Observations of vertical distribution of tropospheric ozone over Indian Ocean and its comparison with continental profiles during INDOEX FFP-1998 and IFP-1999

S. K. Peshin*, T. K. Mandal[†,§], H. G. J. Smit[‡], S. K. Srivastava*, A. P. Mitra[†]

*India Meteorological Department, Lodi Road, New Delhi 110 012, India
National Physical Laboratory, Dr K.S. Krishnan Marg, New Delhi 110 012, India
[‡]Institute for Chemistry of the Polluted Atmosphere, Forschungszentrum, Juelich, Germany

The vertical distribution of ozone over the Indian Ocean was measured during the first field phase (FFP) of Indian Ocean experiment from 15°N to 20°S in February/March 1998. Similar but exhaustive observation was taken during INDOEX-IFP in January/March 1999. A pocket of low ozone (~ 10 ppbv) was observed near the surface in addition to high ozone concentration observed at 8–12 km within the region of 5–15°S during both INDOEX FFP-98 and INDOEX IFP-99. However, the north-south gradient in ozone concentration and the layered structure at 5–8 km as observed in INDOEX FFP-98 are not prominent during INDOEX IFP-99.

East-west cross-section of ozone concentration in the troposphere along 20°S and 15°N may be characterized as the background value of pristine and continental air on the northern and southern side of the equator, respectively. Though back trajectory analysis indicates that flow of air masses is mostly from the Indian subcontinent as well as south-east Asian region, it is difficult to distinguish the degree of relative contribution of continental flow to ozone concentration over the Indian Ocean. The comparison between marine and continental ozone profiles suggests that the northern side of the Inter Tropical Convergence Zone (ITCZ) resembles the continental profiles as observed over the Indian subcontinent and African region, rather than east Asian region.

THE Indian Ocean region is unique for its two key features: First, three sides have been surrounded by continental areas with different climatologies, viz. India and south-east Asia with dense population, African continent with dense forest and Australian continent with sparse population, whereas the other side is open to a source of highly pristine air well extended into Antarctica. Second, movement of Inter Tropical Convergence Zone (ITCZ) twice annually, deep into 20° of northern and southern hemisphere provides a unique opportunity of inter-hemispheric mixing of pollutant and pristine air. In addition, horizontal advection of continental air from African and Australian continents provides enough opportunity to study the effect of well-documented biomass burning during October/November. Indian Ocean experiments (INDOEX) have been carried out to study/estimate the extent and role of aerosols (continental and marine), trace gas species, (viz. SO_2, NO_x, O_3, CO and other greenhouse gases) and their reactant products in the radiative forcing of the atmosphere near the ITCZ of the Indian Ocean[1].

Ozone being an important minor constituent of the atmosphere[2], routine measurements of surface ozone and its vertical profiles are available over the continental region for two/three decades. In addition, enough measurements of surface ozone and its vertical distribution are also performed in campaign mode to provide climatology of ozone over the continental region. However, only studies of ozone over ocean are verified. Though few reports of surface ozone and its vertical distribution measured by aircraft as well as ozonesonde over Atlantic and Pacific Ocean are available[3–18], all the observations of ozone concentration over the ocean are in the campaign mode as well as for a small period only. Therefore, global distribution of ozone can be obtained from satellite-based observation only. Fishman *et al.*[19] and Hudson and Kim *et al.*[20] provided the concept of tropospheric 'residual' ozone from satellite-based measurements.

Winkler[8] (references therein) and Singh *et al.*[10] provide a climatology of surface ozone over Atlantic Ocean in addition to field campaign, e.g. STARE/TRACE/SAFARI. Over the Pacific Ocean, a couple of measurements of surface ozone are reported by Routher *et al.*[4], Liu *et al.*[5,6], Piotrowicz *et al.*[7] and Singh *et al.*[10]. Since SAGA-87, surface ozone measurements have begun over Indian Ocean[9,21–23]. Apart from aircraft measurements, the vertical distribution of ozone measured by ozonesonde over the Atlantic Ocean, is reported by Smit *et al.*[11,12], Weller *et al.*[13] and Thompson and Witte[18]. CEPEX[14,17] and PEM[15,16] provide the distribution of tropospheric ozone

[§]For correspondence. (e-mail: tuhin@csnpl.ren.nic.in)

over the Pacific Ocean. Because of different climatological features of the Indian Ocean when compared to the Atlantic and Pacific Ocean, it is important to know the structure and its vertical distribution. Since 1987, a couple of measurements of surface ozone have been reported. However, observations of vertical distribution of ozone over the Indian Ocean for longer period are rare.

We will report vertical distribution of ozone over the Indian Ocean during onward and return journey of INDOEX FFP-98 and IFP-99. A result of intercomparison between closely flown electro-chemical cell (ECC)-German ozonesonde and modified brewer mast (MBM)-Indian ozonesonde will be presented here. A comparative study of zonal cross-section of vertical distribution of ozone along 15°N and 20°S has been made. In addition, we will discuss the comparative study of marine and continent ozone profiles.

Field experiments

During onward and return journey of first field phase experiment (INDOEX) in February/March 1998, a total of 26 ozonesondes were flown on-board *Sagar Kanya* from 15°N to 20°S, out of which 14 are ECC-German ozonesondes and 11 are MBM-Indian of ozonesondes. Similarly, 39 MBM ozonesondes were flown on-board *Sagar Kanya* during the onward and return journey of intensive field phase of INDOEX in January/March 1999. Of these, 20 were during the onward journey and 19 during the return journey. The results of observation over Indian Ocean and model study have been presented in refs 24–26. Complementary observation of total number of sixty ECC ozonesondes was also made on-board *Ron Brown* over Indian Ocean during INDOEX IFP-99 by ICG-2 group (Smit, H. G. J., pers. commun.). In addition, during the Aerosols 99 Trans-Atlantic Cruise from Norfolk, VA to Cape Town, South Africa, a predecessor of INDOEX IFP-99 cruise, daily ozonesondes were launched from the NOAA R/V *Ron Brown* between 17 January and 6 February 1999 (http://code916.gsfc.nasa.gov/Data_services/Shadoz).

ECC ozonesondes and MBM ozonesondes flown following the ground preparation given by Komhyr[27] and Sreedharan[28], give ozone partial pressure, temperature and humidity. Before launching, the ECC ozonesondes were intercompared with a ground-based Dasibi ozonometer. Generally, the normalization factor of MBM, taken from three Indian stations with respect to ground-based Dobson spectrometers remains within 0.8–1.2. The normalization factor of MBM soundings with respect to the column densities measured by total ozone mapping spectrometer-Earth probe or TOMS-EP typically remains within 0.8–1.2, which gives a margin for the accuracy of the data. We have excluded data, with normalization factor out of this range. However, these data have not been corrected in such way in the present analysis.

Intercomparison between ECC and MBM ozonesonde

Quality of ECC and MBM ozonesondes was assessed in several intercomparisons[29–33]. JOISE (Juelich Ozonesonde Intercomparison Experiment, 1996) intercomparison[33] has removed the key shortcomings of earlier intercompa-

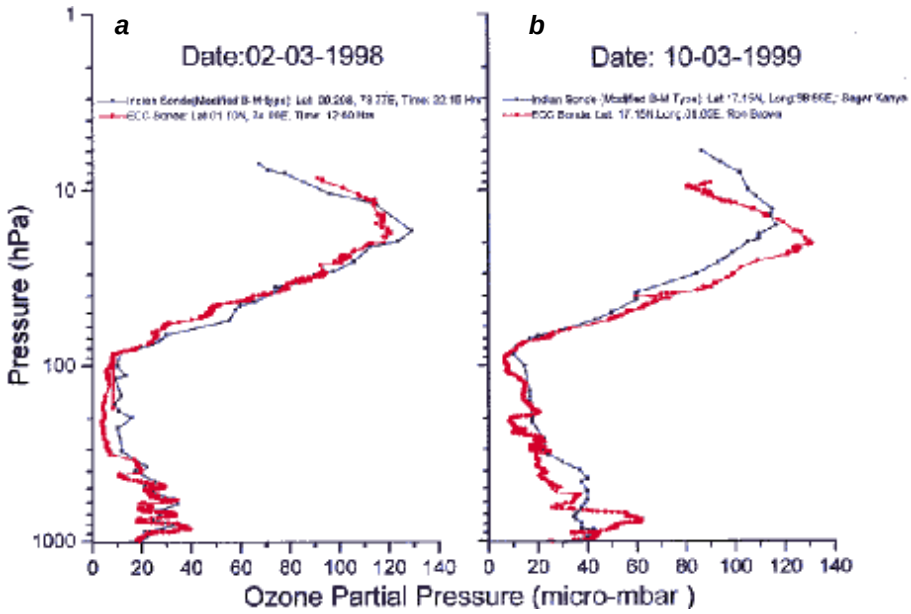

Figure 1 *a*, *b*. Comparison between ECC and MBM ozonesondes during INDOEX FFP-98 and INDOEX IFP-99. (***a***) Observation on 2 March 1998; (***b***) Observation on 10 March 1999.

risons. However, first field phase of INDOEX 1998 allowed us to verify the quality of ECC and MBM ozonesondes. Figure 1 *a* and *b* represents the vertical distribution of ECC and MBM ozonesondes flown on 2 March 1998 and 10 March 1999, respectively. During INDOEX FFP-98 a coherent pattern was observed at all levels, in spite of the fact that the observations during INDOEX FFP-98 were taken at different places and times. However, during INDOEX IFP-99, a difference was observed between ECC and MBM ozonesondes in tropospheric ozone. The MBM ozonesondes do not follow the layered structure as seen in ECC ozonesondes on 10 March 1999. It may be due to smoothening during data reduction. The maximum ozone value of MBM ozonesonde (135 μPa) during FFP-98 is higher than the maximum value of ECC ozonesonde (~ 110 μPa), whereas the pattern during IFP-99 has been reversed. Although several international intercomparisons have been performed towards the convergence of ozone data collected from different instruments with promising results, the results obtained from two field intercomparisons are not conclusive.

Results and discussion

Ozonesondes latitudinal cross-section

Figure 2 *a* and *b* represents the meridoinal cross-section of the vertical distribution of ozone over Indian Ocean during onward (18 February to 13 March 1998) and return (18–28 March 1998) journey of first field phase of INDOEX, respectively. During intensive field phase of INDOEX, we have divided total observations into four zones. The first zone is along 77°E from 20 January to 5 February 1999; the second zone is along 20°E from 5 to 10 February 1999; the third zone is along 58°E from 19 February to 1 March 1999; and the fourth zone is along 15°N from 2 to 10 March 1999. Figure 3 *a* and *b* represents the meridoinal cross-section of ozone during first and third zones of observations. Figure 4 *a* and *b* represents the zonal cross-section of ozone during the second and forth zones of observations.

The common features of meridoinal cross-section of ozone during FFP-98 and IFP-99 are: (i) a pocket of low ozone value (~ 10 ppbv) between 0 and 10°S near the surface; (ii) high ozone (> 100 ppbv) in the upper troposphere within the region of 10–15°S. The observation of low ozone value is quite consistent with the surface ozone observation (Duli Chand *et al.*[34], this issue). However, positive latitudinal gradient in ozone concentration from south to north and layered structure observed between 5 and 8 km during FFP-98, are not prominent in the meridoinal cross-section of ozone during IFP-99.

Earlier studies[3–18,21–23] also reported low ozone near the surface over the Atlantic, Pacific and Indian Ocean. The report compiled by Winkler[8] from 32 cruises over the Atlantic Ocean indicates the minima in ozone concentration (~ 14 ppb) near the equator. Ozone concentration near the surface reported from vertical distribution of ozone over the Atlantic Ocean by Smit *et al.*[11,12], Weller *et al.*[13] and Thompson and Witte[18] also supports the ozone minima (~ 10 ppb) near the surface, approximately within the same latitudinal band.

Similarly Johnson[9] also observed near-zero ozone concentration close to the equator from four cruises over the Indian and Pacific Ocean with seasonal variation. Routher *et al.*[4] also reported the minimum concentration over the Pacific Ocean within the region of 2°N to 13°S during the Gametag experiment. Similarly, Liu *et al.*[6] also measured 7–15 ppb ozone concentration during the Gametag flight. Piotrowicz *et al.*[7] also observed the ozone concentration of the order of 10 ppb south of the equator over the Pacific Ocean. They have examined the role of large-scale

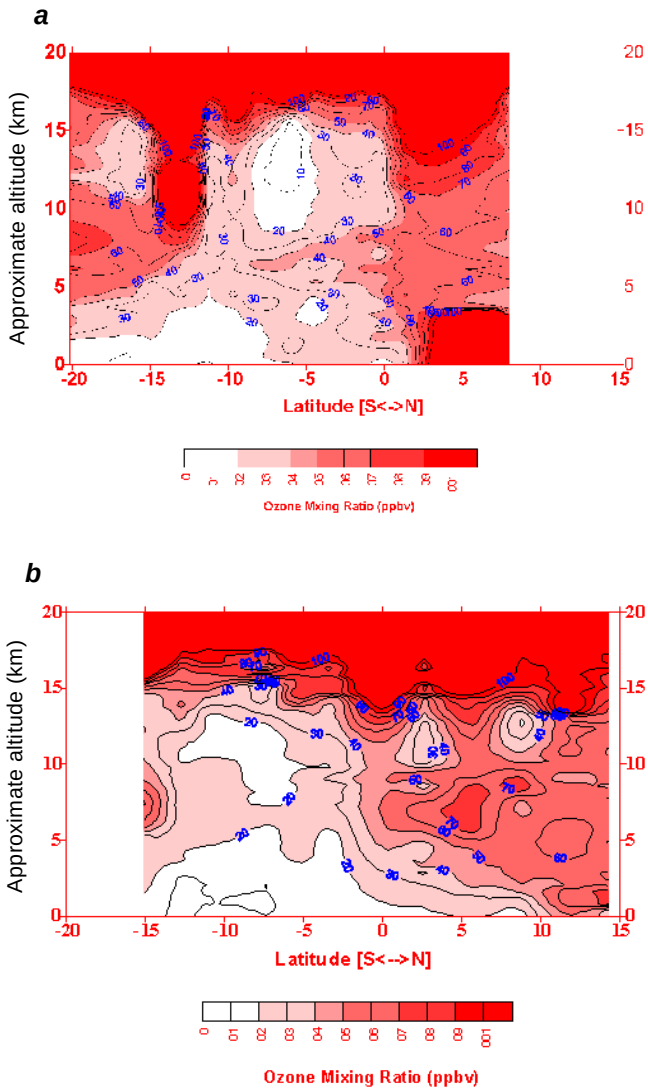

Figure 2 *a*, *b*. Contour diagram of the ozone mixing ratio (ppbv) in the troposphere, evaluated from the individual soundings performed during the onward and return journey of first field phase of INDOEX-98.

circulation and sea surface temperature in determining the low ozone value. Kley *et al.*[17] correlated the low ozone value (~ 5–10 ppb) near the surface as well as in the upper troposphere to halogen photochemistry during Central Equatorial Pacific Experiment (CEPEX) along 2°S between 150°E to 155°W.

Over the Indian Ocean, Lal *et al.*[21] and Rhoads *et al.*[23] reported ozone minima (~ 5–10 ppb) within the range of 0–10°S in all the cases. Similar feature of ozone minima has been observed in the vertical distribution, approximately in the same latitudinal band, during onward and return journey of INDOEX FFP-98 (ref. 24) and INDOEX IFP-99.

Chatfield and Crutzen[35] suggested the global role of sulphur and iodine species in marine air photochemistry. Being well away from the continental area, the critical limit of NO_x is below 10 pptv over the ocean as calculated by Liu *et al.*[5,6], which plays the role of ozone destruction rather than production and may be the cause of low ozone value. Thompson and Lenschow[36] examined the photochemistry of layer tropospheric ozone value in the marine boundary with a time-dependent model. Vogts *et al.*[37,38] suggest that the presence of reactive chlorine in inorganic chlorine gases and hydrocarbons at the remote marine boundary layer and reactions involving chlorine and bromine may affect the concentration of ozone. In addition, because of photolysis of ozone in the lower troposphere, followed by reaction of $O(^1D)$ with water vapour, high relative humidity near the surface may be another cause of low ozone (Figure 5 *a* and *b*).

High ozone concentration (~ 100–200 ppb) is observed at the upper and middle troposphere within the region of 5–15°S during the onward journey of INDOEX FFP-98 and both onward and return journeys of INDOEX IFP-99. These observations are inconsistent with the observation at equatorial Atlantic Ocean and western Pacific Ocean[11–18,39,40], almost in the same latitudinal band. Thouret *et al.*[40] also provide a climatology of high ozone at 9–12 km as seen by the MOZAIC air-borne programme between September 1994 and August 1996. However, the reason behind this elevated ozone concentration is not

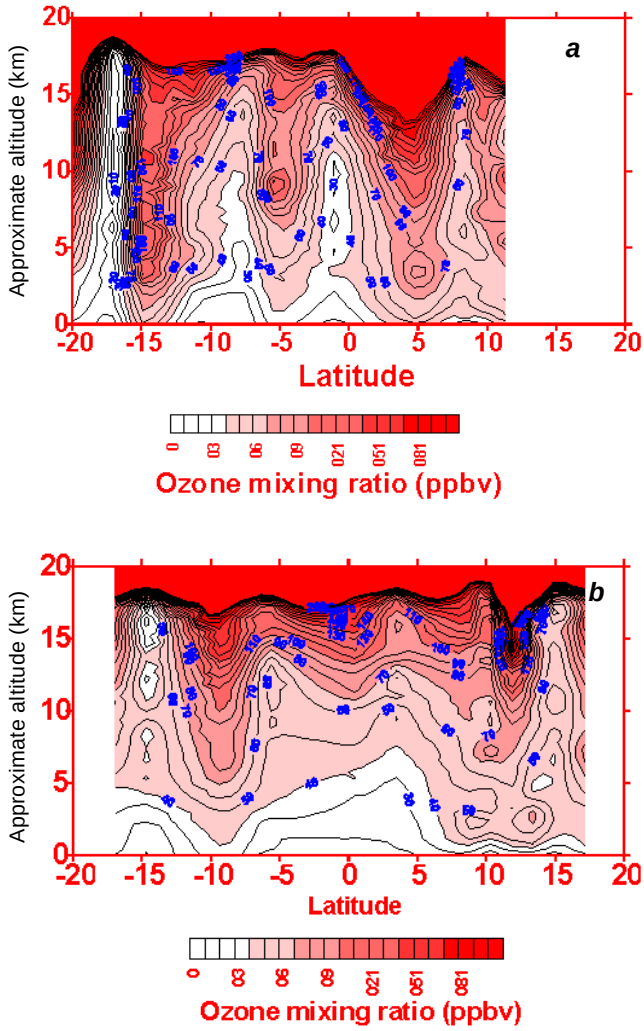

Figure 3. Contour diagram of the ozone-mixing ratio (ppbv) in the troposphere, evaluated from the individual soundings performed during the onward (***a***) and return journey (***b***) of intensive field phase of INDOEX-99.

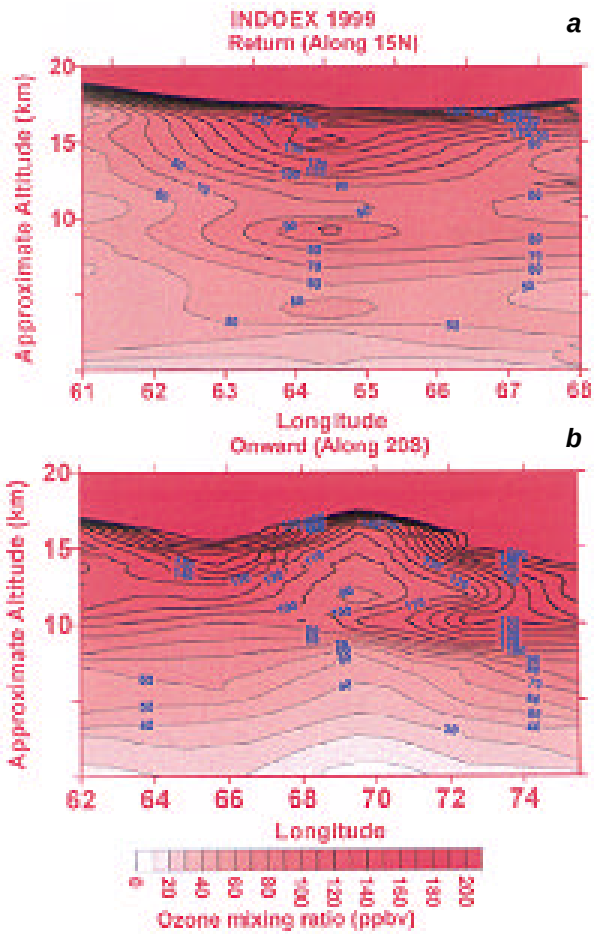

Figure 4 ***a***, ***b***. Contour diagram of the ozone mixing ratio (ppbv) in the troposphere, evaluated from the individual soundings along 15°N and 20°S of intensive field phase of INDOEX-99.

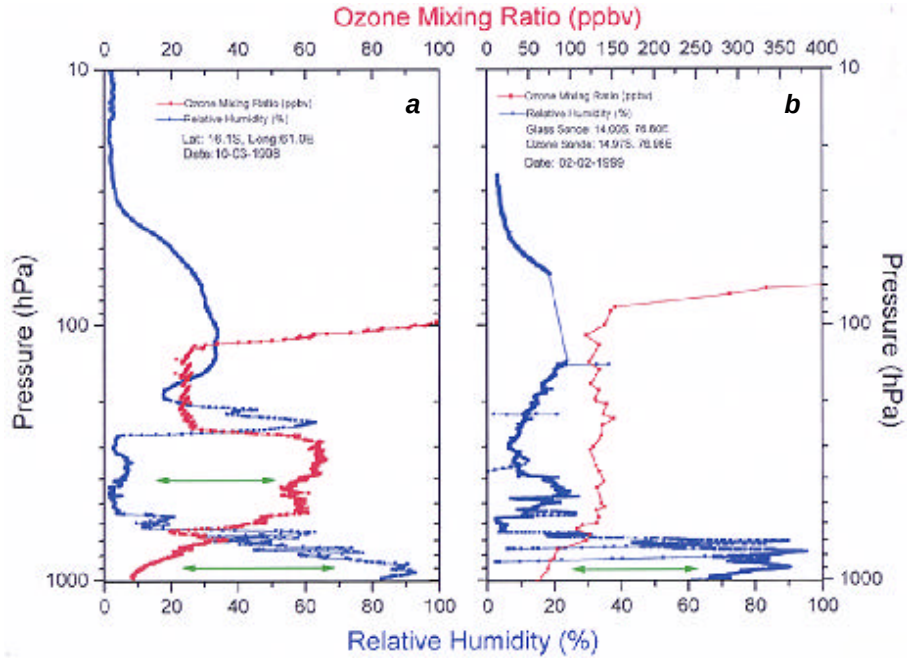

Figure 5 *a*, *b*. Comparison between ECC and MBM ozonesondes during INDOEX FFP-98 and IFP-99.

Table 1. Overview of origin of air masses during INDOEX

		Latitudinal/longitudinal/time-period range	Origin of air masses
INDOEX FFP-1998	950 hPa	Onward: North of the equator: 8.10°N, 75.70°E, 22/02/98 to 1.00°N, 74.00°E, 02/03/98	Indian subcontinent
		South of the equator: 0.0, 73.5°E, 02/03/98 to 16.00°S, 61.00°E, 10/03/98	Over the ocean
		Return: South of the equator: 15.90°S, 61.10°E, 17/03/98 to 3.00°S, 67.4°E, 22/03/98	Over the ocean
		North of the equator: 0.0, 69.00°E, 23/03/98 to 14.00°N, 68.5°E, 28/03/98	Indian subcontinent
	200 hPa	Onward: North of the equator: 8.10°N, 75.70°E, 22/02/98 to 1.00°N, 74.00°E, 02/03/98	East Asia
		South of the equator: 0.0, 73.5°E, 02/03/98 to 16.00°S, 61.00°E, 10/03/98	Southern part of Africa
		Return: South of the equator: 15.90°S, 61.10°E, 17/03/98 to 3.00°S, 67.4°E, 22/03/98	Middle and southern part of Africa
		North of the equator: 0.0, 69.00°E, 23/03/98 to 14.00°N, 68.5°E, 28/03/98	East Asia
INDOEX IFP-1999	950 hPa	Leg-1 (11.27°N, 74.43°E, 22/01/99 to 8.28°N, 76.35°E, 24/01/99)	India, mostly from Western Ghats and southern part of India
		Leg-2 (5.00°N, 76.70°E, 25/01/99 to 16.83°S, 77.00°E, 03/02/99)	Eastern Ghats of India, as well as over the ocean
		Leg-3 (20.00°S, 75.75°E, 05/02/99 to 20.00°S, 62.28°E, 09/02/99)	Over the ocean
		Leg-4 (16.95°S, 61.98°E, 19/02/99 to 11.95°N, 60.92°E, 01/03/99)	Over the ocean
		Leg-5 (15.00°N, 60.58°E, 02/03/99 to 17.15°N, 68.65°E, 10/03/99)	Indian subcontinent and partly from Gulf countries
	200 hPa	Leg-1 (11.27°N, 74.43°E, 22/01/99 to 8.28°N, 76.35°E, 24/01/99)	East Asia
		Leg-2 (5.00°N, 76.70°E, 25/01/99 to 16.83°S, 77.00°E, 03/02/99)	East Asia
		Leg-3 (20.00°S, 75.75°E, 05/02/99 to 20.00°S, 62.28°E, 09/02/99)	Southern part of African continent
		Leg-4 (16.95°S, 61.98°E, 19/02/99 to 11.95°N, 60.92°E, 01/03/99)	East Asia
		Leg-5 (15.00°N, 60.58°E, 02/03/99 to 17.15°N, 68.65°E, 10/03/99)	Gulf countries as well as northern part of Africa

clear. Generally enhancement of tropospheric ozone over Africa and south Asia has been reported during October/November due to exhaustive fires[41–43]. In this context, airflow during January/February from both the continents may not effect the climate over the Indian Ocean. Krishnamurthy *et al.*[43] and Thompson *et al.*[44] examined that the influence of biomass burning over tropical tropospheric ozone over the Atlantic Ocean. Anthropogenic emissions from the Asian continent (so-called Asian outflow), may influence the atmospheric composition over the tropical Pacific Ocean. Mandal *et al.*[24] reported the enhancement of total ozone by 20 Dobson Unit in tongue shape; it seems to be continental flow from east Asia. Roelofs *et al.*[45] reported that the northern hemisphere and southern

hemisphere, subtropical regions are characterized by downward transport of O_3-rich air from the upper troposphere and the areas of relatively high O_3 between 10 and 13 km at 15°–5°S, between 6 and 12 km at 20°N and between 5 and 10 km at 45° are characterized by relatively low water vapour concentration, which indicates that the air may have originated from the stratosphere. This resembles the observations of INDOEX-98 and INDOEX-99 (Figure 5 *a* and *b*). Results of ozonesonde observations at other tropical sites also show high ozone value in the upper troposphere[46–51]. Zacharisasse *et al.*[25] examined the influence of stratosphere–troposphere exchange (STE) over the Indian Ocean by ECHAM4 model. However, Mandal *et al.*[52] attempted to interpret the high ozone by STE mechanisms during 'tropopause weakening'. Folkins *et al.*[53] and Gouget *et al.*[54] suggest that the subtropical break may be one of the methods of STE), which may enhance the ozone concentration in the upper troposphere. However, Fujiwara *et al.*[55] studied the role of the Kelvin wave in tropical STE.

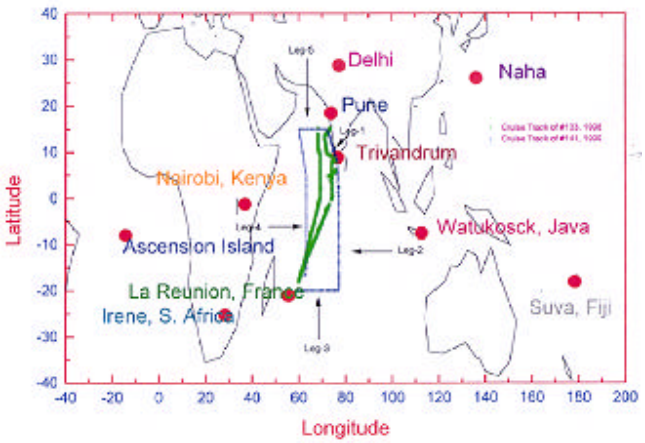

Figure 6. Map of different sites of ozonesonde stations over the Indian subcontinent, east Asia, Africa and Australian subcontinent during the period of INDOEX.

Flat structure in tropospheric ozone concentration is observed in zonal cross-section of ozone along 20°S and 15°N. However, ozone concentration along 15°N is quite higher than that along 20°S. It clearly demarcates of background value of pristine and pollutant air in the north and south sides of ITCZ. Along 20°S, positive gradient in

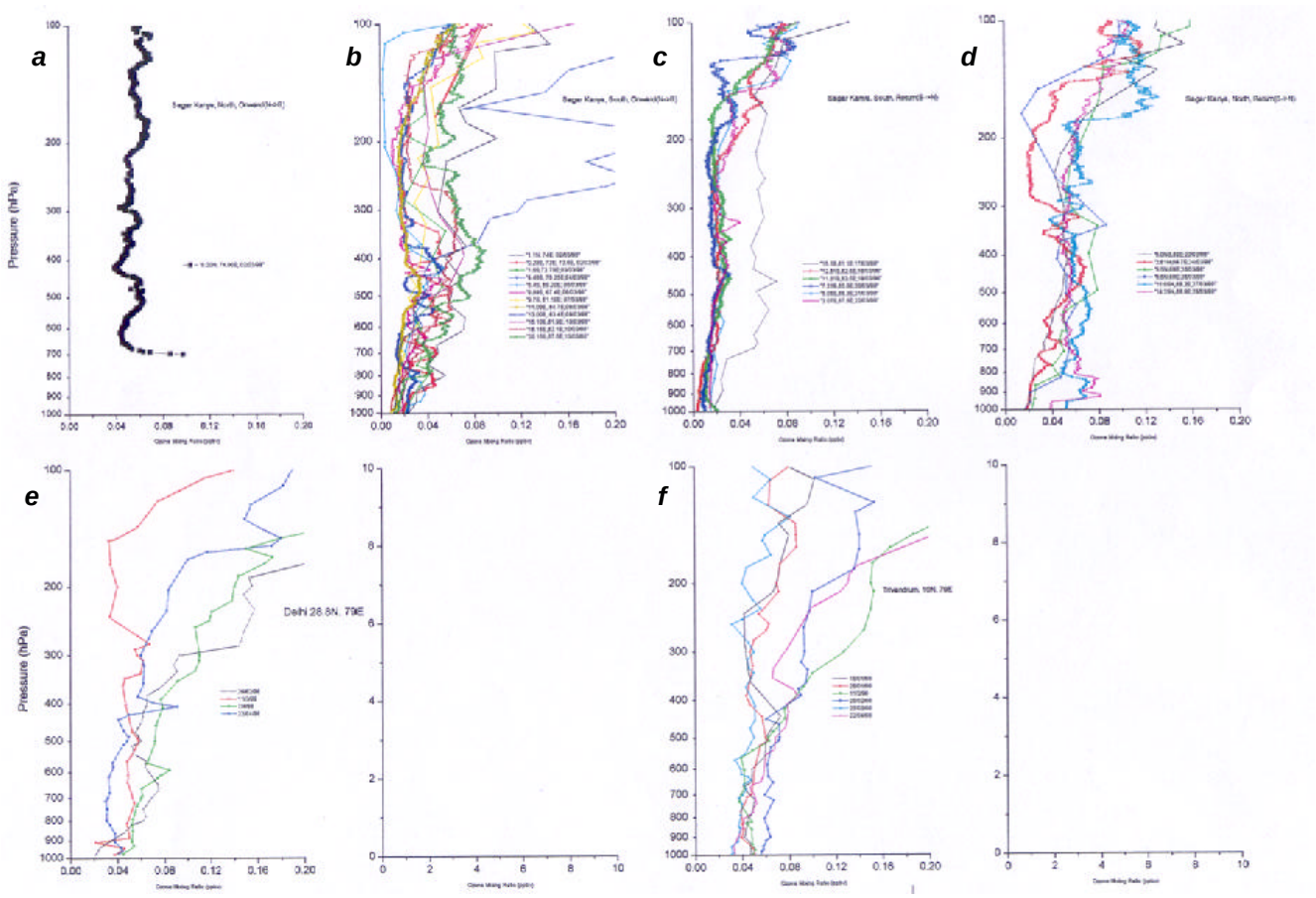

Figure 7. Comparison between the marine and continental ozone profiles during onward and return journey of first field phase of INDOEX-98. (***a***) Ozone profiles over Indian Ocean at the northern side of the equator during onward journey; (***b***, ***c***) Ozone profiles over Indian Ocean at the southern side of the equator during onward journey (***b***) and return journey (***c***); (***d***) Ozone profiles over Indian Ocean at the northern side of the equator during return journey; (***e***, ***f***) Continental profiles for Indian stations (***e***) Delhi (28.8°N, 79°E) (***f***) Thiruvananthapuram (8.9°N, 77°E) during the period of FFP-INDOEX-98.

ozone concentration is observed from African continent to Australian continent, but back trajectories done by Harenduprakash and Iyenger[56] show that mostly air flows are from the African continent. Comparative study of ozone profiles over the Indian Ocean and continental ozone profiles may reveal the real source and relative contribution of continental pollutant on marine ozone.

Meteorological conditions

Based on back trajectory analysis done by Jha and Krishnamurthy[57] and Harenduprakash and Iyenger[56] at 925 hPa and 200 hPa, the origin of air masses corresponding to the ship positions over the Indian Ocean is overviewed in Table 1. During the onward and return journey of INDOEX FFP-98, ozone profiles of the northern and southern sides of the equator over the Indian Ocean are sorted out into four groups, whereas profiles during onward and return journey of INDOEX IFP-99 have been divided into five legs. Ten-days back trajectory analysis done by Jha and Krishnamurthy[57] at 925 hPa during INDOEX FFP-98 shows that mostly air flows from the Indian subcontinent, whereas at 200 hPa, flow is from the east Asian region. Five-days back trajectory analysis at 950 hPa by Harenduprakash and Iyenger[56], starting from the position of *Sagar Kanya* at 00 UTC using NCMRWF global atmospheric analysis, shows that in leg-1, leg-4 and northern side of equator in leg-2, airflow is mainly from the Indian subcontinent, whereas back trajectories in other legs have originated over the Indian Ocean only. Five-days back trajectory analysis at 200 hPa shows that origin of air masses during leg-1 is from the Indian subcontinent, east Asian flow has dominated during leg-2 and leg-4 and South African flow has dominated during leg-3. The most interesting feature is that leg-5, i.e. profiles along 15°N have been affected by the flow from Gulf countries.

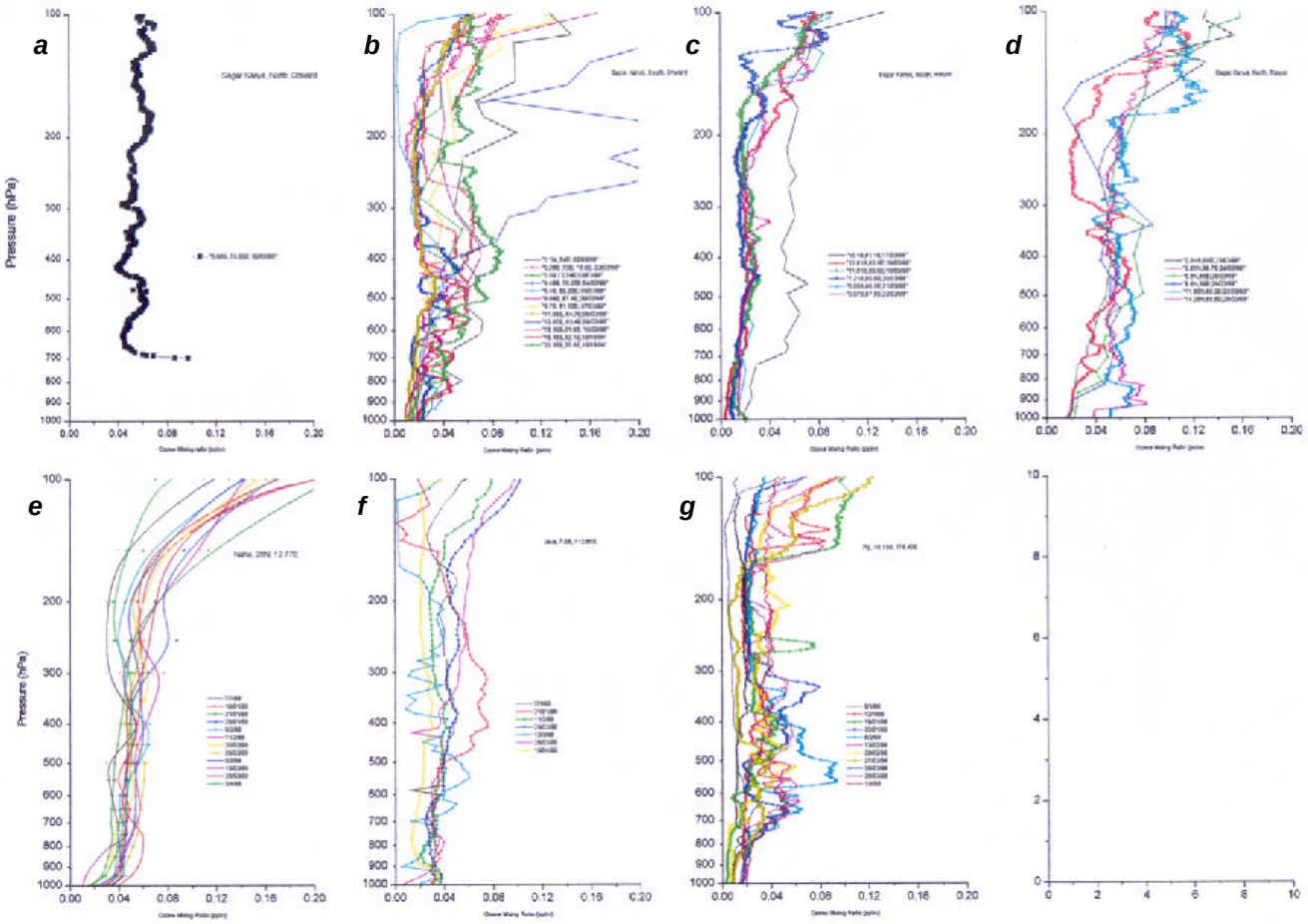

Figure 8. Comparison between the marine and continental ozone profiles during onward and return journey of first field phase of INDOEX-98. (***a***) Ozone profiles over Indian Ocean at the northern side of the equator during onward journey; (***b***, ***c***) Ozone profiles over Indian Ocean at the southern side of the equator during onward journey (***b***); and return journey (***c***); (***d***) Ozone profiles over Indian Ocean at the northern side of the equator during return journey; (***e***–***g***) Continental profiles for (***e***) Naha (26°N, 136°E) (***f***) Java (7.5°S, 112.60°E) and (***g***) Fiji (18.3°S, 178.40°E) during the period of INDOEX FFP-98.

Comparison between marine and continental ozone profiles

We have compared the marine ozone concentration with continental value and divided continental areas surrounding the Indian Ocean into three regions. The first region consists of ozonesonde stations: Delhi, Pune and Thiruvanathapuram; the second region consists of east Asia and Australian ozonesonde stations: Naha, Java and Fiji; the third region consists of African land stations: Nairobi, Ascension Island, Irene and La Reunion (Figure 6).

Figures 7–9 represent comparison of ozone profiles over the Indian Ocean with the profiles over three regions during the period of onward and return journey of INDOEX FFP-98. Ten-days back trajectories done by Jha and Krishnamurthy[57] shows that air flows at the northern side of the equator at 950 hPa are mainly from the Indian subcontinent and east Asia, whereas, air flows at 200 hPa are from east Asia only. The ozone concentration at the northern side of the equator during onward and return journey of INDOEX FFP-98 is in the range of 20–80 ppb. There is good a resemblance between ozone profiles at all levels at Java, Naha and Fiji, i.e. east Asian ozonesonde stations and lower tropospheric ozone value of Indian stations. Though back trajectories at 200 hPa indicate that flow of air masses is mainly from east Asia, ozone concentration at east Asian stations are lower than the marine value compared to the northern side of the equator. Therefore the possibilities of advection from east Asian subcontinent in the lower and middle troposphere are being ruled out. Since ozone concentration at 200 hPa of Delhi and Thiruvananthapuram is in the range of 80 to 200 ppb, there may be a possibility of advection of ozone from the Indian subcontinent. Ozone profiles over the Indian Ocean at the southern side of the equator show variation at different pressure levels. Low tropospheric ozone (10–20 ppb) values are observed in almost all the profiles. Since 10-days back trajectories at 950 hPa have originated over the ocean itself, probably the continental effect is absent here. However, the upper tropospheric ozone value (200 hPa) has shown large variation from 80 to 200 ppb. Mostly all the trajectories have originated from

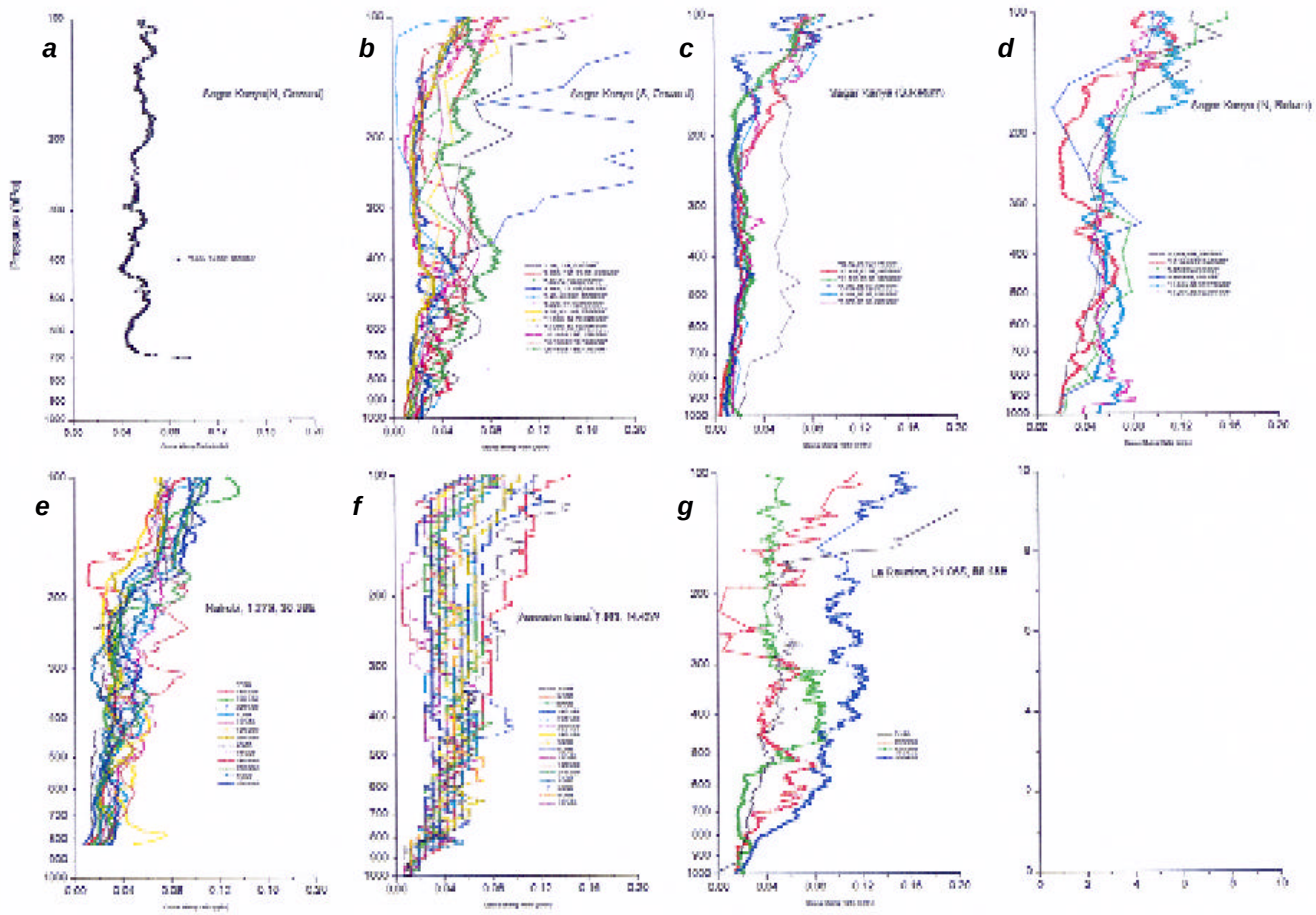

Figure 9. Comparison between the marine and continental ozone profiles during onward and return journey of first field phase of INDOEX-98. (***a***) Ozone profiles over Indian Ocean at the northern side of the equator during onward journey; (***b***, ***c***) Ozone profiles over Indian Ocean at the southern side of the equator during onward journey (***b***); and return journey (***c***); (***d***) Ozone profiles over Indian Ocean at the northern side of the equator during return journey; (***e***–***g***) Continental profiles for (***e***) Nairobi (1.27°S, 36.38°E) (***f***) Ascension Island (7.98°S, 14.42°E) and (***g***) La Reunion (21.06°S, 55.48°E) during the period of INDOEX FFP-98.

the southern side of the African continent and few are from east Asia, advection of ozone at this particular level from African stations is expected. However, advection from east Asia has to be ruled out.

Figures 10–12 represent the comparison of ozone profiles over the Indian Ocean with the profiles over three regions during the period of onward and return journey of INDOEX IFP-99. Observation in leg-1 is along the coastal region of the Indian subcontinent and the trajectories at 950 and 200 hPa are from the Indian subcontinent, particularly the southern part of India. Therefore, ozone concentration has good resemblance with Pune and Thiruvanathapuram values. In fact, it could be characterized as continental profile rather than marine profile. Though lower level (950 hPa) and upper level air flow (200 hPa) in leg-2 are mainly from east Asia, except few trajectories at the northern side of leg-2 at lower level (950 hPa) which have originated from eastern side of India, ozone concentration is very much similar to the ozone concentration over Thiruvananthapuram. Since ozone concentration at Java, Naha and Fiji, i.e. east Asian stations is too low as observed also during January/March 1998, advection of ozone from east Asia has been ruled out. In leg-3, lower level back trajectories (950 hPa) have originated over the ocean, whereas upper level trajectories (200 hPa) have mostly travelled over continental regions of southern side of Africa. Ozone concentration in leg-3 is similar to continental profiles of Irene and Ascension Island rather than Nairobi and La Reunion, though La Reunion is the closest station to leg-3. In leg-4, lower level trajectories (950 hPa) have originated over the ocean, whereas upper level (200 hPa) air flows are mainly from east Asia, not a single profile resembles with ozone concentration in the upper troposphere over east Asia. In leg-5, lower level flows are from the Indian subcontinent, whereas upper level flows are from the northern side of African subcontinent and Gulf countries. It is unfortunate that we do not have any observation over the northern side of African subcontinent and Gulf countries. However, ozone concentration at all levels in leg-5 could be greatly affected by the advection from Pune and Thiruvananthapuram. It is to be noted that the derived trajec-

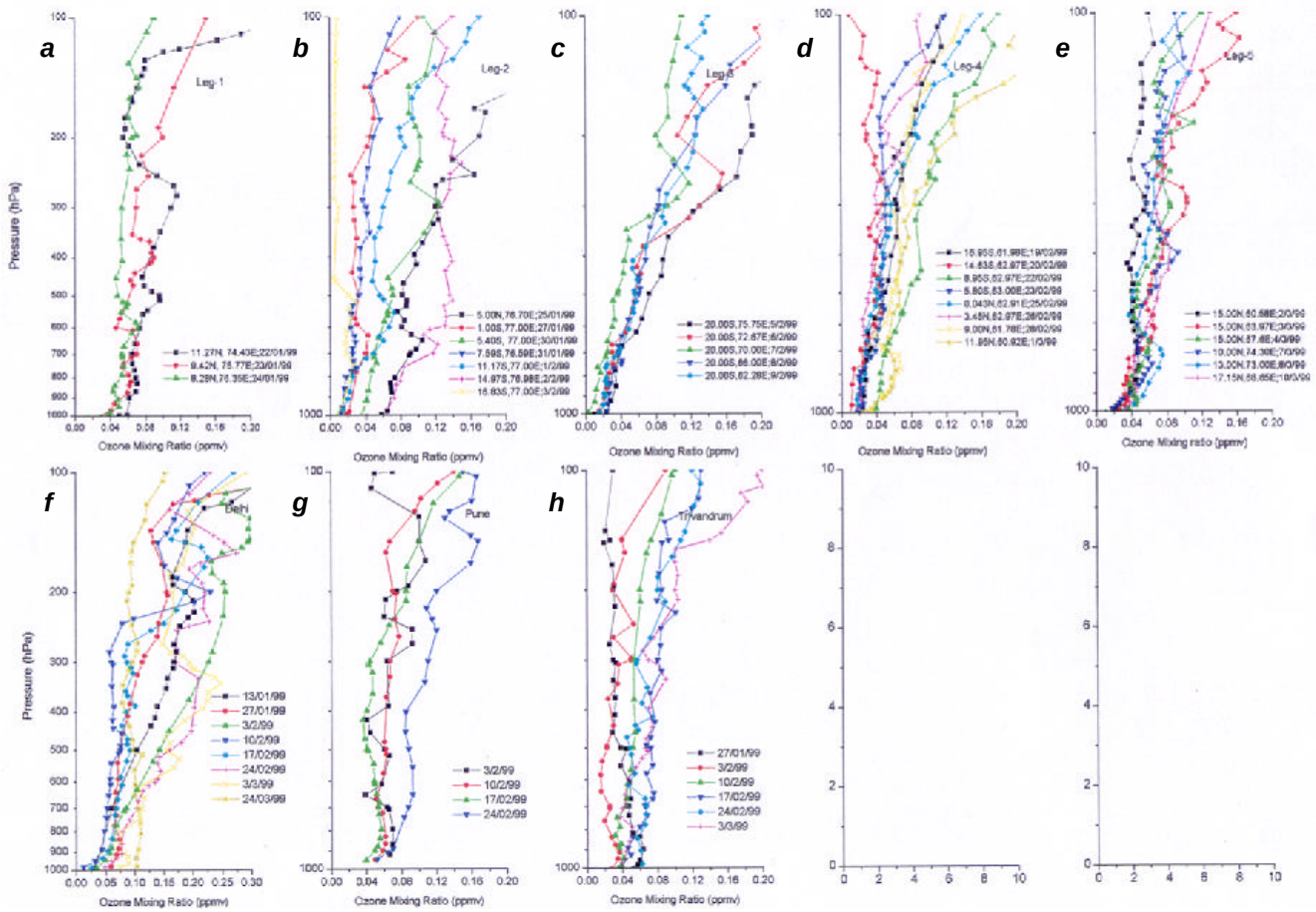

Figure 10. Comparison between the marine and continental ozone profiles during onward and return journey of intensive field phase of INDOEX 99. (***a***) Ozone profiles in leg-1 along the coastal side of India during onward journey; (***b***) Ozone profiles in leg-2 over Indian Ocean along 77°E during onward journey; (***c***) Ozone profiles in leg-3 over Indian Ocean along 20°S during onward journey; (***d***) Ozone profiles in leg-4 over Indian Ocean along 55°E during return journey; (***e***) Ozone profiles in leg-5 over Indian Ocean along 15°N during onward journey; (***f***–***h***) Continental profiles for (***f***) Delhi (28.8°N, 79°E) (***g***) Pune (19°N, 79°E) and (***h***) Thiruvananthapuram (8.9°N, 77°E) during the period of INDOEX IFP-99.

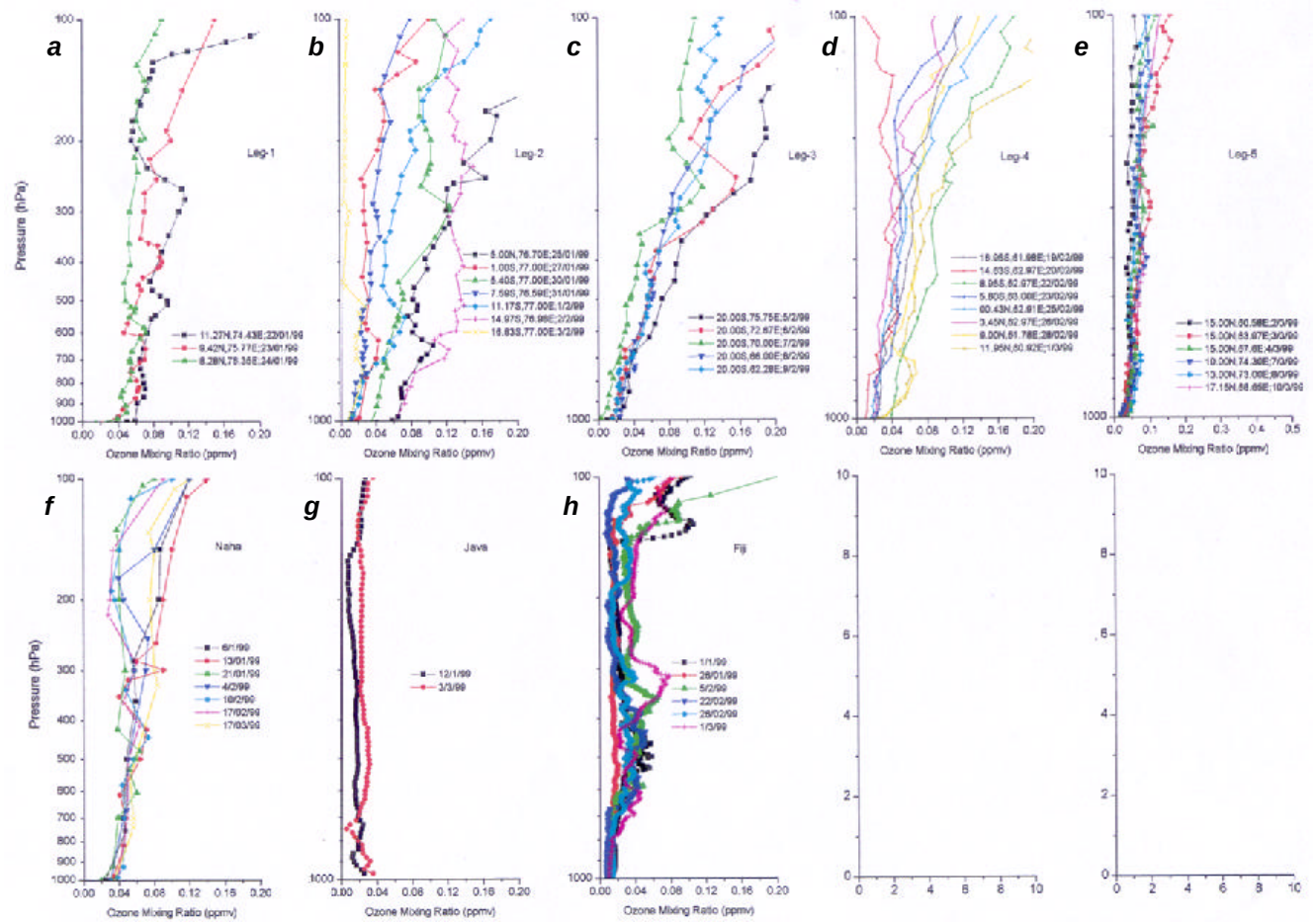

Figure 11. Comparison between the marine and continental ozone profiles during onward and return journey of intensive field phase of INDOEX 99. (***a***) Ozone profiles in leg-1 along the coastal side of India during onward journey; (***b***) Ozone profiles in leg-2 over Indian Ocean along 77°E during onward journey; (***c***) Ozone profiles in leg-3 over Indian Ocean along 20°S during onward journey; (***d***) Ozone profiles in leg-4 over Indian Ocean along 55°E during return journey; (***e***) Ozone profiles in leg-5 over Indian Ocean along 15°N during onward journey; (***f***–***h***) Continental profiles for (***f***) Naha (26°N, 136°E) (***g***) Java (7.5°S, 112.60°E) and (***h***) Fiji (18.3°S, 178.40°E) during the period of INDOEX IFP-99.

tories represent an approximation, and are based on global analysed field value.

Conclusion

The results of measurement of ozone profiles the over Indian Ocean during INDOEX FFP-98 and IFP-99 have been reported and compared. Some specific features observed during INDOEX FFP-98 have been repeated again during INDOEX IFP-99:

(1) A pocket of low ozone value (~ 10 ppb) is observed near the surface within the region of 0–10°S.
(2) A high value of ozone concentration (> 100 ppbv) has been observed during both INDOEX FFP-98 and IFP-99. This resembles the observation made during the period 1995 on-board *Malcolm Baldrige*.

But north–south latitudinal gradient in meridoinal cross-section of ozone and layered structure observed at 5–8 km during INDOEX FFP-98 are not prominent during INDOEX IFP-99. However, background concentration of ozone along 15°N and 20°S suggests the demarcation of pollutant and pristine air on either sides of ITCZ.

The comparison between continental and marine ozone profiles does not give any clear indication as to air masses from which regions have affected comparatively more the Indian Ocean, though back trajectory analysis at different constant pressure levels shows that mostly India and east Asia to be the major sources at the northern side of the equator, whereas African continent to be the major sources of polluted air at the southern side of the equator. Since ozone concentration in east Asian stations is lower than the marine ozone concentation, the hypothesis of horizontal advection of ozone from east Asia is to be verified carefully. Therefore, mechanisms behind controlling the ozone concentration over the Indian Ocean are much more complicated.

We have partly attempted to find out the role of dynamics over Indian Ocean here. However, the role of photochem-

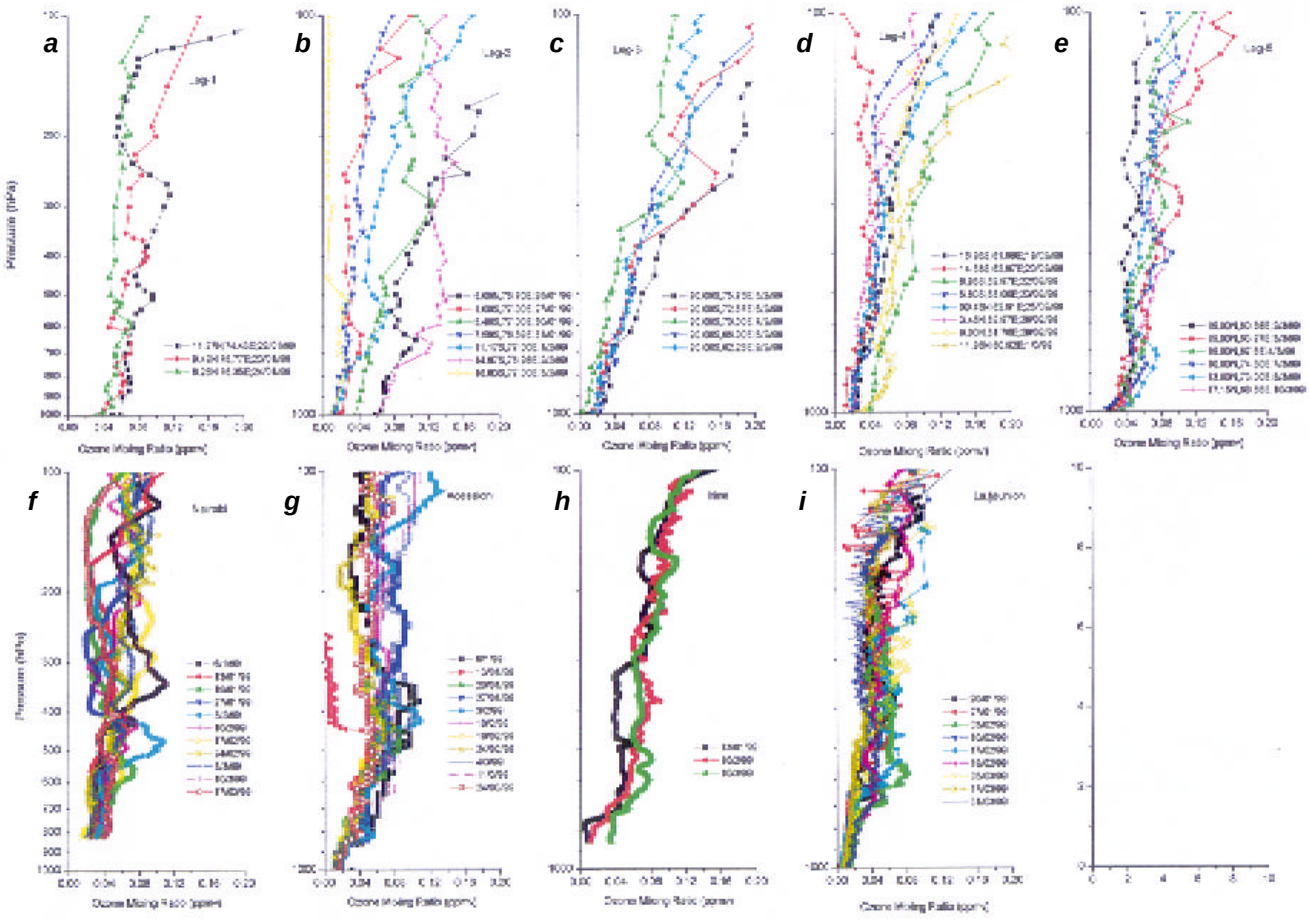

Figure 12. Comparison between the marine and continental ozone profiles during onward and return journey of intensive field phase of INDOEX 99. (***a***) Ozone profiles in leg-1 along the coastal side of India during onward journey; (***b***) Ozone profiles in leg-2 over Indian Ocean along 77°E during onward journey; (***c***) Ozone profiles in leg-3 over Indian Ocean along 20°S during onward journey; (***d***) Ozone profiles in leg-4 over Indian Ocean along 55°E during return journey; (***e***) Ozone profiles in leg-5 over Indian Ocean along 15°N during onward journey; (***f–i***) continental profiles for (***f***) Nairobi (1.27°S, 36.38°E) (***g***) Island (7.98°S, 14.42°E) (***h***) Irne (25.25°S, 28.22°E) and (***i***) La Reunion (21.06°S, 55.48°E) during the period of INDOEX IFP-99.

istry in ozone concentration, in particular, low ozone concentration (~ 10 ppb) near the surface and high ozone (> 100 ppb) in the upper troposphere has to be checked carefully compiled with dynamics.

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