Variations of trace gases over the Bay of Bengal during the summer monsoon

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In situ measurements of near-surface ozone (O₃), carbon monoxide (CO), and methane (CH₄) were carried out over the Bay of Bengal (BoB) as a part of the Continental Tropical Convergence Zone (CTCZ) campaign during the summer monsoon season of 2009. O₃, CO and CH₄ mixing ratios varied in the ranges of 8–54 ppbv, 50–200 ppbv and 1.57–2.15 ppmv, respectively during 16 July–17 August 2009. The spatial distribution of mean tropospheric O₃ from satellite retrievals is found to be similar to that in surface O₃ observations, with higher levels over coastal and northern BoB as compared to central BoB. The comparison of *in situ* measurements with the Monitoring Atmospheric Composition & Climate (MACC) global reanalysis shows that MACC simulations reproduce the observations with small mean biases of 1.6 ppbv, –2.6 ppbv and 0.07 ppmv for O₃, CO and CH₄, respectively. The analysis of diurnal variation of O₃ based on observations and the simulations from Weather Research and Forecasting coupled with Chemistry (WRF-Chem) at a stationary point over the BoB did not show a net photochemical build up during daytime. Satellite retrievals show limitations in capturing CH₄ variations as measured by *in situ* sample analysis highlighting the need of more shipborne *in situ* measurements of trace gases over this region during monsoon.

Keywords. Ozone; carbon monoxide; methane; monsoon; Bay of Bengal; MACC reanalysis.

1. Introduction

Tropospheric ozone (O₃) and Methane (CH₄) are important greenhouse gases with radiative forcing of 0.40 ± 0.20 and 0.48 ± 0.05 Wm^{–2} (IPCC 2013), respectively. Carbon monoxide (CO) is indirect greenhouse gas with an indirect radiative forcing of 0.23 (0.18 to 0.29) Wm^{–2}, through the production of O₃, CH₄ and carbon dioxide (IPCC 2013).

As the major source of Hydroxyl radical (OH), O₃ controls the self-cleaning capacity of the atmosphere. Majority of tropospheric O₃ is produced by *in situ* photochemical reactions involving precursor gases CH₄, non-CH₄ hydrocarbons (NMHCs), and CO and in presence of nitrogen oxides (Seinfeld and Pandis 2006). The anthropogenic activities such as fossil fuel and biomass burning supplemented with oxidation of hydrocarbons (like CH₄ and Isoprene)

are the major sources of CO. CH₄ is emitted from a variety of natural and anthropogenic sources. About 90% of CH₄ is removed through its reaction with OH.

Tropospheric O₃ and its precursors exhibit significant spatial and temporal variability. Elevated O₃ levels have been observed at several rural sites and marine environments which are devoid of major local anthropogenic emissions (e.g., [Lawrence and Lelieveld 2010](#) and references therein), primarily due to transport from source regions. The marine environment of the Bay of Bengal (BoB), being geographically surrounded by landmass on three sides, is conducive for advection and accumulation of aerosols and trace gases. The systematic variations in synoptic winds over the BoB make it a unique environment to study the effects of transport on spatial and temporal variability of trace species. The BoB acts as a corridor for the strongest monsoonal systems of the world (the Indian summer monsoon) and lying downwind to most populated regions of the globe such as South and Southeast Asia.

Several field campaigns such as Indian Ocean Experiment (INDOEX), Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB), winter-ICARB (W-ICARB), Bay of Bengal Experiment (BOBEX)-I, BOBEX-II, Bay of Bengal Process Studies (BOBPS), and a campaign during October–November 2010 have been conducted to measure the variations in trace gases over the BoB. Earlier studies ([Lal et al. 2006, 2007](#); [Sahu et al. 2006](#); [David et al. 2011](#); [Nair et al. 2011](#); [Srivastava et al. 2012](#); [Mallik et al. 2013](#); [Girach and Nair 2014](#)) have covered the spatio-temporal distribution in trace gases during most of the seasons over the BoB, however such measurements have been non-existing during the summer monsoon season (June–August). Various experiments ([Lal et al. 1998](#); [Chand et al. 2001, 2003](#); [Lal and Lawrence 2001](#); [Naja et al. 2004](#); [Ali et al. 2009](#)) discuss spatio-temporal variabilities in trace gases over the Arabian Sea (AS) and the Indian Ocean (IO). The earlier studies have analysed the diurnal variation of surface O₃ over the marine regions. Monsoonal circulation, stronger convection and cloudy/rainy conditions prevailing during the summer monsoon are anticipated to result in chemical and dynamical effects on atmospheric composition of this region. Therefore, to fill the gap of observations, in this paper we analyze ship-based measurements of surface O₃ along with CO and CH₄ over the BoB during summer monsoon conducted as a part of the

Continental Tropical Convergence Zone (CTCZ) experiment under Indian Climate Research Programme (ICRP) of Government of India during July–August 2009. We have studied the diurnal variation of surface O₃ at a stationary point over the BoB during monsoon season.

We have reported the measured spatial and temporal variations in trace gases over the BoB recently ([Girach et al. 2017](#)), which we here further extend by further analysis and comparison with global reanalysis from Monitoring Atmospheric Composition & Climate (MACC). We have also compared the observed mixing ratios and their variabilities with those observed over the BoB, the AS and the IO. The manuscript begins with a description of cruise track in section 2, followed by the experimental details and data in section 3. Model simulations are described in section 4 and results of the work are presented in section 5. A summary of the results is provided in section 6.

2. The cruise track

The cruise track of the Oceanic Research Vessel *Sagar Kanya* during the CTCZ experiment (cruise number-SK 261) is shown in figure 1. The dates corresponding to the mean position of the ship are marked along the cruise track in the figure. The arrows marked on the track show the direction of the movement of the ship. The ship sailed over the BoB starting and ending at Chennai (80.3°E, 13.1°N) during 16 July–17 August 2009, having longitudinal and latitudinal scans. The ship was kept stationary during July 22 to August 6, 2009 (15 days) at 89°E, 19°N as marked by a square in the figure for time series measurements. The wind pattern at 925 hPa (not shown here) during the cruise period was westerly/southwesterly, which was conducive for the transport of O₃ and its precursors from the Indian landmass to the BoB during the summer monsoon season. Further details are given in [Girach et al. \(2017\)](#).

3. Experimental details and data

The measurements of surface O₃ and CO were conducted using an online UV photometric ozone analyser (Model O3 42) and online gas filter correlation CO analyser (Model CO12 Module) respectively, from Environnement S.A, France. The O₃ analyser operates on the principle of absorption of ultraviolet (UV) radiation at 253.7 nm using the

Figure 1. Cruise track (continuous blue line) of the Research Vessel *Sagar Kanya* during the CTCZ experiment (16 July–17 August 2009). Arrows marked on the track show the ship direction. The dates corresponding to approximate ship positions are marked along the track. The circle shows the start and end point of the cruise. The location at which the ship was kept stationary (July 22–August 6, 2009) is marked with a square.

Beer–Lambert law. This instrument has an uncertainty of 5% and lower detection limit of 1 ppbv. The CO-analyser works on the principle of Non Dispersive Infrared (NDIR) absorption of CO at $4.67\mu\text{m}$. CO-analyser has an uncertainty of 10% and lower detection limit of 50 ppbv. More technical details and methodology are given elsewhere (Girach *et al.* 2017).

Air was drawn from a height of approximately 15 m above the sea surface through a teflon tube. Before and after the cruise, both the analyzers were calibrated using custom-made calibrator. The measurements affected by ship exhaust were filtered prior the analysis. Additionally, the air samples, a total of 29 collected in the glass flasks (1 litre) during the ship cruise, were analyzed for methane using a gas chromatograph (GC). A detailed description of the analytical procedure for sampling and analysis is given in Ravikumar *et al.* (2014). The precision for methane measurements is approximately ± 0.1 ppmv.

The Ozone Monitoring Instrument (OMI) and the Microwave Limb Sounder (MLS) on board the EOS Aura spacecraft provide total columnar O_3 and stratospheric O_3 measurements. Combining

these two retrievals, tropospheric column O_3 is determined by subtracting measurements of MLS stratospheric column ozone from OMI total column ozone after adjusting for the intercalibration differences of the two instruments using the convective cloud differential method (Ziemke *et al.* 2006). The monthly mean tropospheric O_3 (mean volume mixing ratios in ppbv) is used in the present study to compare its average spatial variation with that of surface O_3 . The monthly mean tropospheric O_3 with a resolution of 1° latitude $\times$ 1.25° longitude is obtained from https://acd-ext.gsfc.nasa.gov/Data_services/cloud_slice/. The mean tropospheric O_3 is expressed in volume mixing ratio as $1270 \times \text{TCO}/(\text{P}_{\text{surface}} - \text{P}_{\text{Tropopause}})$, where tropospheric O_3 mixing ratio is in ppbv, tropospheric column ozone (TCO) is in DU, and $\text{P}_{\text{surface}}$ and $\text{P}_{\text{Tropopause}}$ are in hPa (Ziemke *et al.* 2006).

Atmospheric InfraRed Sounder (AIRS), a thermal infrared grating spectrometer, on board Aqua spacecraft retrieves CH_4 mixing ratios profiles in both clear and partially cloudy conditions based on the measured spectrum around $7.66\mu\text{m}$. In the latest version 6, 63 channels (out of 200) spanning around $7.66\mu\text{m}$ are used for the retrievals of CH_4 . The daily gridded ($1^\circ \times 1^\circ$) level-3 (version 6) daytime (ascending orbits) and nighttime (descending orbit) retrievals were used in this study for comparison with the *in situ* measurements.

4. Model simulations

We compare the *in situ* measurements of O_3 , CO and CH_4 conducted during this study with a global reanalysis model dataset (MACC at 1000 hPa), to evaluate the global model fields in this sparsely measured region. MACC reanalysis data was obtained at a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and time resolution of 3 hrs. MACC model consists of ECMWFs' (European Center for Medium range Weather Forecasting) Integrated Forecast System (IFS) coupled with the MOZART (Model for OZone and Related chemical Tracers)-3 chemistry transport model. More details of the MACC reanalysis can be found through its website (https://www.gmes-atmosphere.eu/oper_info/macc_reanalysis/) or from previous studies (e.g., Inness *et al.* 2013; Katragkou *et al.* 2015 and references therein).

WRF-Chem model (version 3.5.1) has been used to simulate the diurnal patterns in O_3 over the BoB to investigate the possible role of *in situ*

Figure 2. Spatial variation in O_3 , CO , and CH_4 over the BoB during 16 July–17 August, 2009 along the cruise track measured during the CTCZ experiment (summer monsoon).

photochemistry over the BoB. The description of WRF-Chem setup and input fields can be found in Girach *et al.* (2017). Further details of WRF-Chem performance over this region in reproducing variations of trace gases can be found elsewhere (e.g., Ojha *et al.* 2016; Sharma *et al.* 2016; Girach *et al.* 2017 and references therein).

5. Results and discussions

5.1 Variations in trace gases and comparison with MACC reanalysis

Figure 2 shows the observed spatial variation in surface O_3 , CO and CH_4 along the ship-track during the CTCZ experiment. The spatial and temporal distribution of trace gases discern considerable heterogeneity during the monsoon with O_3 mixing ratios varying from as low as 8 ppbv to as high as 54 ppbv with mean value of 29.7 ± 6.8 ppbv. CO levels were observed to be in the range of 50 ppbv (i.e., lower detection limit) to 200 ppbv with average value of 96 ± 25 ppbv. CO mixing ratios below the detection limit were filtered. CH_4 mixing ratios showed variation from 1.57 to 2.15 ppmv (average overall observations = 1.83 ± 0.14 ppmv). The average mixing ratios of O_3 , CO and CH_4 were $\sim 30 \pm 7$ ppbv, 95 ± 25 ppbv and 1.86 ± 0.12 ppmv, respectively, over the north-BoB, which were slightly higher or comparable to those over the central-BoB (O_3 : 27 ± 5 ppbv, CO : 101 ± 27 ppbv and CH_4 : 1.72 ± 0.14 ppmv). For central and north-BoB regions, monsoon time observations indicate higher variability as compared to other seasons.

Figure 3 shows the spatial variation of tropospheric O_3 averaged over July–August 2009 over the BoB derived from satellite observations. As seen in figure 2, surface O_3 is slightly higher (30–40 ppbv) over north-BoB and along the coast as compared to the central region of the BoB (20–30 ppbv). Similar feature is observed in the case of tropospheric O_3 . As seen in figure 3, tropospheric O_3 is slightly higher (in the range of 35–40 ppbv) over north-BoB and along the east-coast of India as compared to the central and southern part of the BoB (30–35 ppbv). In short, the broad spatial features of tropospheric O_3 compares well with that of surface O_3 .

We use our measurements over the BoB for the monsoon season to evaluate the performance of a global reanalysis data (MACC) as shown in figure 4. The comparison of MACC reanalysis near the surface (at 1000 hPa) with *in situ* measurements shows that MACC reproduces the observed mixing ratios of O_3 , CO and CH_4 . The estimated mean biases for surface O_3 , CO and CH_4 are 1.6 ppbv (5.3% of average *in situ* O_3 , 29.7 ppbv), -2.6 ppbv (2.7% of average *in situ* CO , 96 ppbv) and 0.07 (4% of average *in situ* CH_4 , 1.83 ppmv). The small magnitudes of mean biases show the capabilities of MACC reanalysis in reproducing the observed levels. However, it shows a limitation in capturing the variations. The squared correlation coefficients (R^2) between *in situ* observations and MACC reanalysis at 1000 hPa are 0.03, 0.13 and 0.25 for O_3 , CO and CH_4 , respectively. MACC utilizes the assimilation of atmospheric composition from satellite retrievals (Inness *et al.* 2013). Satellite measurements could have

Figure 3. Mean tropospheric O_3 (ppbv) averaged over July and August 2009 over the BoB. The data is based on OMI and MLS retrievals and were obtained from their website.

Figure 4. (a, b, c) A comparison of surface O_3 , CO and CH_4 from *in situ* measurements (black dots) with MACC reanalysis at 1000 hPa (blue line) along the cruise track over the BoB during the CTCZ experiment (summer monsoon season; 16 July–17 August, 2009). The MACC reanalysis data were obtained through its website.

significant uncertainty during the cloudy rainy conditions, especially, near the surface. This could possibly explain the limitation in capturing the observed variability by MACC reanalysis.

This clearly shows that MACC reanalysis reproduces the observed mean concentration levels of O_3 , CO and CH_4 over the BoB during summer monsoon with a small bias of 2–5%. However, there is a limitation in reproducing observed variabilities of O_3 and CO . Variations in CH_4 are reproduced better by MACCreanalysis as compared to O_3 and CO .

As discussed in Girach *et al.* (2017), the WRF-Chem simulations reproduced O_3 and CO mixing ratios with mean biases of 1.9 and 18 ppbv and squared correlation coefficient of 0.58 and 0.19, respectively. The WRF-Chem simulation reproduced the observation with similar magnitude of biases and better variabilities (higher correlation coefficients).

5.2 Diurnal variation in O_3 at a stationary point in the BoB

The ship was kept stationary for a period of 15 days (22 July–6 August 2009) at $89^\circ E$, $19^\circ N$ and surface O_3 , CO and CH_4 varied in the range of 9–6 ppbv, 58–144 ppbv and 1.71–1.89 ppmv, temporally averaged to the 28 ± 7 ppbv, 91 ± 19 ppbv and 1.81 ± 0.06 ppmv, respectively. Figure 5 shows the mean delta-diurnal variation in surface O_3 , i.e., the mean value subtracted from the mean diurnal pattern from the measurements and WRF-Chem simulations at $89^\circ E$, $19^\circ N$ for this period of about 15 days. O_3 values at each hour here is an average of 10–15 observations. Ship exhaust contaminated the observations for a period of time between 5 and 14 hrs long; the data corresponding to this period is therefore discarded from the analysis, leading to a gap. Both the WRF-Chem model and observations showed only small variability from mean values ($\Delta O_3 = -2$ to $+2$ ppbv) during the summer monsoon season. Neither our limited measurements nor the model simulations exhibit any tendency of net photochemical production of O_3 after sunrise during the monsoon. The observations available during 5–14 hrs on July 23 and 24, 2009 also do not show any daytime enhancement in O_3 mixing ratios. A net daytime photochemical build up in O_3 has been reported over the BoB during both pre-monsoon (Nair *et al.* 2011) and post-monsoon season (Mallik *et al.* 2013), as shown for comparison in figure 5. The absence of net O_3 build-up suggests that spatio-temporal variations in surface

Figure 5. The mean delta-diurnal variation of surface O_3 at a stationary location ($89^\circ E$, $19^\circ N$) over the BoB, along with that from WRF-Chem simulations during summer monsoon. The dotted and dashed curves show the diurnal variations in surface O_3 (adopted from Nair *et al.* 2011 and Mallik *et al.* 2013) during pre-monsoon and post-monsoon season, respectively.

O_3 over the BoB during monsoon season are associated with the direct transport supplemented with en route photochemistry. Note that, due to the insufficient number of observations, diurnal variations in CO and CH_4 could not be studied here.

The earlier observations (Lal *et al.* 1998; Lal and Lawrence 2001; David *et al.* 2011; Nair *et al.* 2011; Mallik *et al.* 2013) have shown *in situ* photochemical production of O_3 over the AS and the BoB, especially in the coastal air masses or polluted air masses. In these studies, enhancements in the mixing ratios of O_3 were observed during daytime or in the morning hours. But in the remote marine regions, O_3 shows ‘virtually no diurnal variation’ (Liu *et al.* 1983) indicating absence of net *in situ* photochemical production. Similar to the present study, there are observations (Naja *et al.* 2004; Sahu *et al.* 2006; Lal *et al.* 2007; Ali *et al.* 2009) which show no net O_3 photochemical production. Mainly scarcity of O_3 precursor gases over remote marine environment limits the photochemical production of O_3 . In the present study, absence of *in situ* photochemical production of O_3 could be attributed to cloudy conditions of monsoons as well as lower concentration of precursor gases. Table 1 summarises the ranges of O_3 mixing ratios over different marine regions and whether *in situ* photochemical production was observed. Table 1 is further discussed in section 5.5.

Table 1. Mixing ratios of O₃, CO and CH₄ over the Arabian Sea, the Bay of Bengal and the Indian Ocean during various study periods and experiments. *CO mixing ratios below the detection limit (i.e., 50 ppbv are not considered in the analysis).

Study period	Campaign	Reference	O ₃ (ppbv)	CO (ppbv)	CH ₄ (ppmv)	Whether <i>in situ</i> photochemical production of O ₃ observed?
January 5–February 3, 1996	INDOEX-1996	Lal et al. (1998)	BoB: No data AS: ~25–100 IO: ~7–35	BoB: No data AS: ~50–240 IO: ~30–120	BoB: No data AS: ~1.6–1.8 IO: ~1.6–1.8	Yes
December 27, 1996–January 31, 1997	INDOEX-1997	Naja et al. (2004)	BoB: No data AS: ~39 IO: ~18 (Northern IO), 8 (Southern IO)	BoB: No data AS: ~250 IO: ~185 (Northern IO), 90 (Southern IO)	BoB: No data AS: ~1.71 IO: ~1.69 (Northern IO), 1.61 (Southern)	No
February 18–March 30, 1998	INDOEX-1998	Chand et al. (2001, 2003)	BoB: No data AS: ~13–55 IO: ~4–30	BoB: No data AS: ~110–280 IO: ~90–260	BoB: No data AS: ~1.70–1.87 IO: ~1.60–1.80	Yes
January 20–March 12, 1999	INDOEX-1999	Lal and Lawrence (2001); Chand et al. (2001, 2003);	BoB: No data AS: ~30–70 IO: ~4.30	BoB: No data AS: ~110–330 IO: ~60–220	BoB: No data AS: ~1.65–1.85 IO: ~1.57–1.80	Yes (over the AS)
March 14–23, 2001	BOBEX-I, 2001	Lal et al. (2006)	BoB: ~15–63 AS: ~25–41 IO: ~14–50	BoB: ~100–350 AS: ~75–125 IO: ~120–250	BoB: ~1.74–2.50 AS: ~1.71–1.80 IO: ~1.75–1.86	Not clear
June 21–August 16, 2002	ARMEX-2002	Ali et al. (2009)	BoB: No data AS: ~5–15 IO: No data	No data	No data	No

Table 1. (Continued.)

Study period	Campaign	Reference	O ₃ (ppbv)	CO (ppbv)	CH ₄ (ppmv)	Whether <i>in situ</i> photochemical production of O ₃ observed?
March 17–11 May, 2006	ICARB-2006	Nair <i>et al.</i> (2011, 2013); Srivastava <i>et al.</i> (2012)	BoB: 3–34 (18±7) AS: 3–22 (13.5±2) IO: No data	AS: ~80–240 (145±38) AS: ~50–125 (86.7±14.1) IO: No data	BoB: ~1.75–1.84 (1.81±0.03) AS: ~1.71–1.81 (1.74±0.02) IO: No data	Yes (over coastal region of the BoB) No over the AS
14 September–12 October, 2002	BOBPS-2002	Sahu <i>et al.</i> (2006)	BoB: ~17–35 (27±6) AS: No data IO: No data	BoB: ~108–211 (143±23) AS: No data IO: No data	BoB: ~1.67–1.86 (1.75±0.05) AS: No data IO: No data	No
19–28 February, 2003	BOBEX-II, 2003	Lal <i>et al.</i> (2007)	BoB: ~22–53 (34±6.4) AS: No data IO: No data	BoB: ~125–295 (193±40) AS: No data IO: No data	BoB: ~1.65–1.85 (1.72±0.04) AS: No data IO: No data	No
27 December 2008–30 January, 2009	W_ICARB-2009	David <i>et al.</i> (2011) Girach and Nair (2014)	BoB: 11–73 (42±15) AS: No data IO: No data	BoB: 80–480 (242±89) AS: No data IO: No data	No data	Yes (over coastal region of the BoB)
16 July–17 August, 2009	CTCZ-2009	Present study and Girach <i>et al.</i> (2017)	BoB: 8–54 (29.7±6.8) AS: No data IO: No data	BoB: 50–200 (96±25)* AS: No data IO: No data	BoB: 1.57–2.15 (1.83±0.14) AS: No data AS: No data	No
28 October–17 November, 2010	–	Mallik <i>et al.</i> (2013)	BoB: ~11–60 (41±9) AS: No data IO: No data	BoB: ~45–260 (197±44) AS: No data IO: No data	BoB: ~1.65–2.06 (1.8±0.08) AS: No data IO: No data	Yes (in the polluted airmass)

5.3 Comparison of *in situ* measured CH_4 with AIRS retrievals

Figure 6 (top panel) shows the temporal variation of *in situ* measured CH_4 along with AIRS retrievals at 925 hPa. Figure 6 (bottom panel) shows the scatter plot analysis between the two datasets. AIRS retrievals of CH_4 lie around 1.8 ppmv, showing a limitation in capturing the variability as indicated by the large deviation from 1:1 line. The correlation coefficient is also low (0.17) and statistically insignificant. This might have been due to presence of thick clouds during the study period. This highlights the need for more *in situ* measurements of trace gases during summer monsoon over the Indian subcontinent and the adjacent marine regions. Note that, the comparisons for O_3 and CO are not possible to carry out due to unavailability of satellite data under cloudy conditions.

5.4 Correlation between surface CH_4 and O_3

Since the surface O_3 measurements are of high temporal resolution, 30 min of O_3 measurements were averaged around the sampling time of CH_4 for the correlation analysis. Figure 7 shows the scatter plot between thus calculated 30-min mean O_3 and CH_4 . As discussed in subsection 5.2, a net photochemical production of O_3 is not observed during the monsoon (present study) and hence the *in situ* production of O_3 from methane would have contributed insignificantly to the observed variations in O_3 over the BoB. Thus, the observed strong positive correlation ($R = 0.64$) between O_3 and CH_4 is attributed to their transport from common source regions. In addition, there could be a contribution from methane oxidation to O_3 formation over the source regions.

Similar correlation analysis was carried out for CO and O_3 (not shown here). CO being a precursor for O_3 , was expected to exhibit positive correlation with O_3 . But no statistically significant correlation between CO and O_3 was observed, probably due to the absence of photochemistry.

5.5 Comparison with earlier measurements

There are several measurements of O_3 , CO and CH_4 over the AS, the BoB and the IO during various seasons. The ranges of concentration levels are shown in table 1. As discussed in section 5.2, table 1 also includes whether photochemical production of O_3 was observed during various studies. In the

Figure 6. Temporal variation of *in situ* measured CH_4 along with those retrieved from AIRS at 925 hPa along the cruise track over the BoB (top panel) during summer monsoon. Scatter plot analysis between the *in situ* measurements and AIRS retrievals of CH_4 at 925 hPa (bottom panel). Error bars show the error in the retrieved CH_4 . The dotted line is the 1:1 line. The AIRS retrieved CH_4 mixing ratios were obtained from the AIRS website.

present study surface O_3 , CO and CH_4 varied from 8 to 54 ppbv, 50 to 200 ppbv and 1.57 to 2.15 ppmv, respectively. The earlier study shows surface O_3 as low as ~ 5 ppbv (June–August 2002; Ali *et al.* 2009) and as high as 100 ppbv (January–February, 1996; Lal *et al.* 1998) over the AS. CO was observed to be as low as 30 ppbv (January–February, 1996; Lal *et al.* 1998) over the IO and as high as 480 ppbv (December 2008–January 2009; Girach and Nair 2014) over the BoB. The lower value of CH_4 (~ 1.57 ppmv) was observed over the IO (January–March, 1999; Chand *et al.* 2001) which is similar to what is observed in the present study. The higher mixing

Figure 7. Scatter plot between *in situ* measured surface O_3 and CH_4 mixing ratios during 16 July–17 August, 2009 over the BoB. The Y-error bar represents the standard deviation in 30-min of continuous O_3 measurements around the sampling time of methane. A linear regression fit is shown by the dotted line.

ratio of CH_4 was observed to be 2.5 ppmv over the BoB (March 2001; Lal *et al.* 2006).

6. Summary

In this paper, we presented the ship-borne measurements of trace gases (O_3 , CO, and CH_4) which were carried out as a part of the CTCZ experiment over the BoB during July–August 2009, for the first time during the summer monsoon. A comparison of these measurements with satellite data (AIRS) and model simulations (MACC reanalysis and WRF-Chem) is also made. The main conclusions from the study are as follows:

- The averaged tropospheric O_3 is slightly higher over coastal and northern BoB (35–40 ppbv) as compared to central and southern BoB (30–35 ppbv). This feature is similar to that of surface O_3 .
- The observed mixing ratios of surface O_3 , CO, and CH_4 during the summer monsoon period are generally reproduced by a global reanalysis, MACC. The MACC, typically overestimated absolute levels of O_3 and CH_4 by 1.6 ppbv

and 0.07 ppmv, respectively and underestimated CO by 2.6 ppbv. These small biases show the capabilities of MACC reanalysis in reproducing observed levels of O_3 , CO, and CH_4 over the BoB during summer monsoon season.

- The mean diurnal variations in O_3 at a stationary location over the BoB did not show a net photochemical buildup during monsoon, indicating that the observed O_3 variations were primarily due to transport supplemented with en-route photochemistry.
- *In situ* measurement of CH_4 shows only small correlation coefficient with satellite retrievals during the CTCZ experiment, which highlights the need for more *in situ* observations during the monsoon season over the Indian subcontinent.
- O_3 mixing ratios show strong positive correlation of 0.64 with surface CH_4 indicating the transport of O_3 (and precursors) from common source regions to the BoB.

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