Possible evidence of new particle formation and its impact on cloud microphysics from airborne measurements over Bay of Bengal

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ABSTRACT

Airborne measurements conducted under a special mission over Bay of Bengal (BoB) during the CAIPEEX (Cloud Aerosol Interaction and Precipitation Enhancement Experimen) in 2011 were analyzed in the present study. Research flights were carried out on 19 and 20 October, 2011 (referred as RF1 and RF2), in the region over BoB, which was influenced by a depression to evaluate the aerosol–cloud interactions over marine environment. The increased concentration of aitken/accumulation mode particles was observed at 500 m above sea surface level over the ocean after the passage of the depression. The source of these particles and their subsequent growth during RF1 at about 200 km from coastline has been attributed to (i) increased production of aerosols due to oxidation of dimethyl sulfide (DMS) because of upwelling of the deep ocean water during the depression and (ii) anthropogenic aerosols transported from inland. Moreover, measurements of accumulation and coarse mode particles with diameter ranging from 0.1 to 3 μm and cloud droplets in the range 3 to 47 μm show systematic growth associated with cloud microphysical/rain formation process. On the other hand, no such evidence of increasing particle concentration and growth has been observed at about 60 km from coastline towards southeast during RF2. Evidently, the rain event observed during the night hours of 19 October caused the washout and scavenging of aerosols which contributed towards the decreased aerosol concentration observed near the coast.

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1. Introduction

It is well known that the aerosol particles play an important role in many atmospheric processes. They are responsible in altering Earth’s energy balance via direct and indirect effects (Hudson and Yum, 2001; Lohmann and Feichter, 2005). Natural sources of atmospheric aerosol particles are gas-to-particle conversion, volcanoes, dust-storms, wave-breaking over the oceans etc. Being the large areal extent of the oceans, marine aerosol constitutes one of the most important natural aerosol systems at the global level. The bursting of white caps, the oxidation of gases emitted by the ocean and the transport of continental air are the main sources of aerosols over a marine region (Blanchard and Woodcock, 1980; O’Dowd et al., 1997, 1998, 1999, 2007; Clarke et al., 1998; Shenoy et al., 2006). The new particle formation, chemical processes leading to the nucleation and their subsequent growth are particularly important for better understanding of these aerosols. The theories proposed to be responsible for the nucleation and growth of newly formed particles include binary water–sulphuric acid nucleation theory (Kulmala and Laaksonen, 1990), ternary water–sulphuric acid–ammonia nucleation theory (Napari et al., 2002; Merikanto et al., 2007), cluster activation theory (e.g. Kulmala et al., 2004b, 2006), ion-mediated nucleation (Yu and Turco, 2000), and the nucleation mechanisms involving organic vapors (O’Dowd et al., 2002a)
or iodine (O’Dowd et al., 2002b). Moreover, it has been observed that the nucleation rates are highly dependent on the environmental conditions, such as the chemical composition of the atmosphere, water vapor content, and the amount of solar radiation (Kulmala et al., 2004a and references therein, Sogacheva et al., 2008).

Formation of new particles in the low tide conditions in coastal regions due to emission of dimethyl sulfide (DMS), the most abundant volatile sulfur compound, by the marine microbiota has been proposed as a strong source for particles in coastal regions (Pirjola et al., 2000; O’Dowd, 2002; O’Dowd et al., 2007). These particles are <20 nm in size at the time of formation but can grow to Aitken particle size range in few hours through condensational growth by deposition of sulfate derived from the oxidation of DMS (Leck and Bigg, 2005). From long term measurements at Hyytiala, Southern Finland, new aerosol particle formation in different synoptic situations was identified by Sogacheva et al. (2008) suggesting that it tends to occur on days after passage of a cold front and on days without frontal passages. Hussein et al. (2008) have inferred from their long term measurements of fine particle number-size distributions at Helsinki that these events occurred most frequently during spring and autumn. Large increases in concentration of new particles are relatively common over the central Arctic Ocean in summer and have occasionally been observed over lower latitude oceans (Leck and Bigg, 2010). Over the tropical region, occurrence of aitken mode particles has been demonstrated from submicron aerosol size distribution measurements over the tropical and South Pacific by Hoppel and Frick (1990). Similarly, new particle formation due to gas-to-particle conversion processes has been reported over tropical Indian Ocean from submicron aerosol measurements by Deshpande and Kamra (2002).

After its initial formation due to nucleation, an aerosol particle may grow to several hundreds of nanometers in diameter and can act as a cloud condensation nuclei. In the last decade, several airborne experiments such as Indian Ocean Experiment (INDOEX) (Hudson and Yum, 2002; de Reus et al., 2001), Integrated Campaign for Aerosols, Gases and Radiation Budget (ICARB) (Murugavel et al., 2008), Pacific Dust Experiment (PACDEX) (Lee et al., 2010), African Monsoon Multidisciplinary Analysis (AMMA) (Chen et al., 2011), Suppression of Precipitation (SUPRECP) (Rosenfeld et al., 2008a,b), and Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS) (Lance et al., 2009) were conducted worldwide to address the extent of the aerosols and pollutant transport over the ocean, aerosol–cloud interaction and role of increased pollution on precipitation. Airborne measurements of the aerosol number concentration and the size distribution conducted over the northern Indian Ocean during INDOEX in February–March 1999 reported that the aerosol in the marine boundary layer can be characterized by high number concentrations of submicron and accumulation mode particles, which gradually decreases with distance from the Indian subcontinent (Hudson and Yum, 2002; de Reus et al., 2001). Airborne measurements of sub-micron aerosols made at four vertical levels over the Bay of Bengal (BoB) across the coastline at Bhubaneswar (20.3°N, 85.8°E), India during ICARB campaign show that the land-to-ocean dispersion of aerosols in stable atmosphere may extend up to 500 m altitude. Further, these results demonstrate that the newly-formed particles in coastal zones may be convected up to 1000 m in altitude even in stable meteorological conditions in the lower atmosphere (Murugavel et al., 2008). This confirms the earlier results reported by O’Dowd (2002) around the coastline at Mace Head. The CCN concentrations and the activation characteristics of atmospheric aerosols in a diversity of air masses sampled at Finokalia Island over Eastern Mediterranean Sea during the Finokalia Aerosol Measurement Experiment-2007 (FAME-07) campaign by Bougiatioti et al. (2009) show dependency on air mass origin.

A major Indian national experiment, ‘Cloud Aerosol Interaction and Precipitation Enhancement Experiments’ (CAIPEEX) was conducted during the period of 2009–2011 to explore the variability of thermodynamic properties, aerosol, clouds and precipitation through airborne measurements over the Indian region. In-situ observations of clouds and aerosol at several locations in India were carried out during Phase-I and Phase-II of this experiment with an instrumented aircraft. More details of this experiment were given in Kulkarni et al. (2012). The aircraft observations during CAIPEEX-2009 were utilized to understand the elevated pollution layers, cloud microphysical properties over Indian monsoon regions and role of aerosols in controlling the depth of warm rain in convective clouds (Padmakumari et al., 2012; Morwal et al., 2012; Konwar et al., 2012).

The objective of this work is to present the airborne measurements over the Bay of Bengal (BoB) from Bhubaneswar (20.3°N, 85.8°E), India during 19–20 October, 2011 to highlight the possible evidence of new particle formation and the evolution of associated growth of the primary marine aerosols to cloud droplets. Also, the role of prevailing synoptic forcing due to cyclonic conditions and transport of aerosols in modifying the local aerosol distributions and its effect on cloud microphysics have been examined.

2. Data and methodology

2.1. Sampling platform and instrumentation

Large variations in size, concentrations and composition of aerosols and cloud parameters coexist in convective clouds. The ability to analyze the microphysical properties of all these types of particles requires in-situ measurements with appropriate airborne instrumentation. During the CAIPEEX program, a twin-engine turboprop ‘Aero-Commander’, a pressurized research aircraft was used during the intensive observational period in 2011. For aerosol measurements the instruments used onboard are high-flow automated Differential Mobility Analyzer (DMA) system (Collins et al., 2000), a Droplet Measurement Technologies (DMT) Passive Cavity Aerosol Spectrometer Probe (PCASP) and a DMT continuous flow cloud condensation nuclei (CCN) Counter. The DMA system, operated over the size range of 0.02 to 0.49 μm, covers accumulation mode of aerosols and the PCASP operated in the size range from 0.1 to 3 μm, covers the accumulation and part of the coarse mode of aerosols. The forward scattering spectrometer probe (FSSP) is used to measure the cloud droplet size distribution in the size range from 3 to 47 μm.
The aerosols were brought into the cabin with an inlet that was designed to perturb the sample as little as possible. The inlet system used on the research aircraft consists of a stainless steel nozzle mounted 30 cm above the fuselage, with an inlet diameter of 15.4 mm, and a maximum radius of 48 mm. The nozzle tip is tapered to a 3 mm radius. This maintains a near isokinetic flow condition at the typical true airspeed of 80–100 m/s. The pipe downstream of the cone has two bends in it to bring it inside the aircraft cabin, where it runs parallel to the cabin roof. The flow rate through the inlet system is 1125 lpm. Submicron particles are sampled at near 100% efficiency.

For the first time during CAIPEEX, the DMA system operated as described in Collins et al. (2000), is designed for high flow aircraft measurements. The DMA system includes DMA column paired with TSI 3760A Condensation Particle Counter (CPC) and other devices that classifies and counts particles. The scanning DMA system data were processed using a fixed voltage transfer function (Collins et al., 2004). The DMA system scan time is 85 s and by using the near isokinetic inlet, the DMA is unlikely to experience any sampling bias due to the inlet design. All the instruments were calibrated periodically and performed satisfactorily throughout the campaign. Also, a standard set of meteorological and aircraft parameters was simultaneously recorded, including temperature, pressure, altitude, wind direction, and wind speed. A detailed description of the CAIPEEX project can be found on the web page: http://www.tropmet.res.in/~caipeex/.

2.3. Measurement locations

A special mission was conducted over the BoB in order to document the nature of aerosols in the coastal region and their interaction with cloud microphysics during CAIPEEX-Phase II. These measurements were conducted over the regions influenced by a cyclonic storm during 19–20 October, 2011. The flight plan to conduct vertical profiles over the BoB was executed when meteorological and aerosol conditions were deemed most suitable. Fig. 1c shows the geographical locations of the experimental regions including research flight tracks to the BoB.

Case I: On 19 October the first research flight (RF1) departed from Bhubaneswar at 0745 UTC as shown in Fig. 1c. The aircraft flew 200 km to the southeast limit of the operational area where convective clouds were observed in the region 17.2°N, 87.2°E. To map the microphysical properties and aerosol concentrations, vertical downward profiling of convective cloud was conducted from 6400 m to the cloud base at around 430 m. CCN measurements were also done at cloud base after which the aircraft returned back to Bhubaneswar at 1130 UTC at 457 m above sea level.

Case II: On 20 October another research flight (RF2) was carried out from Bhubaneswar at 0615 UTC towards the southwest along the coastal waters (19.2°N, 85.90°E) about 60 km from coastline where similar vertical profiling in convective cloud and CCN measurements at the cloud base at about 470 m were conducted. The aircraft crossed the coastline near Vishakhapatnam, cruised along coastline at 4120 m and landed at 0930 UTC at Vijayawada. At the time of the aircraft observations on 20 October, the depression turned into a low pressure area and after crossing the Myanmar coast it moved eastward, after which the atmospheric and oceanic conditions in the operational area returned to the normal undisturbed conditions.

The stability of boundary layer, estimated based on the \( \Omega_e \) profile has been plotted for both RF1 and RF2 that are shown in Fig. 2. A sharp decrease in \( \Omega_e \) values up to 1500 m on both days shows that the boundary layer was highly unstable.

2.4. Back trajectory analysis

The 5-day backward trajectories obtained from Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (NOAA, Air Research Laboratory, Draxler and Rolph, 2010) at heights of 500, 1000 and 1500 m over the observational location and time over the BoB on 19 and 20 October 2011 are plotted in Fig. 3(a,b) to understand the generation and growth mechanism of aerosols in marine boundary layer and their advection. One common feature observed from the trajectories at 500 and 1000 m levels during both RF1 and RF2 is that the air mass traveled from the coastal regions of Thailand, Burma and Bangladesh while at 1500 m level; air mass had a long journey over the inland of same region for the preceding 5 days. During RF1, the air parcel reaching the observational area was traveling over the oceanic surface for the past 24 h and experiences lift carrying the oceanic air mass to higher levels. On the other hand, though the air mass traveled last 24 h over the ocean, the subsidence is observed on RF2 instead of uplift as observed on RF1.
3. Results and discussion

3.1. Total number concentration

Fig. 4 (a,b) shows time series of the total number concentration measured by DMA system, PCASP, CCN and FSSP during RF1 and RF2. The flight altitude during the cruise is also shown in the figure. The low level sampling at a constant height of about 500 m from 0940 to 1045 UTC and 0740–0800 UTC on RF1 and RF2, respectively, is highlighted within the box. The higher number concentration observed in aerosol and CCN measurements at the beginning and end of the research flights on both days is due to continental aerosols during take-off and landing of the aircraft.

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Fig. 1. (a) Track of the depression on 19 and 20 October 2011 over Bay of Bengal. Notation D represents depression and DD as deep depression. (b) Indian satellite Kalpana-1 cloud images on 19 October, 2011 at 1200 UTC shows convective clouds over parts of Mizoram, Manipur, Kerala, northeast & central BoB and south Andaman Sea in association with the depression over the BoB. Also observational area on RF1 is denoted with black cross and on RF2 as white cross. (c) The geographical locations of the observational regions including research flight tracks of RF1 and RF2 to the BoB. The marked dotted circles show the area of vertical profiling.
observational region has been under the influence of a depression over BoB, as discussed in Section 4, and pollutants are transported from long-range through the strong north-easterly winds.

3.1.1. Aitken/accumulation mode particle total number concentration

Measurements of aerosol particles of diameter range 20–490 nm using DMA system show decrease in total aerosol number concentration with increasing altitude on both days (Fig. 4a,b). However, at a constant altitude of 500 m above sea surface (shown in highlighted box), the aerosol concentration on RF1 is found to be of the order of 3000 particles/cm³ while RF2 is about 500 particles/cm³. It is worth mentioning that the sampling location of RF1 was in the ocean about 200 km from coastline and RF2 was about 60 km from coastline. From the back trajectory analysis, although the air-mass reaching the sampling locations is from the coasts of Thailand, Burma and Bangladesh, during the past 24 h it traveled over the ocean on both days. However, vertical uplift of airmass is observed on RF1 while the subsidence is observed during RF2. The increased concentration of aitken/accumulation mode particles observed on RF1 at 500 m above sea surface level may be attributed to production of aerosols due to oxidation of dimethyl sulfide (DMS) and the strong winds upwelling at the ocean surface layer during the depression as reported by Shenoy et al. (2006), demonstrating the abundance of new particles due to DMS production in the surface layer over BoB region.

Several marine observations report the high aerosol concentration associated with new particle generation processes (O’Dowd et al., 2007; Murugavel et al., 2008; Pant et al., 2009). Moreover, anthropogenic pollution from Bangladesh and adjoining regions associated with long distance transport shown in Fig. 3a with favorable winds may also contribute to these higher concentrations. Earlier observations also show such transport of pollutants over BoB and
Indian Ocean region with favorable wind direction (Deshpande and Kamra, 1995; Lelieveld et al., 2001; Deshpande and Kamra, 2002).

Evidently, the rain event was observed during the night hours of 19 October. The TRMM 3 hourly precipitation data averaged for longitude 82°–96°E of 20 October 2011 have been plotted from latitude 13° to 22°N in Fig. 5. TRMM data shows continuous rainfall from 0000 UTC to 0600 UTC, approximately 2 mm/h along 17°N in the RF2 observational region. The lower concentration of aitken/accumulation mode particles observed during 0745–0815 UTC on RF2 may be attributed to the washout effect due to this rainfall event.

3.1.2. Accumulation/coarse mode particle total number concentration

The total aerosol number concentration from PCASP measured during RF1 and RF2 shows decrease with altitude over BoB (Fig. 4). Further, during low level sampling at
constant altitude of 500 m above sea surface, an increase in the aerosol number concentration was observed on both days as shown and highlighted in figure. However, aerosol concentrations exhibit higher values of about 1000–2000 particles/cm³ on RF1 at about 200 km in the ocean as compared to the lower values of about 200–400 particles/cm³ on RF2 at about 60 km from coastline. The trend of similar variation in PCASP number concentration and DMA system number concentration on RF1 may be due to the existence of coarse mode particles of marine origin and simultaneous growth of submicron particles to coarse particles elevated to measured altitude. The enhanced concentration of aerosol particles obtained over the ocean on RF1 may be associated with possible aerosol generation mechanisms in the surface layer due to residual cyclonic circulation and/or anthropogenic aerosols transported from inland. Lower number concentrations observed on RF2 may be attributed to washout associated with large scale precipitation during night hours of 19 October 2011.

The vertical profiles of PCASP aerosol concentrations while descending over the ocean on RF1 and RF2 are compared in Fig. 6. Three distinct aerosol layers were observed on RF1 with the total aerosol concentration of about 1000 particles/cm³ in the lowest 1000 m and a sharp decrease of an order of magnitude up to 100 particles/cm³ with altitude. However, the total aerosol concentration in the range 50–200 particles/cm³ was observed throughout 4000 m altitude on RF2.

3.1.3. Cloud condensation nuclei (CCN) concentration

During the campaign, the CCN counter was both pre and post calibrated and operated at 0.2, 0.4, 0.6, and 0.8% super-saturations (SS). In consistence with the observed high concentration of accumulation and coarse mode particles at low level altitude at 500 m, the higher values of total CCN concentration on RF1 were observed in the range of 200–1800 particles/cm³ and during RF2 it was 180 particles/cm³ (Fig. 4a,b). Moreover, these concentrations are comparable with the CCN measurements of Bougiatioti et al. (2009) at the Finokalia station at 0.38% SS, a remote marine background site. Our measurements over the ocean suggest that the natural sea salt aerosols generated due to bursting of whitecap bubbles on the sea surface (Blanchard and Woodcock, 1957; Blanchard, 1963) and biological or organic aerosols found over marine region (Cavalli et al., 2004; O’Dowd et al., 2004; Decesari et al., 2006; Facchini et al., 2008) may have contributed for CCN generation.

3.1.4. Cloud droplet number concentration

From Fig. 4a and b, the cloud droplet number concentration measured using FSSP shows higher values ranging from 200 to 800 droplets/cm³ on RF1 as compared to the low values of about 20–200 droplets/cm³ observed on RF2. The cloud droplet concentrations observed on RF1 and RF2 are in accordance with the available CCN in the atmosphere. During RF1, aerosol generation due to oxidation of DMS and anthropogenic pollution from Bangladesh/adjoining regions associated with long distance transport may contribute for CCN formation. These hygroscopic particles may grow in high humidity condition and contribute effectively to the CCN formation process. However, low aerosol concentration observed during RF2 due to washout process associated with rain event, might have contributed to low CCN activation processes and thereby low number concentration of cloud droplets.

3.2. Aerosol size distribution

Two-dimensional contours with the color scale representing number concentration during RF1 and RF2 have been plotted in Fig. 7a and b, respectively, to examine the Aitken/accumulation mode particle number size distribution of DMA system observed during the low level sampling at constant altitude of 500 m (shown in highlighted box in Fig. 4). The monomodal size distribution is observed with maxima at about 60 nm diameter at 500 m altitude on both days. This mean mode diameter represents the Aitken mode of typical marine aerosols. Significant contribution of aitken particles <100 nm was observed in both cases, which play important role in the cloud
formation processes. During the constant passage at 500 m above sea level, the concentration of aitken mode particles is one order higher on RF1 than that on RF2. Airborne measurements of aerosol size distribution over same region by Murugavel et al. (2008) show maxima of about 60 nm at 500 m level which supports our present measurements of mean mode diameter. Bougiatioti et al. (2009) have conducted CCN and aerosol measurements at the Finokalia station, a remote marine background site. Their size distribution measured during polluted and clean environment shows maxima at 60 and 100 nm, respectively with average number concentration of 3500 and 7800 particles/cm³, respectively. These values are comparable with present values during RF1.

The data measured by PCASP and DMA system in common size range from 0.1 to 0.5 μm was compared by converting the optical diameters of the PCASP into aerodynamic diameters for quality check. The size distributions in this size range are in good agreement at different timings.

3.3. Cloud drop size distribution

The cloud drop size distribution measured on RF1 and RF2 is plotted in Fig. 8a and b, respectively. The cloud drop size distribution was measured up to 7.5 km on RF1 and up to 6.0 km on RF2. It is important to report that the concentration of drop size distribution is one order higher and the broadening of size spectra is dominant on RF1 due to more CCN and cloud droplet concentration. However, the low concentration of drop size distribution observed on RF2 may be due to low CCN and droplet concentration available. The broadening of size spectra starts at about 1984 m on RF1 and same was at 2290 m on RF2. Though, the Cₙ values on both days show that the boundary layer was highly unstable, the large scale precipitation that occurred before RF2 observations has caused the washout effect. As a consequence of the same, the drop size distribution observed on RF2 is one order lower than that on RF1. Also the synoptic situation shows that the depression is dominant on RF1 flight and it moved eastward and inland towards Myanmar on RF2. Thus the upwelling process is more efficient during RF1 which contributed for more sea salt and biological aerosols from surface layer over the ocean.

4. Discussion

The marine aerosol is composed of both primary and secondary aerosols. Primary aerosols mainly consist of the sea-salt particles produced by the mechanical disruption of the ocean surface, and these particles have diameters ranging from 0.01 to 100 μm. The secondary aerosol mainly consists of non-sea-salt sulfates, nitrates, and some organic species formed by gas-to-particle conversion processes, and these particles are typically of nanometer size. Dust particles and pollutants transported over the oceans may also sometimes significantly contribute to the marine aerosol. The submicron aerosol size distribution over tropical and sub-tropical ocean shows that the size distribution is relatively stable and has double-peaked characteristics (Hoppel et al., 1985; Hoppel and Frick, 1990; Covert et al., 1996). Besides, the number of excellent review papers on marine aerosols has been published by Junge (1972) and Fitzgerald (1991) to update our knowledge of the physical and chemical characteristics of aerosols in the marine environment. Dimethyl sulfide (DMS) produced by marine microbiota is the most abundant volatile sulfur compound emitted into the atmosphere from the ocean (Andreae, 1990; Bates et al., 1992). These aerosols may also play a role as nuclei for CCN-sized particles over the remote oceans, through condensational growth by deposition of sulfate derived from the oxidation of DMS (Leck and Bigg, 2005). During the southwest monsoon season, the BoB region has abundance of phytoplankton. Fresh water discharge from all the rivers surrounding the BoB during the southwest monsoon season (June–September) brings nutrients important for phytoplankton growth. These processes result in enhanced DMS production over BoB in the monsoon season and further in the month of October. Also it has been observed that DMS production increases with prevailing strong winds (Shenoy et al., 2000, 2006). Additionally, anthropogenic aerosols from land are transported over the BoB and the Indian Ocean with suitable winds (Deshpande and Kamra, 1995; Lelieveld et al., 2001; Deshpande and Kamra, 2002).

A deep depression was formed over northeast BoB and moved northeastswards during 19–20 October, 2011. During this period, strong winds and upwelling associated with depression prevailed over the BoB. The observational location on RF1 was within the area disturbed by the depression. Both the processes are known to enhance the new particle formation associated with DMS production. The higher concentration of aitken/accumulation particles observed during RF1 in the oceanic regions of BoB at 500 m altitude may be attributed to the higher DMS production with high wind speed and upwelling. Such newly formed particles are of a few nanometers in size and thus may not be counted.
with our instrument. But they may grow to measurable sizes by the time they are transported to 500 m. Thus, the new particle formation due to emission of DMS by the marine biotic life has been proposed as a possible source for particles in the marine surface layer. Secondly, the back trajectories show that the anthropogenic aerosols from Bangladesh region are transported to the observational site. These aerosols also may contribute to the measurements. The back trajectory analysis on RF1 shows transportation of continental air mass to higher levels. Observations of earlier studies (O’Dowd, 2002; Murugavel et al., 2008) showed that these nucleation mode particles can be lifted up to 1000 m even in stable atmosphere.

The marine biogenic aerosol particles (20–50 nm) may act as nuclei to form CCN particles over the oceans, through condensational growth by deposition of sulfate derived from the oxidation of DMS (Andreae et al., 1995, 1999; Prospero et al., 1991; Ayers et al., 1997; Leck and Bigg, 2005). Our observations of enhancement of CCN during RF1 support such process. Further, these CCN particles grow to cloud droplets and initiate the precipitation formation process. Modeling studies of Pirjola et al. (2000) show that the enhancement of CCN concentrations during their advection may be due to both, the condensation of sulphuric acid and biogenic vapor.

During RF2 on 20 October, 2011, the observational location was at about 60 km from coastline towards southeast, where the anthropogenic aerosols are present. The back trajectory analysis on RF2 suggests that the air parcel consists of anthropogenic aerosols from coastline. However, our observations show lower concentration of aitken/accumulation mode aerosol particles and subsequent less growth of CCN and cloud droplets. Evidently, the rain event was observed during the night hours of 19 October. This has been confirmed with TRMM 3 hourly precipitation data showing continuous rainfall (2 mm/h) in the RF2 observational region from 1800 UTC of 19 October.

![Fig. 7. Two dimensional contour plots with the color scale representing concentration of aerosol number size distribution obtained during the low level sampling at constant altitude of 500 m (shown in highlighted box in Fig. 4), during (a) RF1 and (b) RF2, respectively.](image)
2011 to 0600 UTC of 20 October 2011 (Fig. 5). Also, the RH values from back trajectory analysis were in the range of 80–95% on both days. It is well known that the precipitation events are effective wet deposition processes for scavenging of atmospheric aerosol particles and drastically affect the number concentration in a very short duration after the rain starts. Further, the scavenging process is temperature-dependent and removes aerosols more efficiently at high relative humidity and warm temperatures (Garrett et al., 2011; Browse et al., 2012). Our observations of lower concentration of coarse mode particles on RF2 support the existence of such mechanism over BoB. Moreover, the depression moved further northeasterward and weakened gradually into a low pressure area, which made the influence of the depression less effective on RF2 causing less aerosol generation mechanisms over the ocean.

5. Conclusions

Generation of sub-micron particles over the ocean is attributed to the DMS production due to marine biological processes in surface layer. Also, the anthropogenic aerosols transported from inland contribute to marine aerosols. These nanometer sized particles are lifted up to 500 m above sea level, can act as CCN and grow to become cloud droplets under the favorable conditions. Over the ocean, the aerosols play an important role in cloud microphysical processes for the initiation and formation of precipitation. Our observations potentially demonstrate the systematic growth of the sub-micron sized aerosols to coarse mode particles over BoB regions. Over the oceanic environment, possible new particle formation due to oxidation of gases in surface layer provides more hygroscopic nuclei for CCN activation and enhances the cloud microphysical processes for precipitation initiation. Moreover, the strong winds and upwelling due to depression formed over BoB at observational location might have enhanced this growth mechanism. On the contrary, washout mechanism due to rain event, reduced subsequent effects of depression and lack of new particle formation processes contributed towards the decreased aerosol concentration observed near the coast.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.atmosres.2014.01.014.

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