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Cloud Condensation Nuclei activity in the tropical marine regions during Indian southwest monsoon

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ABSTRACT

This paper presents the first onboard measurements of cloud condensation nuclei (CCN) distributions at super-saturations (*ss*) less than 0.5% (0.2% and 0.4%) and more than 0.5% (0.6% and 0.8%) as a function of prevailing winds during July and August over south to southeastern head-Bay region of Bay of Bengal (BoB). During monsoon season of 2012, the cross equatorial flow (CEF) along the belt 50°N–50°S was towards north and prevailing winds were stronger than normal by 2.6 ms^{-1} and 5.14 ms^{-1} respectively. Also, 2 and 5 low-pressure systems were formed during July and August 2012 respectively. Due to the strength of CEF, winds and low-pressure systems, mean value of wind speeds (U) observed onboard the ship during August was found to be stronger than that for July by 28%. As a result, mean values of CCN concentrations in August when winds were above 10 ms^{-1} were higher in magnitude by 9.5%, 15.6%, 13.4%, 12.13% and 11.9% for supersaturations of 0.2%, 0.4%, 0.6%, 0.8% and 1.0% respectively compared to corresponding means of CCN concentration during July when winds were below 10 ms^{-1}. Wind-driven (U above 10 ms^{-1}) CCN activity is found to be of high CCN concentrations at *ss* more than 0.5% despite active monsoonal cloud-aerosol interaction in the tropical marine environment. Relationships between CCN concentration and U when winds were above 10 ms^{-1} are found to be $\log_{10}CCN = 0.057U + 2.4$ and $\log_{10}CCN = 0.047U + 2.6$ at *ss* of 0.6% (R = 0.43) and 0.8% (R = 0.4) respectively, slopes of which appear to be reasonable climatic regulators for wind-induced CCN activity over south to southeastern head-Bay region of BoB.

1. Introduction

Cloud condensation nuclei (CCN) activity refers to the ability of a particle to uptake moisture (water vapour) from surrounding environment at different super-saturations (*ss*). It is hard to distinguish between natural and anthropogenic CCN fractions due to aerosols activation up to cloud particle sizes from both natural and anthropogenic sources. Over marine environment, aerosols formed by sea-spray could be of sea-salt, non-sea-salt (nss)-sulphates and sea-originated organic species (de Leeuw et al., 2011; Shank et al., 2012; Clarke et al., 2013; Frossard et al., 2014). Most of the marine CCN particles (e. g. sea-salt) are likely to activate at *ss* less than 0.5% (Clarke et al., 2013; Fitzgerald, 1991; Quinn & Bates, 2011). As a result, sea-salt aerosols must form a large fraction of CCN concentrations at *ss* less than 0.5% owing to their strong hygroscopic nature, though types of particles other than sea-salt (e.g. secondary organics) compete for water vapour uptake at *ss* less than 0.5% (Nenes, Ghan, Abdul-Razzak, Chuang, & Seinfeld, 2001). Nevertheless, for numerous smaller CCN in the marine environment, researchers (Hudson & Da, 1996; Twomey, 1968, 1971) have demonstrated that the sea-salt aerosol is only a minor ingredient for CCN number concentrations.

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CCN population over marine regions continues to be a major theme of cloud physics research (Squires, 1956, Squires and Twomey, 1966). Recently, Ramana and Devi (2016) reported onboard measurements of CCN concentrations at *ss* of 0.4% (*ss* less than 0.5%) from the data collected with the "*Sagar Nidhi*" cruise during monsoon season of 2012 in south to southernmost regions of Bay region of Bay of Bengal (boB). A strong aerosol source resulted in high CCN concentrations at *ss* less than 0.5% (Ramana & Devi, 2016) despite the active sink to aerosol loading due to monsoonal rain-aerosols interaction in the marine sectors of Indian seas (Chate et al., 2007). During monsoon of 2012, Pai and Bhan (2013) reported 10 low-pressure systems over India and 8 of these systems occurred over BoB (India Meteorological Department, 2012). Out of these 8 low pressure systems that occurred over BoB, 2 systems were observed in July whereas 5 were observed during August 2012. Further, cross equatorial flow (CEF) along the equatorial belt 50°N–50°S towards north and winds were stronger than normal by 2.6 ms^{-1} and by 5.14 ms^{-1} respectively during July and August. They could have strengthened the wind shear and water vapour uptakes of sea-originated aerosols through symmetrical supply of moisture during active and break monsoon over BoB. Wind shear on the sea surface naturally produces sea-salt aerosols Clarke, Owens, and Zhou (2006). Also, wind-induced aerosols other than sea-salt particles are expected to activate at *ss* more than 0.5% which seems to be responsible for high CCN concentrations during the active/break monsoon conditions. Therefore, large variability in CCN population at *ss* less than 0.5% and at *ss* more than 0.5% with prevailing south-westerly winds exert the greatest impact on monsoonal rainfall over Indian region. To the authors' knowledge only known shipboard observational results available for wind-induced CCN activity in the central Indian Ocean are of Bigg, Gras, and Mossop (1995). For the onboard datasets between May and July 1990, they reported upward trends for CCN concentrations with wind speed (U) greater than 10 ms^{-1}. However, there is a paucity of shipboard observational results for CCN activity at *ss* less than 0.5% and *ss* more than 0.5% as a function of winds during monsoon season for larger marine regions of India.

This paper presents first shipboard measurements of CCN concentrations at wide range of *ss* from 0.2% to 1% (in *ss* of 0.2% steps) as a function of prevailing winds. During July and August months of monsoon season 2012 in the south to southeastern head-Bay region of BoB. Data of CCN distributions at *ss* of 0.2%, 0.4%, 0.6%, 0.8% and 1.0% and winds were collected onboard research vessel "*Sagar Kanya*" (SK-296) during the cruise period from 10th July to 08th August 2012. The dataset for CCN concentrations at *ss* from 0.2% to 1% represents CCN activity on a larger tropical marine region. Further, nearly 30 days of sampling from 10th July to 08th August over ocean is long enough to represent the CCN activity at various *ss* during monsoon period with prevailing winds in the tropical marine regions. Though the exact categorization of CCN types in marine environments is not a straightforward task, variability in CCN activity at *ss* less than 0.5% (*ss* of 0.2% and 0.4%) and at *ss* more than 0.5% (*ss* of 0.6% and 0.8%) with the prevailing winds during July and August may be useful to segregate the CCN population types in the marine regions. Additionally, during the cruise, distances from the coastline differed with the sailing period owing to its tracks followed during July and August. These factors essentially regulate the CCN concentrations at *ss* less than 0.5% and *ss* more than 0.5%, water vapour uptake potential of sea-originated aerosols and winds (U) over the BoB. Therefore, more emphasis needs to be on comparative analysis of CCN distributions at *ss* less than 0.5% and *ss* more than 0.5% as a function of winds for the measurements period of July and August.

2. Instrumentation

Aerosol particles that transform into CCN were measured with a CCN counter as described by Roberts and Nenes (2005). It is a

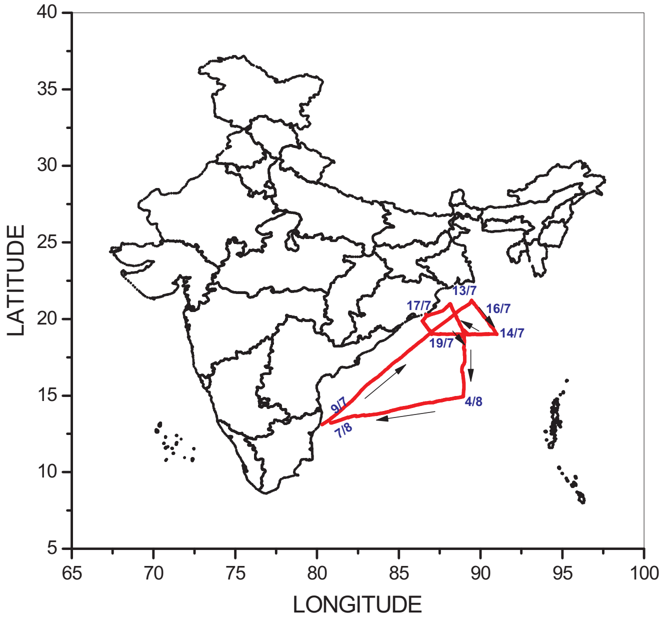

Fig. 1. Positions of a research vessel "*Sagar Kanya*" (SK-296 cruise) over the BoB during the observational campaign period for CCN activity.