

Trace gases over marine regions around India

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Measurements of O₃, CO, CH₄, NO and SF₆ were made during four ship cruises in January, February and March months of years 1996, 1997, 1998, and 1999 over the Arabian Sea and the Indian Ocean. Measurements were also made over the Bay of Bengal in February and March of the year 2001. All the measured trace gases show systematic gradient with decrease in their mixing ratios from the Coastal India to the South Indian Ocean. Transport of these gases also takes place from the surrounding countries over the marine regions. Ozone and CO show higher values over the Bay of Bengal than over the Arabian Sea, indicating stronger transport of polluted air-masses from northeast India and south Asia. Dramatic increase in ozone levels in the marine boundary layer (MBL) while showing no signature of *in-situ* photochemical production indicates the role of dynamical processes. The diurnal patterns in ozone are very different over the marine environments when compared with continental site, which is due to the nature and levels of pollutants transported from the continental regions and emissions of certain gases over the marine regions. Estimate shows that ozone production over India is less efficient, when compared to mid latitude.

[**Key words** : Trace gases, ozone, marine region, Asia, photochemistry, transport, Bay of Bengal, Arabian Sea, Indian Ocean, INDOEX, BOBEX]

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1. Introduction

India is surrounded from three sides east, south and west by the Bay of Bengal, Indian Ocean and Arabian Sea respectively. The transport of pollutants from the surrounding Asian countries could affect these three marine regions. Asia is the region of rapid development with faster growing number of industries and human population. NO_x emission over the Asian region has been observed to be increasing with highest rate in recent years, compared to Europe and USA^{1,2}. Model results show future increase in pollutants and ozone levels in this region due to increased industrial activities³. Increase in background surface ozone value by about 0.5% per year has already been reported from 1950s to 1990s over Ahmedabad, an industrial city in India⁴. It is known that regional-scale change in some trace gases over one continent is controlled by the meteorology and photochemistry within the continent and also by intercontinental long-range transport in the hemispheric scale. Therefore, increasing levels of trace gases over Asia could also have impact in the tropospheric chemistry and radiation budget over other marine and continental regions and *vice versa*.

The production of hydroxyl radicals [OH] is highest in the tropical region due to availability of intense solar radiation and large water vapor content (80% of the global budget). Photochemistry is also intense over the tropical South Asia, covering south India, the Arabian Sea, Bay of Bengal and Indian Ocean. The unique meteorology over the Indian Ocean makes the continental polluted air mix with the pristine air of the Indian Ocean through ITCZ (Inter-Tropical Convergence Zone). This mixing occurs during November-March, when the wind blows northeasterly from Indian subcontinent. Measurements made over the Indian Ocean during INDOEX have shown transport of pollutants from this subcontinent to the Arabian Sea and Indian Ocean⁵. However, sources of these pollutants are not well understood^{5,6}. Composition and type of emissions are also different over Asia. It is shown that simultaneous occurrence of biomass burning and fossil fuel burning emissions in the same air masses over Asia may have unique situation here⁷. Contrary, biomass burning dominates mainly in Africa, South America etc. and fossil fuel burning sources dominate in Europe and the USA.

In order to study transport of pollutants over the marine regions in the Indian region, the Indian Ocean Experiment (INDOEX) was planned. During this international experiment, systematic measurements were made in winter season of 1996, 1997, 1998, and 1999 only over the Arabian Sea and Indian Ocean but Bay of Bengal was not studied. The first detailed national campaign to study air chemistry over the Bay of Bengal (Bay of Bengal Experiment - BOBEX) was conducted during February-March 2001. We summarize some of the important results of O_3 , CO, CH_4 , NO and SF_6 observed during INDOEX and BOBEX over marine regions surrounding India.

2. Materials and Methods

Two prelude campaigns in years 1996 and 1997 were made before the main INDOEX campaign. These two campaigns (INDOEX 1996 and INDOEX 1997) were national campaigns with only Indian participation and latitudinal coverage was shorter, covering only up to $5^\circ S$ and $14^\circ S$ respectively. The First Field Phase (FFP) campaign of INDOEX was made in 1998 and Intensive Field Phase (IFP) campaign of INDOEX was made in 1999. All these campaigns were made during winter when northeast

wind dominates. Later, measurements were also made over the Bay of Bengal in the year 2001 to study outflow of airmasses from the Indian subcontinent towards this region. Figure 1 shows the cruise tracks of *ORV Sagar Kanya* and Table 1 gives the details of all these five campaigns.

We have divided the marine regions surrounding India in five different zones- the regions along the west coast as well as along the east coast of India (within about 2° from the coast line) is defined as Coastal India. We have defined the Arabian Sea and the Bay of Bengal from the north most point to $5^\circ N$ on west and east side of India respectively. The Indian Ocean is divided in two parts; the North Indian Ocean from $5^\circ N$ to $5^\circ S$ and the South Indian Ocean from $5^\circ S$ to $20^\circ S$.

2.1 Meteorological conditions

The observations in all five cruises were conducted from December to March. During the study periods, the general synoptic scale wind pattern revealed surface level northeasterly/easterly winds so that the oceanic region covered by the cruises during all the years were on the downwind side of the continent^{8,9}. Generally, the Indian winter season is characterized

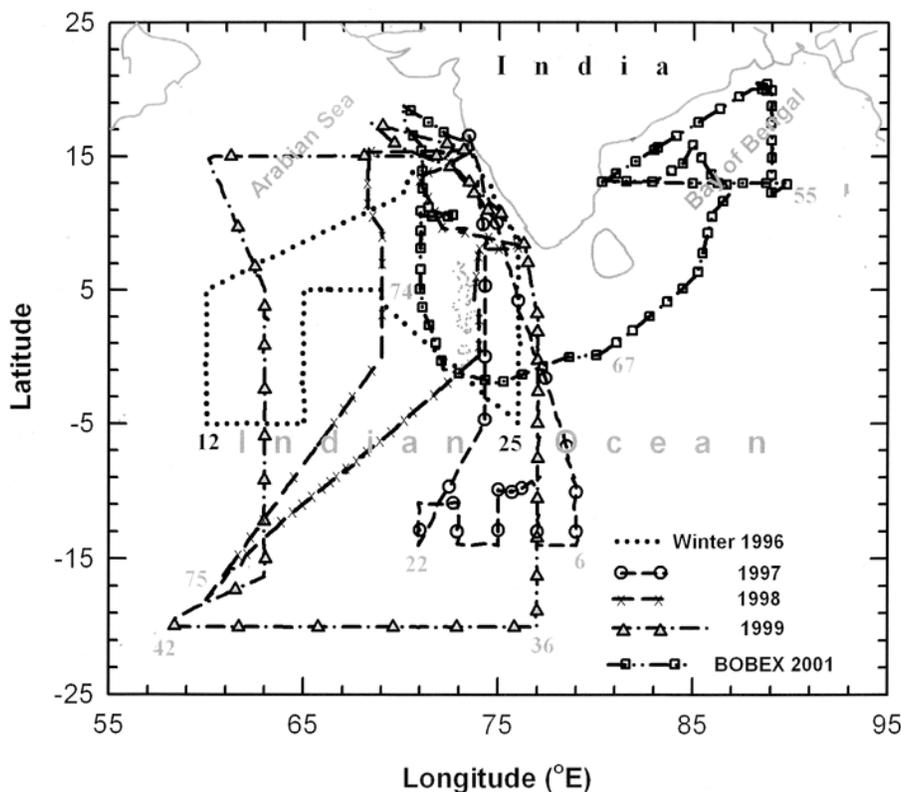


Fig. 1—Ship cruise tracks of four INDOEX and one BOBEX campaigns. Numbers mentioned along the tracks are day of year (DOY) during respective cruises. Only few DOY are mentioned for clearer visibility of the tracks.

Table 1—Details of INDOEX and BOBEX ship cruises over the Arabian Sea, Bay of Bengal and Indian Ocean. [Ozone, CO, and NO were measured *in-situ* and other gases were analyzed by gas chromatography techniques from the air samples collected during the cruises.]

Campaigns	Period	Gases measured	Geographic. Position	Position of ITCZ
INDOEX 1996	Jan 5 – Feb 3	O ₃ , CO, and CH ₄	15°N – 5°S	—
INDOEX 1997	Dec 27, 1996- Jan 31, 1997	O ₃ , CO, and CH ₄	15°N – 14°S	0-10°S
INDOEX 1998	Feb 18 – Mar 30	O ₃ , CO, NO, CH ₄ , and SF ₆	15°N – 20°S	5°S-11°S
INDOEX 1999	Jan 20 – Mar 12	O ₃ , CO, NO, CH ₄ , and SF ₆	18°N – 20°S	3°N-8°S
BOBEX 2001	Feb 18 – Mar 23	O ₃ , CO, CH ₄ , and SF ₆	20°N – 3°S	5°S

by lower tropospheric wind, which generally flows in two major channels. One channel carries the continental outflow from the north-west or north-east over the Bay of Bengal on the eastern side of India. The other channel of the flow goes from north-west or north-east regions over the Arabian Sea on the western side of India. Both these channels finally take the pollutants over the Indian Ocean as shown in Fig. 2.

The ship *ORV Sagar Kanya* did not cross the ITCZ during INDOEX 1996, and it showed dramatic movement during INDOEX 1997, moving about 5° within a day. ITCZ was crossed at about 0° and again at about 10°S. The ITCZ was located at 10°S-11°S in onward journey and at 8°S-5°S in return journey during INDOEX 1998. The ITCZ was relatively on northern side during INDOEX 1999 when compared to INDOEX 1998, at 5°S-8°S in onward journey and 6°S-3°N in return journey. The monsoonal flow from the Indian continent was stronger in February 1999 as compared to that in February 1998. The winter period of the year 1999 had many anti-cyclones and stronger inversions^{5,10}. There were anti-cyclonic activities over the Bay of Bengal as well as over the Arabian Sea during the BOBEX 2001. The ITCZ was located near 5°S, south of the southern point of the cruise. There has been significant change in wind speed between onward and return journeys in all the cruises that could be due to the Madden-Julian oscillation, which has a period of 30-60 days^{11,12}.

2.2 Measurement techniques

Surface ozone was measured using an onboard online UV absorption based analyzer (Dasibi USA, model RS-1008) and averaged data were collected at 1 to 5 minutes interval during all the cruises. This technique is standard and well known. More descriptions of the system used in this study including its calibration, zero checking, maintenance and other details have been given elsewhere^{4,13-15}, only brief information is being provided here in Table 2. Air samples were also collected (approximately two

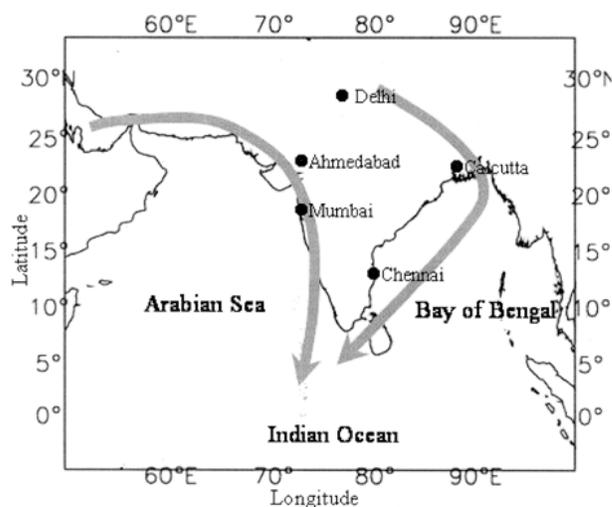


Fig. 2—Depiction of wind flow from Indian subcontinent to the pristine Indian Ocean via two major channels.

samples per day) in pre-evacuated glass bottles at a pressure of about 2.0 bar using a metal bellow pump for CH₄, CO and SF₆ analyses. These air samples were analyzed by gas chromatographic techniques. Details about the system, analysis procedure and calibration are provided in Lal *et al.*^{13,14} and Chand¹⁶ and brief information is shown in Table 3. *In situ* measurements of CO and NO have also been made using the analyzers based on the standard techniques of IR absorption (NDIR) and chemiluminescence respectively. Nitric oxide (NO) was measured using a high sensitivity chemi-luminescent analyzer (Eco Physics CLD 780 TR)¹⁶. More details on these analyzers and calibrations have been provided elsewhere^{14,16-18} and brief information is given in Table 2.

3 Results and Discussion

3.1 Trace gases in different zones

In general, mixing ratio of ozone decreases on moving from the coastal zone to the South Indian Ocean, except in case of BOBEX (Fig. 3). Ozone mixing ratios are considerably low at east coast of

Table 2—Details of different online analyzers, which were used for the measurements

Gas	Method	Make and model	MDL	Response time
Ozone	UV absorption	Dasibi, USA; Model 1008-RS	1 ppbv	10 sec
CO	Non-Dispersive IR (NDIR) gas filter correlation	Monitor Labs, USA; Model ML 9830	50 ppbv	60 sec
NO	Chemiluminescence	Eco Physics, Switzerland; Model CLD 780TR	~ 5 pptv	13 sec

Table 3—Details of gas chromatography analyses of different gases

Gas	Detector	Column	Carrier Gas	Uncertainty	Calibration Standard
CH ₄	Flame Ionization Detector (FID)	Molecular sieve 13X packed SS column	Nitrogen	2-3%	NIST (1.19±0.01 ppmv) Linde (0.98±0.05 ppmv)
CO	FID, CO converted to CH ₄ by Methanizer (heated Ni catalyst)	Molecular sieve 13X packed SS column	Nitrogen	6-10%	Linde (1000±7.5 ppbv)
SF ₆	Electron Capture Detector (ECD)	Molecular sieve 5A packed SS column	Nitrogen	2%	From Institut fur Umweltphysik, Uni of Heidelberg

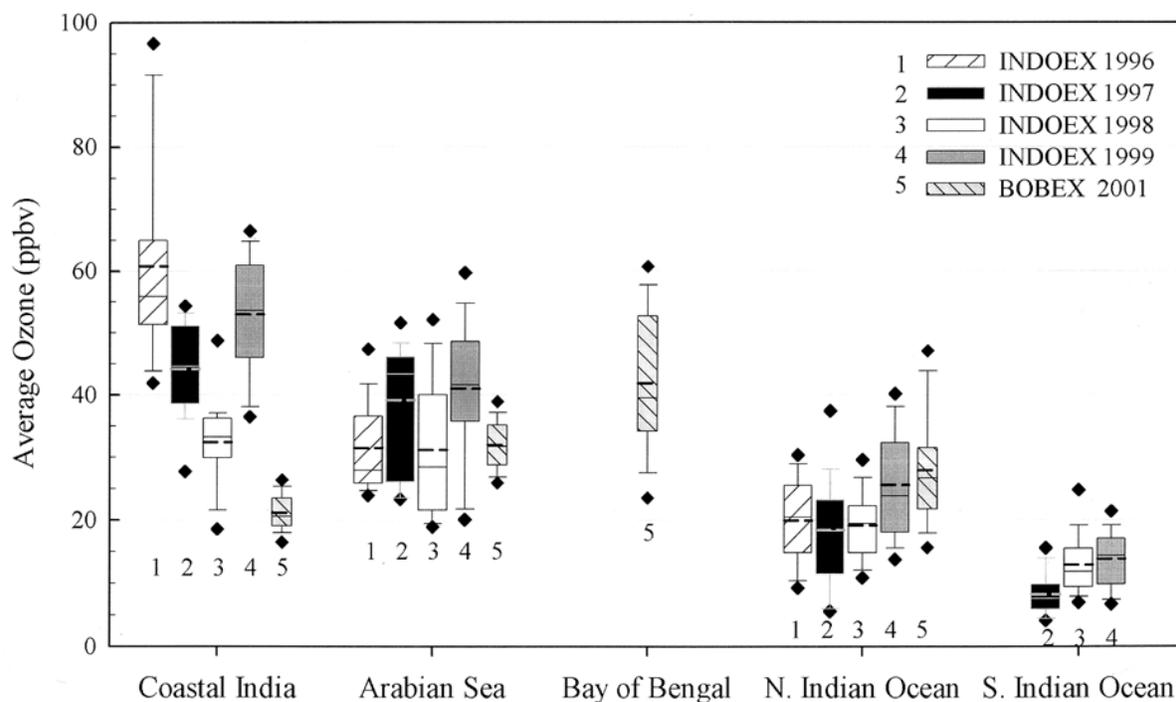


Fig. 3—Ozone mixing ratios in five different marine zones over South Asia during five different ship borne observations. In the box plot, inside solid and thick dash lines are median and mean respectively. Box boundaries are 25th-75th percentiles, whiskers are 10th-90th percentiles and tilt square represents 5th-95th percentiles. Measurements in the Coastal India during BOBEX 2001 are in the east coast whereas rest of the data in the Coastal India are from west coast.

India (observed during BOBEX), when compared to west coast of India (observed during all INDOEX cruises). Average ozone at east coast is about 20 ppbv, which is even lower than mean value for the Arabian Sea, that is due to flow of cleaner marine air from the Indian Ocean towards the east coast of India during the BOBEX 2001. Ozone mixing ratios in the Coastal India are quite higher during INDOEX 1996 and higher values are followed by INDOEX 1999. Both these cruises moved along the west coast of India at relatively closer distance (Figure 1). Mixing ratios of more than 100 ppbv were observed during INDOEX 1996 when the ship was approaching to its final destination, i.e. Goa port. Ozone mixing ratios during INDOEX 1998 were lower in the coastal India zone. This is because the ship had only one instance to come closer to coast (apart from leaving and coming to Goa port). Therefore average ozone mixing ratios at the Coastal India and Arabian Sea were nearly similar during INDOEX 1998.

Mean mixing ratio of ozone over the Bay of Bengal is higher by about 8 ppbv when compared to the mean mixing ratios over the Arabian Sea during BOBEX 2001. Variability in ozone is also larger over the Bay of Bengal. This is in-contrast to its east coast ozone values showing much lower values than the west coast. It has been suggested that central region of

the Bay of Bengal might be receiving the polluted air masses from northeast India^{5,6,19}. However, average ozone values over the Bay of Bengal during BOBEX 2001 are approximately similar to the average ozone values over the Arabian Sea during other years (INDOEX 1997 and INDOEX 1999). Similar to the ozone values over the Bay of Bengal, mean ozone value over the north Indian Ocean during BOBEX 2001 is higher by more than 5 ppbv when compared with mean ozone in this region during INDOEX 1996, 1997, 1998. This is possibly due to the measurements in eastern side of the defined region of the north Indian Ocean during BOBEX 2001 and also this region might have received polluted air-mass from the eastern flank of the Indian subcontinent. The Southern Indian Ocean region, which is generally considered a pristine region, shows lowest ozone mixing ratio (mean value 10-15 ppbv).

Figure 4 shows average CO values in five regions. CO mixing ratios from the gas chromatographic (GC) analysis of air samples are also shown for some years. CO mixing ratios from online analyzer and GC analysis compares well over the North Indian Ocean and South Indian Ocean. The Coastal India and the Arabian Sea show differences of about 50 ppbv between these two sets of analyses. Online analyzer was running 24 hours whereas air samples were

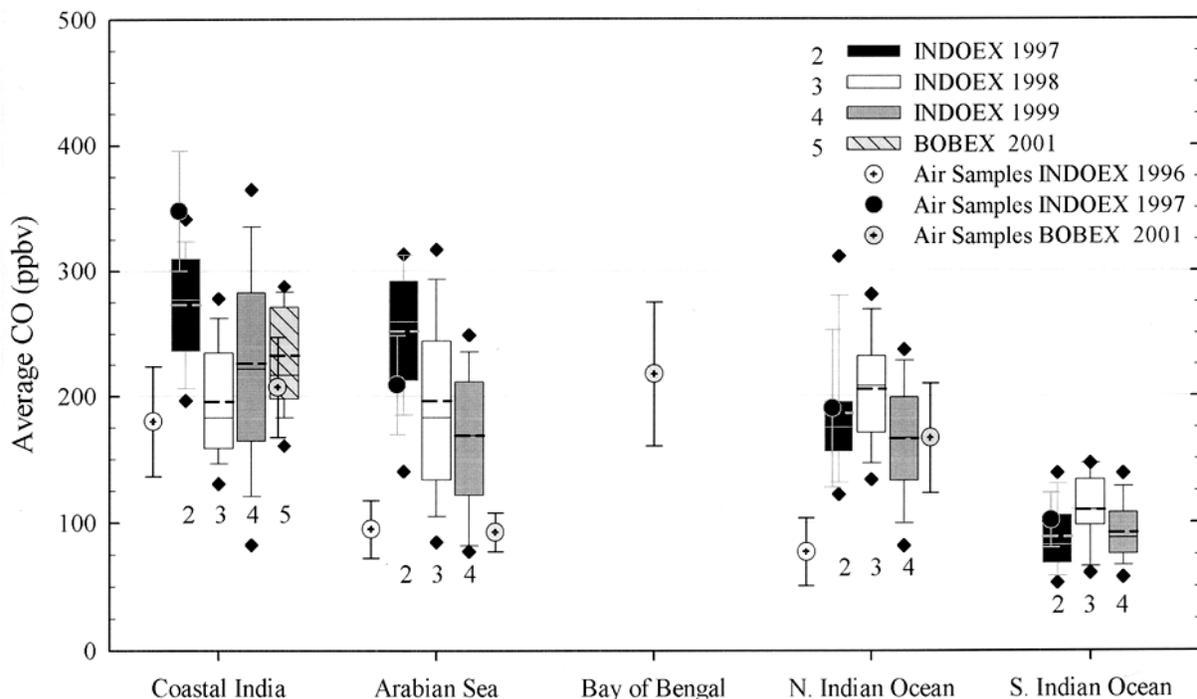


Fig. 4—Same as in Figure 3, but for CO. This figure also shows the CO mixing ratio obtained from the GC analysis of air samples, which were collected on-board the ship.

collected only 1-2 samples per day, which could have collected specific air-mass and therefore possibly this could be the reason for this difference. The shorter lived trace gases (like O_3 and CO) show much variation over the Coastal India and Arabian Sea in short time interval. Basically, CO variations in the five regions are similar to those observed in ozone in these regions. Mean CO mixing ratios over the Arabian Sea and North Indian Ocean were lower during INDOEX 1996, however CO mixing ratios over the Arabian Sea were also lower during BOBEX 2001.

Figure 5 shows latitudinal variations in the ratios of O_3 and CO. Basically higher ratios are indication of transport of ozone rich and CO poor air and also indicate efficient ozone production. The mean ratios are 0.16 to 0.28 in the Coastal India and little lower over the Arabian Sea. These ratios are only 0.1 to 0.16 over the North and South Indian Ocean. Ratios show higher variability (ranging from 0.07 to 0.8) during INDOEX 1999, as compared to INDOEX 1997 and INDOEX 1998. However, mean ratios show relatively smaller differences between them. It has been shown that there were many anticyclones and strong inversion during INDOEX 1999, which could have lead to transport of higher levels of ozone (and low levels of CO) from higher heights. However, it is not possible to distinguish and confirm the vertical or horizontal transport in the present case. Ozone and CO ratio was estimated to be 0.16 at an Island site

(Kaashidhoo; $5^{\circ}N$, $73.5^{\circ}E$) in the Indian Ocean. Onboard measurements at the *R/V Ronald H. Brown* during INDOEX 1999, which had different cruise track, gave 0.14 for ozone to CO ratio²⁰. All these measurements show lower values of ratios over South Asia than the values in mid latitude (0.3-0.4). This could be due to rapid removal of ozone in the MBL or could be due to less efficient ozone production over South Asia. Recently, smaller value of O_3/CO slope has been reported over Asia compared to North America²¹. Further, photochemical ozone production per NO_x molecule is also much lower ($3.3 O_3$ per unit of NO_x) over India than other estimates over mid latitude ($6-7 O_3$ per unit of NO_x)²².

Average mixing ratios of CH_4 in five regions are shown in Fig. 6. The gradient in CH_4 from the Coastal India to the South Indian Ocean is lower than observed in other gases. The Coastal India zone shows larger variations in mean mixing ratio of CH_4 during cruises in different years. Mean CH_4 mixing ratio from all cruises is about 1.79 ± 0.08 ppmv in the Coastal India and it becomes about 1.71 ± 0.05 ppmv over Arabian Sea. Its value remains same over the North Indian Ocean (1.71 ± 0.05 ppmv) but decreases in the South Indian Ocean (1.65 ± 0.06 ppmv). In contrast to CH_4 levels, O_3 mixing ratios were lower on east coast (Bay of Bengal side) than at west coast (Arabian Sea side).

Mean mixing ratios of sulfur hexafluoride (SF_6) in five regions during INDOEX 1998, INDOEX 1999

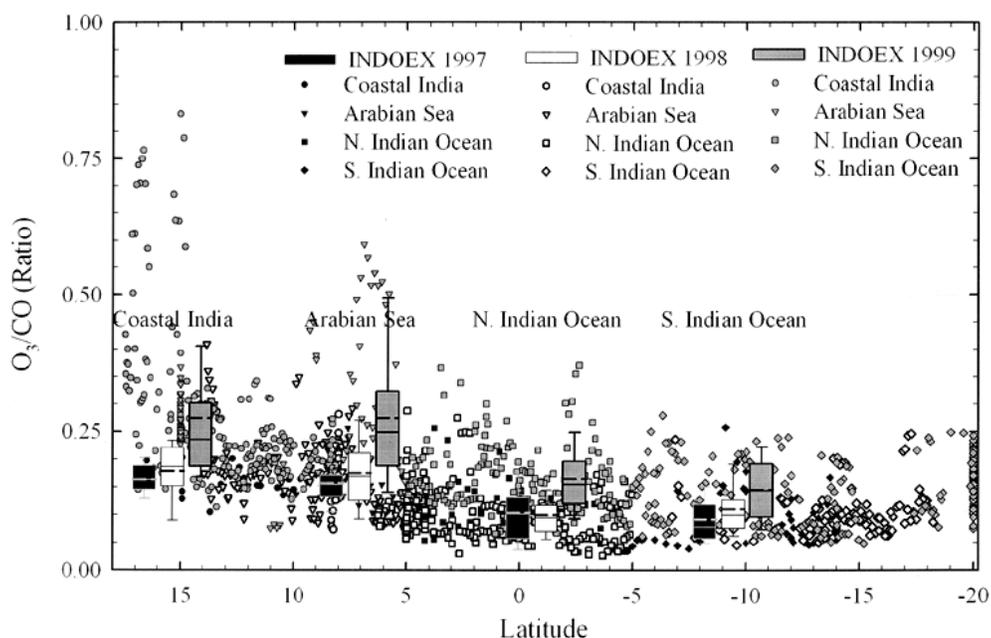


Fig. 5—Same as in Figure 3, but shows ratio of O_3 and CO. Ratios from individual measurements are also shown by small symbols.

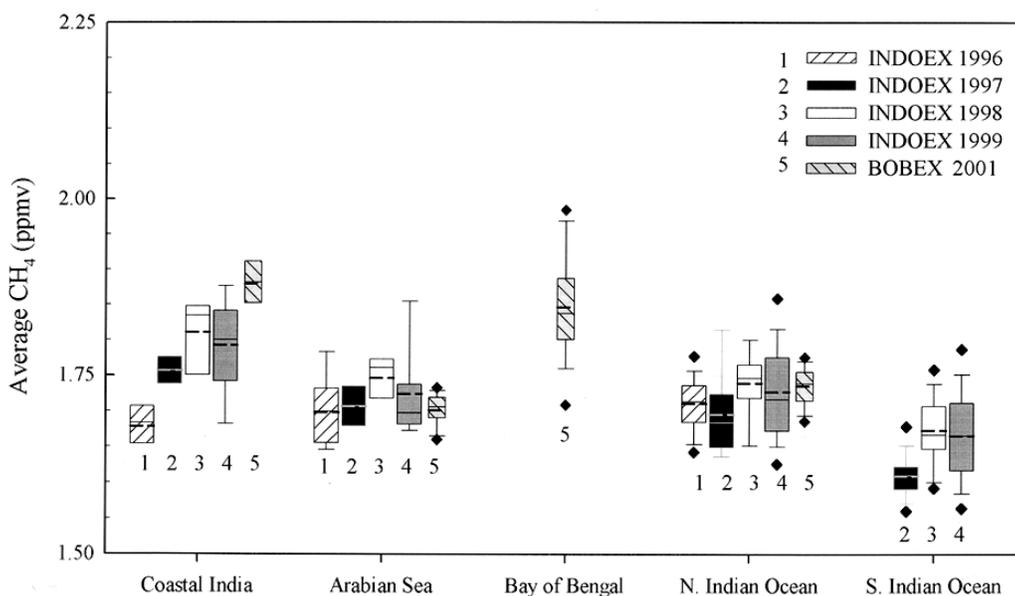


Fig. 6—Same as in Figure 3, but shows CH_4 mixing ratios.

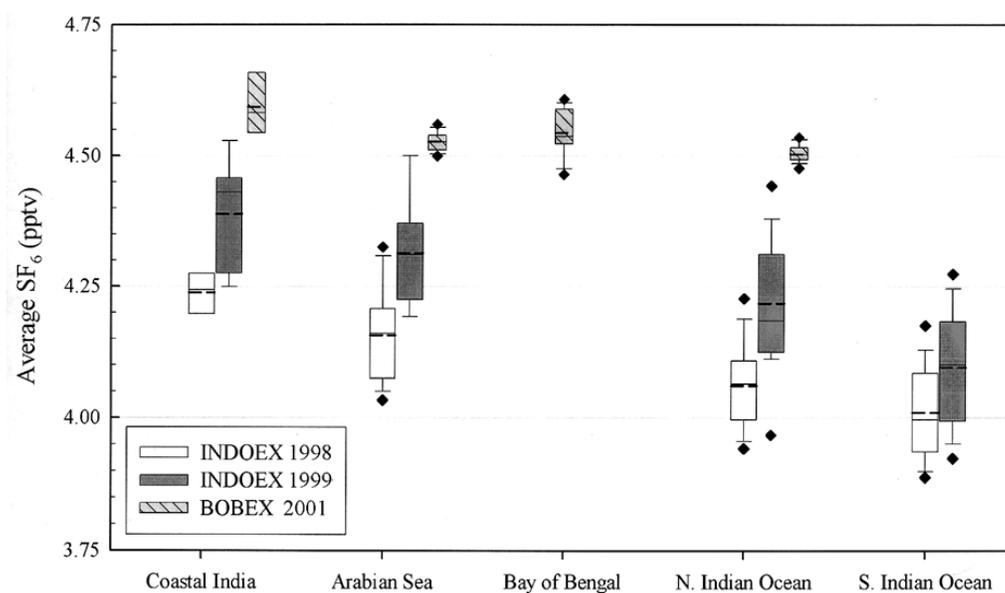


Fig. 7—Same as in Figure 3, but shows SF_6 mixing ratios.

and BOBEX 2001 are shown in Fig. 7. SF_6 , which is used as a tracer also, shows very clear gradient from the Coastal India (source region) to South Indian Ocean (almost no source). SF_6 data are only for three years but never the less there is very rapid increase from the year 1998 to 2001 in all regions. The observed growth rate in different regions varies from 0.12 pptv/year to 0.15 pptv/year. It was reported that its growth rate was very high over the Indian region²³.

Measurements of short lived gas, NO, which were made only during INDOEX 1998 and INDOEX 1999,

are shown in Fig. 8. During INDOEX 1999 measurements were made in onward journey only due to technical problems in NO analyzer in return journey. Figure 8 shows NO mixing ratio during 1000-1600 hours. Mean mixing ratio of NO over the South Indian Ocean was only 21.9 ± 11.5 pptv where as it was 53.6 ± 24.1 and 72.7 ± 38.1 pptv over the Coastal India and the Arabian Sea respectively. NO levels are very critical in deciding the ozone production and loss processes in different environments. Basically NO, NO_2 and O_3 are in

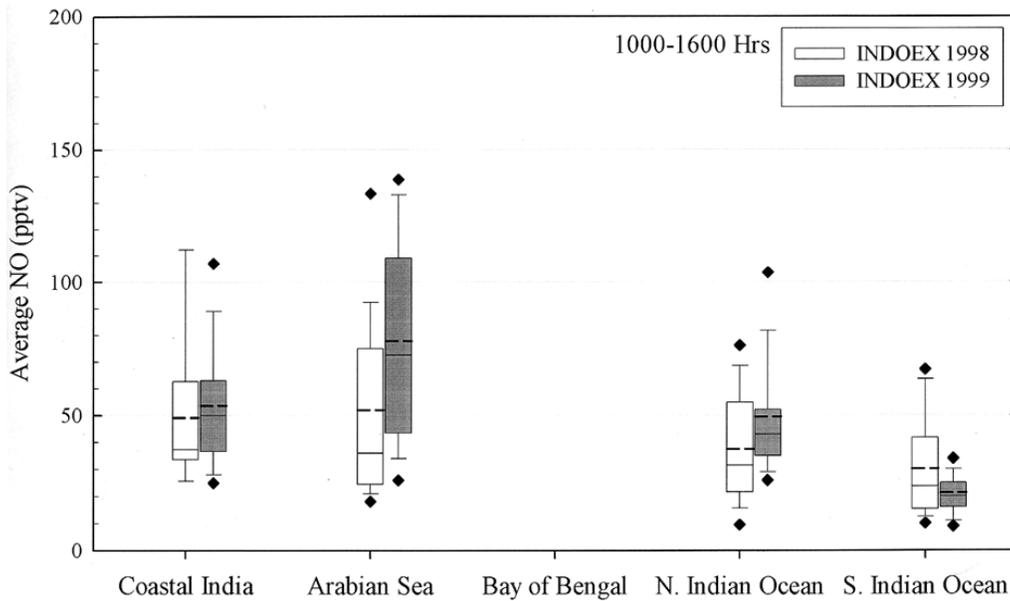


Fig. 8—Same as in Figure 3, but shows NO mixing ratios. Data of 1000-1600 hrs are used in this figure.

steady state during daytime in pristine regions with their inter-conversion time of about 100 seconds. Nighttime NO mixing ratios are expected to be very low (almost zero) in very pristine air, since there is no activation of photochemistry. Figure 9 shows diurnal variation of NO during INDOEX 1998 and INDOEX 1999. Increase in its values during the noon hours is a typical feature of cleaner environment and it is basically due to photodissociation of NO_2 . The diurnal variations during both the cruises are similar, however daytime values during INDOEX 1999 are relatively higher. It has been shown that mixing ratios of ozone are also higher during INDOEX 1999, than during INDOEX 1998.

3.2 Diurnal variations in Ozone

Diurnal variations in ozone over different marine regions have been discussed by many groups^{13,15,24-26}. Ozone shows gradual decrease after sunrise and it increases gradually after sunset over the pristine marine regions, however the diurnal pattern is different over continental cleaner and polluted regions with relatively sharp lower and higher values in noontime respectively. Daily mean ozone mixing ratios could also have differences of 2 to 3 folds between marine and continental regions. There were several attempts using halogen chemistry²⁵, entrainment²⁷ and advection²⁸ to explain the large diurnal amplitudes in ozone over marine boundary layer (MBL). It has also been shown that the diurnal amplitude over the Indian Ocean was much larger

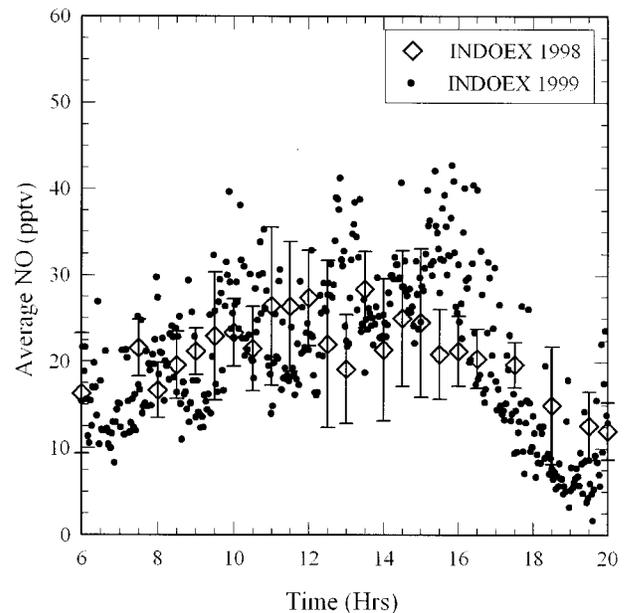


Fig. 9—Diurnal variations of NO during INDOEX 1998 and 1999.

than observed over the Pacific and the Atlantic Oceans^{13,24}. Figure 10 shows diurnal patterns in ozone over four different marine regions. These are discussed in detail below.

3.2.1. Arabian Sea and Bay of Bengal

Generally there are not many instances of a clear diurnal pattern over the Arabia Sea or over the

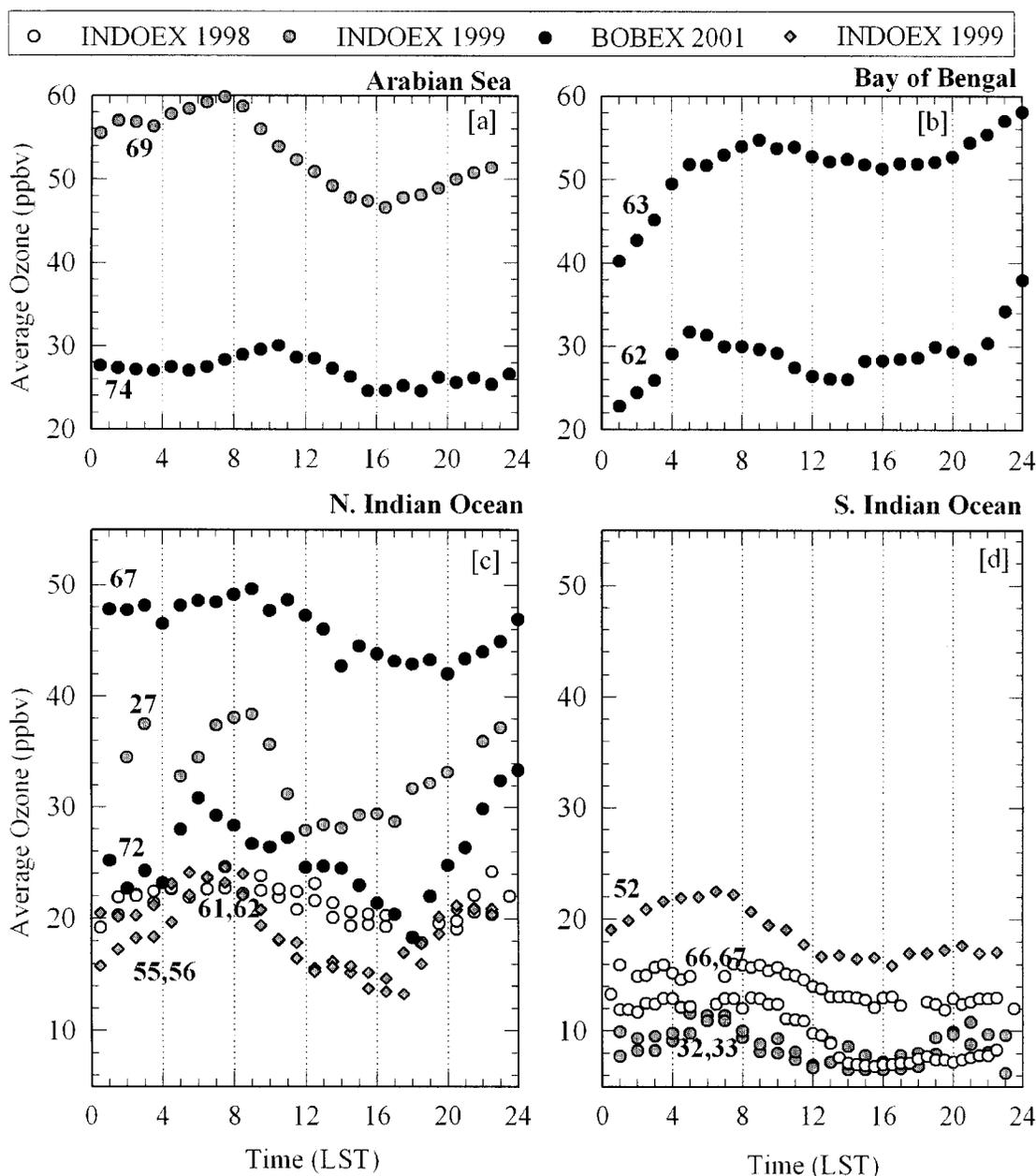


Fig. 10—Diurnal variations in ozone over four marine regions for individual days during INDOEX 1998, INDOEX 1999, and BOBEX 2001. Circles are for onward journey and titled squares are for return journey. Days of year (DOY) are mentioned during respective cruise. Note the differences in scaling of ozone values among these four figures.

Bay of Bengal mainly due to large variabilities in ozone as well as in other precursor gases in these two regions. However, only few days show very clear diurnal variations. Figure 10a shows such a single day examples of clear diurnal pattern over the Arabian Sea during INDOEX 1999 (Day of year, DOY 69) and BOBEX 2001 (DOY 74). Average ozone mixing ratio was about 26 ppbv during BOBEX 2001 and diurnal patterns show nearly marine type variations.

However, in contrast, the average ozone mixing ratios are much higher during INDOEX 1999 and show a clear marine type of diurnal pattern (peak-to-peak amplitude 13 ppbv) with no ozone production in day time. Further, Fig. 10b shows diurnal pattern in ozone for two consecutive days (DOY 62 and 63) over the Bay of Bengal during BOBEX 2001. Ozone levels are lower on first day (DOY 62) but increased by two fold on next day (DOY 63). Diurnal pattern remains

to be marine type and does not show *in-situ* photochemical ozone production. Therefore, both these individual events (69th day in the Arabian Sea and 63rd day in the Bay of Bengal) of much higher ozone levels are clear indication of transport of ozone rich air and not *in-situ* photochemical ozone production over the respective regions. Dramatic increase in ozone of about 15 ppbv in 24 hours from DOY 62 to DOY 63 is an ideal example of the large amount of ozone transport in short time. Other trace gases¹⁹ also showed large increase on the day 63.

3.2.2. North and South Indian Ocean

Figure 10c shows diurnal variations over the North Indian Ocean. Ozone levels were higher on DOY 67 during BOBEX 2001 and showed no explicit signature of ozone photochemical production. Ozone levels decreased after some days (see DOY 72) and showed clear marine type diurnal pattern with very large peak-to-peak amplitude (about 10 ppbv). During INDOEX 1999, mean mixing ratio of ozone was about 30 ppbv on DOY 27 and showed marine type of diurnal pattern. Ozone levels decreased to about 15 ppbv during return journey (DOY 55 and 56) in this region and diurnal pattern remained to be marine type (peak-to-peak amplitude about 10 ppbv). Ozone levels were about 20 ppbv in this region during INDOEX 1998 with marine type of diurnal pattern. The South Indian Ocean, which is assumed to be more pristine, also showed changes in means ozone levels from about 8 ppbv to about 20 ppbv (Fig. 10d). However ozone diurnal patterns remained to be of marine type in all cases in this region. Mean ozone mixing ratio changed by about 5 ppbv in two consecutive days (DOY 66 and 67) during INDOEX 1998. Peak-to-peak amplitude over this region was also observed to be quite high (6-7 ppbv).

3.2.3. Role of chemistry and dynamics

It has been suggested, as mentioned earlier that diurnal variation of ozone in the MBL is controlled by chemistry, advection and entrainment. The ozone chemistry is mainly of photochemical destruction due to generally lower levels of NO in the MBL. However, simple NO chemistry is insufficient to explain the large diurnal amplitude in this region¹³. Halogen chemistry has been proposed to explain the observed diurnal variations^{24,29,30}. These proposed mechanisms of halogen chemistry, which consider the conventional release of Br^{29,30} and inclusion of entrainment²⁷ and advection²⁸ are still inadequate to

explain the diurnal amplitude of about 10 ppbv or more as observed over the Indian Ocean^{13,15}. Therefore, in recent years there have been different efforts to overcome these limitations. Toyota *et al.*³¹ have suggested a size segregated sea-salt aerosols chemistry, which explicitly accounts for size-dependent chemical properties of sea-salt particles. This assumption leads to decrease in gas phase bromine mixing ratio but does not show significant effect on diurnal amplitude of ozone. Measurements over the Indian Ocean show additional source of Br from continental air pollution (mainly 1,2-dibromoethane and Pb, Br, Cl from fuels) but this also did not affect the ozone diurnal amplitude³². There has been another suggestion that marine algae (phytoplankton) could be additional source of volatile halocarbons³³, which were not considered by earlier studies. The additional amount of halocarbons (CHBr₃, CH₂Br₂, CHBr₂Cl, CH₂I₂, CH₂ClI) and hence additional Cl, Br and I released from the phytoplankton could trigger large ozone loss and hence larger amplitude. Measurements made over the Bay of Bengal show existence of significant amount of these halocarbons in the seawater samples³⁴. Recently, existence of iodine monoxide IO (as high as 4 pptv) has been reported in MBL³⁵ and it was shown that iodine catalyzed ozone destruction could be up to 13% of available ozone per day³⁶. It is important to note that previous studies did not include iodine chemistry as it was considered to be of non-existence in MBL. Nevertheless, apart from gas phase and aqueous phase chemistry, the role of dynamical processes like entrainment and advection also appear to be important. Dramatic changes in ozone levels on consecutive days without affecting the marine type of diurnal pattern as shown over the Bay of Bengal and Indian Ocean indicate the importance of dynamical processes.

4. Summary and Conclusion

The measurements of ozone and other trace gases during the four INDOEX cruises and one BOBEX cruise showed very clear decrease in their mixing ratio from the Coastal India to the South Indian Ocean. The Coastal India shows much larger variability, as expected, mainly due to variabilities in source strengths of precursors and due to changes in meteorology. Generally, there is no photochemical production of ozone over the remote Indian Ocean as it is a region of ozone destruction and coastal area could be of photochemical ozone productive regions due to higher levels of NO. Ozone levels were

reasonably higher over the Arabian Sea and the Indian Ocean during INDOEX 1999, as compared to other years. NO levels were also higher during INDOEX 1999. It has been reported that diurnal patterns were clearer and showed large amplitude during INDOEX 1999. Radiative forcing at surface derived from NOAA-AVHRR show higher forcing during INDOEX 1999. The forcing is as high as 3.4 Wm^{-2} higher over Arabian Sea³⁷.

It was shown during BOBEX that O₃, CO, and CH₄ were higher over the Bay of Bengal, as compared to over the Arabian Sea. Aerosol forcing, aerosol optical depth, soot and water-soluble aerosols were also very high over the Bay of Bengal as compared to the Arabian Sea and Indian Ocean³⁸.

Estimate of O₃/CO ratio indicates rapid removal of ozone in the MBL or less efficient ozone production over South Asia. It has been reported that ozone production over South Asia is lesser efficient, when compared to North America. There have been events, when ozone levels changed dramatically but did not show any signature of *in-situ* photochemical ozone production and showed very clear marine type of diurnal patterns. Such events indicate the important role of dynamical processes. There have been events with very large diurnal amplitude in ozone variation (more than 10 ppbv), which are difficult to explain with present existing chemical and dynamical schemes. The emissions of halocarbons from phytoplankton and existence of IO in MBL could help in understanding these features in MBL.

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