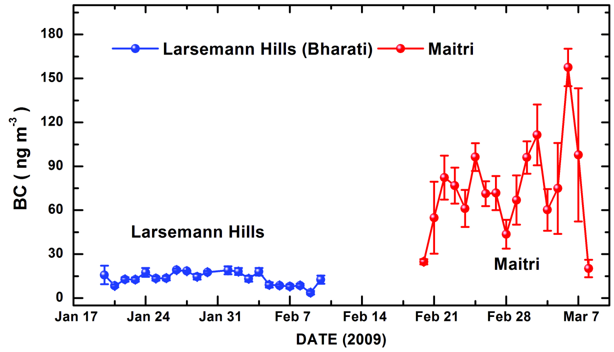

Fig. 2: BC mass concentration over the Indian stations Bharati (Larsemann Hills) and Maitri during the summer expedition, 2009. The BC measurements were made at Larsemann hills before the establishment of the permanent station, Bharati. The day to day variability in BC is mainly due to the snow scavenging associated with blizzards (Chaubey *et al.*, 2010)

exponent (α_{ABS}) for absorption estimated from the spectral values of absorption coefficients (β_{ABS}) is found to vary from 0.5 to 1, indicating a high BC/OC ratio typical of BC of fossil fuel origin (Chaubey *et al*., 2010).

One of the major removal mechanisms of BC from the polar atmosphere is through snow scavenging. It is found that the mass concentrations of BC were reduced to half of the normal day values during snow fall event but recovered rapidly to the normal day's values shortly after the cessation of the episode (Chaubey *et al*., 2010). BC scavenged or dry-deposited on snow and ice can produce large climatic and radiative implications.

Air mass back trajectories computed for the summer period (1 December 2007 to 31 March 2008) showed that, aerosol properties over both Maitri and Bharati are modified by the wind coming from the high latitude polar regions (Chaubey *et al*., 2010). Based on the analysis of snow samples collected from two regions in East Antarctica, Mahalinganathan and Thamban (2016) have reported the presence of calcium nitrate aerosols transported from the southern South American regions. With the increased tourism and scientific activities during summer, there can be a large day to day variability in the aerosol characteristics at coastal Antarctica due to the air mass coming at the stations from inland continental stations.

Aerosol Properties Over Southern Oceans

The scientific expeditions from India to Antarctica also provide an excellent opportunity to study the aerosol properties over different oceanic regions in the Indian longitude sector from the Arabian Sea to the southern oceans. During the 16th ISEA, Deshpande and Kamra (2002) has made measurements of aerosol size distributions over the oceanic regions en route to Maitri. They have reported the presence of nucleation mode particles in great abundance up to 30°S. Perhaps the first of its kind measurements of BC over Southern Ocean was made by Moorthy *et al*. (2005), on board Sagar Kanya, during its first pilot expedition to Southern Ocean from January to April, 2004. They reported a steady BC values (~ 50 ng m^{-3}) over southern ocean which exponentially increases to 2000 ng m^{-3} over Arabian Sea. Based on the measurements over oceans during January-April, 2006 onboard R/V Akademik Boris Petrov from the Antarctic coast to Indian coast, Vinoj *et al*. (2007) reported extremely low (< 0.1) and steady AOD over southern ocean which increases nearly exponentially to 0.7 in the northern Arabian Sea. Based on the measurements of various aerosol properties, such as spectral AOD, total aerosol mass concentration as well as BC mass concentration, on board SagarKanya during its first pilot expedition to Southern Ocean Babu *et al*. (2010) reported that the aerosol radiative forcing at surface level over southern ocean in the range –4 to –5 Wm^{-2} increases to –10 to –23 Wm^{-2} over the ocean north of equator. Compiling the dataset from various expeditions to southern ocean as well as to Antarctica, Chaubey *et al*. (2013) have reported the seasonality in latitudinal gradient in aerosol properties over the oceanic regions and the role of long range transport in the observed seasonality.

Conclusion

Scientific literatures on the aerosol measurements from Indian side over Antarctic regions are available from the 6th Indian Scientific Expedition to Antarctica onwards. Most of these measurements were happened in random years and focussed on one or two aerosol parameters only. Systematic measurements on various aerosol parameters were initiated after the International Polar Year (2007-2008). These measurements were also in campaign mode and the data duration over Antarctic region was very limited. It is important to have a dedicated atmospheric science laboratory at the Bharati station for the continues and long term observation of aerosols, gases and other atmospheric parameters which will be useful not only for the assessment of long term changes in the back ground aerosol properties but also for the scientific understanding of various process responsible for aerosol - Cryosphere interaction.

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