Replies to Anonymous Referee #2 comments/suggestions

The paper presents the impact of cyclones that occurred over the North Indian Ocean during 2007-2013 on stratosphere-troposphere exchange using satellite measurements. Changes in ozone and water vapour distribution in the upper troposphere and lower stratosphere were analyzed. The cross-tropopause mass flux was estimated. The manuscript has some significant shortcomings. Therefore, I recommend some important revisions to address the comments listed below before publication by ACP.

Reply: First of all we wish to thank the reviewer for going through the manuscript carefully and offering potential solutions to improve the manuscript content further.

General comments:

1) Scientific significance

The paper presents new interesting results, however the results need to be better developed.

Reply: Thanks for appreciating actual content of the manuscript. We have revised the manuscript while considering both the reviewers comments/suggestions.

2) Scientific quality

One important questions is whether the MLS measurements have sufficient spatial and temporal resolution to apply the used methodology? This has to be demonstrated. The explanation how the cross tropopause mass flux is calculated and which data are used is confusing. The method is explained in Sect. 2 and the used data are introduced in Sect. 3.1. I recommend to combine this in one Section. Further, the method of Ravindra Babu et al., 2015 is used (e.g. Fig. 2). However, the reader cannot understand this method without reading Babu et al., 2015. I recommend to provide more information about this method in Sect. 2. Many general statements have not been established with references (e.g. within the introduction, see below specific comments).

Reply: More details are provided in the revised manuscript with related to MLS data resolution, tropopause mass flux calculation and the methodology that is adapted from Ravindra Babu et al. (2015). We have not provided these details earlier to avoid repetition and/or plagiarism report.

For MLS data resolution, first we separated MLS overpasses with respect to cyclone centre for each day of cyclone period and we made it cyclone-centre composite of corresponding ozone and water vapor, respectively.

For tropopause mass flux, we considered whatever available tropopause temperature and pressure within 500km from the cyclone centre taken from Ravindra Babu et al. (2015) and winds within 500 km from the cyclone centre are taken from ERA-Interim data sets.

3) Presentation quality

The presentation quality needs some improvements. There are number of language and grammar issues. Further a lot of blank characters are missing, in particular after mathematical symbols or brackets. In the manuscript, abbreviations are still used that are not introduced. In some figures, the legend is missing.

Reply: We are sorry for the grammatical mistakes which have been reduced to the maximum possible extent in the revised manuscript. Missing of blank characters is mainly due to software problem loaded in one of our computers which is rectified now. We have elaborated all the abbreviations used in the manuscript when they appear for the first time in the manuscript.

Specific comments:

1. Introduction:

p. 3, line 51: ‘Tropical cyclones with deep convective synoptic scale systems persisting for a few days to weeks play an important role on the mass exchange between troposphere and stratosphere and vice versa.’ Please add some references.

Reply: Added.

p. 3, line 52: ‘They transport large amount of water vapor, energy and momentum to the upper troposphere and lower stratosphere (UTLS) region.’ Please add some references.

Reply: Added.

p. 3, line 60: ‘The transport of water vapour and ozone around the tropopause caused by the cyclones can affect the radiation balance of the atmosphere.’ Please add some references.’

Reply: Added.

p. 3, line 62: ‘Increase of water vapor in the LS region will leads to a warming and ozone loss in this atmospheric region (Stenke and Grewe, 2005).’ An increase of stratospheric water vapor contributes to tropospheric warming and stratospheric cooling, see e.g.: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ed. S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller and Z. Chen, Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2007, pp. 1-996.

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P. Forster and K. P. Shine, Geophys. Res. Lett., 1999, 26, 3309-3312

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G. Myhre, S. J. Nilsen, L. Gulstad, K. P. Shine, B. Rognerud and I. S. A. Isaksen, Geophys. Res. Lett., 2007, 34, L01807.

However, small changes of water vapor in the lower stratosphere have an impact on surface climate, see e.g: Riese et al., Impact of uncertainties in atmospheric mixing on simulated UTLS composition and related radiative effects, J. Geophys. Res., 117, D16305, doi:10.1029/2012JD017751, 2012.

Solomon et al., Contributions of stratospheric water vapor to decadal changes in the rate of global warming, Science, 327, 1219-1223, 2010.

Reply: Thanks for updating us while providing above references. Most of the above mentioned references are included in the revised manuscript at appropriate places.

p. 3, line 65: troposphere air ! tropospheric air

Reply: Corrected.

p. 4, line 82: ’TC event’: abbreviation is not explained

p. 4, line 86: ’MST Radar observations’: abbreviation is not explained

p. 4, line 87: ’BoB’: abbreviation is not explained

Reply: These are explained in the revised manuscript.

p. 4, line 87: ‘More literature related to influence of cyclones on the UTLS structure and composition is presented in Cairo et al. (2008).’ Unspecific statement: please add some details or remove Cairo et al. 2008.

Reply: We have added major findings of Cairo et al. (2008) in the revised manuscript.

p. 5, line 105: 'COSMIC' is not explained
Reply: Explained in the revised manuscript.

2. Data and Methodology
p. 5, line 116: How many MLS profiles or measurements (spatial and temporal resolution, horizontal distance between tracks) contribute to one typhoon event. Please add here some information and demonstrate that the data density is sufficient.
Reply: We have included details in the revised manuscript in the form of table (table 2).

p. 5, line 120: Which definition is used for the tropopause?
Reply: We used cold point and lapse rate tropopause definitions in this present study. For calculating tropopause mass flux, we used lapse rate tropopause definition only.

p. 6, line 135: Please add the precise time period for pre- and post-monsoon season and explain why you exclude the monsoon season.
Reply: Added in the revised manuscript. We also included monsoon season.

p. 7, line 149: 'tropopause parameters': Which parameters? Please combine this paragraph with details from Sect. 3.1'.
Reply: We combine and explained clearly this aspect in the revised manuscript.

3. Results and discussion
p.7, line 162: How are the climatological mean values calculated? Is the monsoon season in the climatological mean excluded? During the Asian monsoon season the tropopause above the Asian monsoon anticyclone is elevated. Therefore, during this time period the lapse rate tropopause altitude differs from the altitude during the rest of the year. Is this considered in your analysis?
Reply: We have not considered this in the calculation. There could be day-to-day to the inter-annual variability in the observed climatological tropopause parameters. Since large data (14 years) have gone through climatology, we assume that variability less than the solar cycle is nullified, if not removed completely. Further Asian monsoon anticyclone aspect is related to the latitudes greater than 25^{o}N, thus, do not affect our study in a significant manner. However, upper level anti-cyclonic circulation over the cyclones is reflected very well in our observations.

p. 7, line 169: How many measurements (tracks) do you have within 1000 km radius for one cyclone?
Reply: The total available RO measurements are not fixed for each cyclone; the RO measurements will change one cyclone to another. For example, the total RO measurements in the case of Nargis cyclone are 73. These details are provided in the revised manuscript.

p. 7, line 175: How is the cyclone intensity considered in the methodology of Ravindra Babu et. al, 2015? Please give a short summary about the method of Ravindra Babu et al., 2015 used for Fig. 2. How is vertical uplift at different flanks of the cyclone and difference between individual cyclones considered?
Reply: In Ravindra Babu et al. (2015), we did tropopause analysis based on different intensities of the cyclones such as depression (D), deep depression (DD), cyclonic

storm(CS), severe cyclonic storm (SCS) and very severe cyclonic storm (VSCS). After detailed analysis we found that there is no major variation between D and DD, SC and SCS. So we combined the results of D and DD as one category and CS and SCS as another category and VSCS as one category. From each cyclone we separated the RO measurements based on the intensity and we combined.

p. 12, line 280-284: '...higher ozone mixing ratios are observed in the western and northwest side and more water vapor is located at the eastern side of the cyclonic center....' Why do you have this preference for the western and eastern side, respectively? In the schematic diagram Fig. 6 upward and downward transport of water vapor and ozone is shown. The diagram implies rotational symmetry around the center of the cyclone. How fits the rotational symmetry together with the preference at the western and eastern side?

Reply: Our results from Ravindra babu et al. (2015) shows the integrated RH is more in the east and south east side within 500 km from the cyclone centre and the COH, TTL thickness also shows high in the north and north west side within 500 km from the cyclone centre. From these we assume that different sides within 500 km from the centre there may be different variations in the ozone and water vapour as well as cross tropopause flux. That's why we calculated the flux with respect to sector wise from the cyclone centre.

The diagram shown in the figure 6 it is just assumption of the cyclone structure only. Our main aim of the figure 6 is to show the variation of tropopause parameters in the schematic way i.e., ozone coming down from the lower stratosphere due to subsidence at the centre and water vapour entering in to the lower stratosphere due to anti-cyclonic circulation above the cyclone.

The higher ozone mixing ratios are observed in the western and northwest side and more water vapour is located at the eastern side of the cyclone centre because of the upper level anti-cyclonic circulation over the cyclones. This will push the water vapour towards the south and east side of the cyclone centre. In the other side of the cyclone, the detrainment of the lower stratospheric air may occur along with strong subsidence in the cyclone centre. This might be the region for higher ozone in the west and northwest side and more water vapour in the east and southeast side of the cyclone centre. Note that Ray and Rosenlof (2007) also reported higher water vapour mixing ratios in the east side of the cyclone centre for Atlantic and Pacific oceans. Further, very recently Reutter et al. (2015) reported that the more stratosphere- troposphere transport takes place in the west side of the cyclone centre due to west ward tilt of the cyclone with height.

p. 12, line 294: 'by assuming change in the tropopause pressure by 0.5 hPa' Why 0.5 hPa is used?

Reply: Since we do not have pressure variation with time we have assumed different pressures while considering minimum to maximum possible pressure variations.

p. 13, line 299: Please explain why different cross-tropopause flux occurs in different sectors.

Reply: As we found different variations in the water vapour and ozone transport in different sectors, we have estimated cross-tropopause flux for these different sectors. Please see reply for above comment (p. 12, line 280-284) for more details.

4. Summary and conclusions

p. 14, line 335: 'The main findings of the present communication are summarized below.' ! Our main findings are summarized below.'

Reply: Modified.

p. 14, line 336-339: 'Lowering of CPH (0.6 km) and LRH (0.4 km) values with coldest CPT and LRT (2-3K) within a 500 km radius from the cyclone centre is noticed. Higher (2 km) COH leading to the lowering of TTL thickness (3 km) is clearly observed (Ravindra Babu et al., 2015).' That is a result from Ravindra Babu et al, 2015 and not from the present paper Ratman et al.. That should be clearly recognizable in the text.
Reply: We have already provided reference when it is mentioned.

p. 15, line 346-347: 'Interestingly significant enhancement in the lower stratosphere (82 hPa) water vapor is noticed in the east and SE side from the cyclone centre.' Again, why only at the east and SE side?
Reply: Please see explanation provided for the comment p. 12, line 280-284.

p. 15, line 355-357: 'Strong convective towers with strong updrafts extending up to the tropopause altitude in the form of spiral bands extending from 500 to 1000 km are present.' In Fig. 6, three bands of downward transport of ozone and three bands for upward transport of water vapor are drawn which are not visible in Fig. 3 and 4. Please explain this discrepancy or adapt Fig. 6. To confirm the spiral bands of upward and downward transport illustrated in Fig. 6 trajectory calculations would be very helpful.
Reply: Note that figure 3 and 4 are cyclone-centre composite of ozone and water vapour obtained from all 16 cyclones and the figure 6 is the only schematic picture of a cyclone. Our main aim in figure 6 is to show the variation of tropopause parameters in the form of schematic way i.e., ozone coming down at the centre from the lower stratosphere due to subsidence and water vapour entering in to the lower stratosphere due to anti-cyclonic circulation above the cyclone above the spiral bands.

Figures:
Fig. 1: 'strom' ! 'storm'
Fig. 3: Legend from a-d is missing.
Fig. 4: Legend from a-d is missing.
Reply: Corrected in the revised manuscript.

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Replies to Anonymous Referee #3 comments/suggestions

This is an interesting study of the impact of cyclones on ozone and water vapour in the upper troposphere and lower stratosphere. It is based on the analysis of some cases study, using satellite measurements to estimate the air flux across the tropopause. It is surely a valuable contribution on a hot topic in stratospheric research, since the ability to predict future changes in the stratosphere relies on correct estimates on how tropical troposphere to stratosphere transport might evolve. I definitely agree that the role of deep convection in cyclones is worth of more research, and it is appropriate for the journal, so I encourage the publication of this work. However, there are a number of open issues that have to be addressed; therefore I recommend a revision before publication. I had the chance to read the general comments of the Anonymous Reviewer #2 and I do share all his/her general comments.

Reply: First of all we wish to thank the reviewer for going through the manuscript carefully, appreciating actual content of the manuscript and offering potential solutions to improve the manuscript content further. We have revised the manuscript while considering both the reviewers comments/suggestions.

In particular I find strange how the results from previous work of Ravindra Babu et al. (2015) are used in the present paper: on one hand, figures and conclusions from that paper are reproduced in a way that seems redundant, on the other hand a description of the method used in that work, which is duplicated in the present one, is lacking so to force the reader to go to the original reference. I therefore suggest to briefly summarize the results AND methods presented in Ravindra Babu et al., and to skip fig.2.

Reply: The methodology explained in Ravindra Babu et al. (2015) is re-produced briefly in the current manuscript as suggested. Note that figure 2 is very important even for the current manuscript and thus retained.

Detailed comments:

lines 49-52: These sentences seems more to describe what the article is aimed for, than an introduction, The authors should support their claims with references, or the sentences should be made less assertive.

Reply: We have provided more references at the appropriate places as also mentioned by other reviewer.

61: Again, the assessment of the effectiveness of cyclones in promoting STE is the objective of the paper. References should be made to previous studies supporting this claim, or the sentence should be dropped, or reformulated to introduce the aim of the paper.

Reply: We have added relevant references for the text used in the present study at appropriate places.

62-63: The Stenke and Grewe paper deals mainly with the impact of water vapour increase on ozone chemistry. I did not find any claim of temperature increase induced by an increase of WV, there. On the contrary, there is a lot of modeling evidence (and even some experimental study, see as instance Maycock et al., Q. J. R. Meteorol. Soc., 2014), in the literature, that an increase stratospheric water vapor would lead to a cooling of stratospheric temperatures. So the sentence in the paper seems not correct.

Reply: We have corrected the sentence while adding suitable reference.

82, 86, 87,96: TC, MST, BoB, COSMIC, abbreviations have not been introduced earlier.

Reply: The abbreviations are elaborated when they appear for the first time in the revised manuscript.

91: The findings presented in Cairo et al. (2008) should be reported.
Reply: Reported.

128-134: Such information should be presented as a table.
Reply: We have added one more table with the classification of cyclones over north Indian Ocean as suggested.

139-140: This sentences is not clear. Is it suggesting that only long lasting cyclones have been selected in order to have enough MLS WV profiles in the cyclone area? This is quite an important point, and the average number of MLS profiles used should be quoted, maybe even in the form of a table, for each cyclone (the developing stage of the cyclone corresponding to the observations could also be accommodated there, see line 192). Moreover, I think it is worthwhile to discuss in further detail how the horizontal (given the spatial variability of the WV and ozone in the cyclone area) and vertical resolution of MLS are adequate to the goals of the paper.
Reply: We reported available MLS profile for each cyclone in the form of table in the revised manuscript.

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162-177 and fig. 2: I do not see the point to reproduce Fig.2, from Ravindra Babu et al. (2015), here. In 3.1 I do not see any novelty with respect to the analysis presented in that 2015 paper. The methodology and main results of that paper could be just shortly described and summarized.
Reply: It is well known that the tropopause characteristics play and important role in controlling the STE processes. Though the tropopause characteristics are mentioned in our earlier draft, we would like to retain figure 2 in this paper as it will be easy to refer the tropopause characteristics by the readers so that this paper will remain stand alone. This will also avoid going through our earlier paper as rightly mentioned by both the reviewers.

207-209: How robust is this feature in the data? Are all cyclones contributing to such enhancement?
Reply: It will change based on cyclone intensity. This will be more in the case of maximum intensity of cyclone such as SCS and VSCS category. Please see figure 5 for more details. Note that we calculated based on intensity and are not showed in the manuscript. However, our analysis confirms that the ozone is more in the case of VSCS compare other SCS and DD categories. During the VSCS time the ozone detrainment is reached to the 146 hPa level. Since the available profiles of MLS are less for different intensities so we combined all the profiles that are available within 1000 km from the centre of all 16 cyclones.

224 and 246: Cyclone winds can lose their axial symmetry near the top of the cyclone, and concentrate in one or two curved outflow jets. The authors may review the literature and see whether this can explain the upper level asymmetry in ozone and WV anomalies.
Reply: This is very important point that the cyclone winds play important role in the distribution of the water vapour and ozone above the cyclone. As mentioned earlier, the higher ozone mixing ratios are observed in the western and northwest side and more water vapour is located at the eastern side of the cyclone centre because of the upper

level anti-cyclonic circulation over the cyclones. This will push the water vapour towards the south and east side of the cyclone centre. In the other side of the cyclone, the detrainment of the lower stratospheric air may occur along with strong subsidence in the cyclone centre. This might be the region for higher ozone in the west and northwest side and more water vapour in the east and southeast side of the cyclone centre. Note that Ray and Rosenlof (2007) also reported higher water vapour mixing ratios in the east side of the cyclone centre for Atlantic and Pacific oceans. Further, very recently Reutter et al. (2015) reported that the more stratosphere-troposphere transport takes place in the west side of the cyclone centre due to west ward tilt of the cyclone with height. These aspects are mentioned in the revised manuscript.

294: the authors should dwell more on the method they used to estimate the term Fam. At present, it seems their choice of 0.5 hPa is quite arbitrary.

Reply: Since we do not have pressure variation with time we have assumed different pressures while considering minimum to maximum possible pressure variations, which is the best way when no observations are present.

299- 303: It seems this spatial asymmetry is a common, constant feature throughout the database ". . . the downward flux is always more. . ." . the authors should really dwell more on that, trying to find possible explanation in terms of the cyclone dynamics.

Reply: The tropopause flux is calculated for each cyclone maximum intensity day only so on the higher intensity time within 500 km from the cyclone centre the anti-cyclonic flow dominated and cause the upward flux in the east and southeast side. Whereas, subsidence dominating in the other side cause downward flux in the west and northwest side of the cyclone.

330: "intensify" for "intensity"? 330-339: It seems that (exactly) these results are already been reported in the quoted Ravidra Babu et al., 2015 paper. I do not understand why they are repeated here.

Reply: For completeness we have included these sentences in this paper also as someone may be interested to see the tropopause variations during these cyclones and to make this manuscript standalone we retained those statements and related figure.

364: "intensity" for "intense" ?
366: "effecting" for "affecting"?
Figure 1 caption, "strom" for "storm"

Reply: Corrected in the revised manuscript.

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Effect of tropical cyclones on the Stratosphere-Troposphere Exchange observed using satellite observations over north Indian Ocean

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Abstract

Tropical cyclones play an important role in modifying the tropopause structure and dynamics as well as stratosphere-troposphere exchange (STE) processes in the Upper Troposphere and Lower Stratosphere (UTLS) region. In the present study, the impact of cyclones that occurred over the North Indian Ocean during 2007-2013 on the STE processes is quantified using satellite observations. Tropopause characteristics during cyclones are obtained from the Global Positioning System (GPS) Radio Occultation (RO) measurements and ozone and water vapor concentrations in the UTLS region are obtained from Aura-Microwave Limb Sounder (MLS) satellite observations. The effect of cyclones on the tropopause parameters is observed to be more prominent within 500 km from the centre of the tropical cyclone. In our earlier study, we have observed decrease (increase) in the tropopause altitude (temperature) up to 0.6 km (3 K) and the convective outflow level increased up to 2 km. This change leads to a total increase in the tropical tropopause layer (TTL) thickness of 3 km within the 500 km from the centre of cyclone. Interestingly, an enhancement in the ozone mixing ratio in the upper troposphere is clearly noticed within 500 km from cyclone centre, whereas the enhancement in the water vapor in the lower stratosphere is more significant on south-east side extending from 500 -1000 km away from the cyclone centre. ~~We estimated~~ The~~the~~ cross-tropopause mass flux for different intensities of cyclones are estimated and found that the mean flux from the stratosphere to the troposphere for cyclonic storms is $0.05\pm0.29\times10^{-3}$ kg m^{-2} and for very severe cyclonic storms it is $0.5\pm1.07\times10^{-3}$ kg m^{-2}. More downward flux is noticed in the north-west and south-west side of the cyclone centre. These results indicate that the cyclones have significant impact in effecting the tropopause structure, ozone and water vapour budget and consequentially the STE in the UTLS region.

(**Key words:** Tropical cyclone, tropopause, ozone, water vapor, STE processes.)

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1. Introduction

The Ttropical cyclones with deep convective synoptic scale systems persisting for a few days to weeks and play an important role on the mass exchange between the troposphere and the stratosphere, and vice versa (Merril, 1998; Emmanuel, 2005). They transport large amount of water vapor, energy and momentum to the upper troposphere and lower stratosphere (UTLS) region (Ray and Rosenlof, 2007). Cyclones provide favorable conditions for entry of the water vapour-rich and ozone-poor air from surface to the lower stratosphere (LS) and water vapor- poor and ozone-rich air from the LS to the upper troposphere (UT) leading to the stratosphere-troposphere exchange (STE) (Romps and Kuang 2009; Zhan and Wang, 2012; Vogel et al., 2014). These exchanges occur mainly around the tropopause and change the thermal and chemical structure of the UTLS region. The concentration of the water vapour transported from troposphere to stratosphere is controlled by the cold temperatures present at the tropopause and this is a major factor in the STE (Fueglistaler et al., 2009). These As a consequence, the STE eventsSTE events play an important role in controlling the ozone inozone in the UTLS region, which will affect the radiation budget of the Earth atmosphere (Intergovernmental Panel on Climate Change, 1996).

Increase of water vapor in the LS region will leads to troposphere warming and stratospheric cooling might be due to lose ozone (Rind and Lonergan, 1995; Forster and Shine, 1999; Dvortsov and Solomon, 2001; Forster and Shine, 2002; Myhre et al., 2007; Intergovernmental Panel on Climate Change, 2007) . Even very small changes in lower stratospheric water vapor could affect the surface climate (Riese et al., 2012). Soloman et al. (2010) reported the relation between global warming and lower stratospheric water vapor. LS water vapor plays an important role on the distribution of ozone in the lower stratosphere (Shindell, 2001). It is important contributor for long term change in the LS temperatures (Maycock et al., 2014).

In general, most of the air enters into the stratosphere over the tropics (Brewer, 1949; Dobson, 1956). As suggested by Newell and Gould-Stewart (1981), Bay-of-Bengal (BoB) is one of the active regions where troposphere air enters into the stratosphere. It is also one of the active regions for the formation of deep convection associated cyclones which contains strong updrafts. Earlier studies have shown a close relationship between cyclones and moistening of the upper troposphere (Wang et al., 1995; Su et al., 2006; Ray and Rosenlof, 2007).

Several studies have been carried out related to water vapor, ozone transport as well as STE processes around the UTLS region during cyclones. Koteswaram (1967) described the thermal and wind structure of cyclones in the UTLS region with the major findings of cold core persisting just above the 15 km and the outflow jets very close to the tropopause. Penn (1965) reported enchantment in ozone and warmer air situated above the tropopause over the eye region during hurricane Ginny. Danielsen (1993) reported on troposphere-stratosphere transport and dehydration in the lower tropical stratosphere during cyclone period. Baray et al. (1999) studied the STE during cyclone Marlene and they observed maximum of ozone change at 300 hPa level. Zou and Wu (2005) observed the variations of columnar ozone in different stages of hurricane by using satellite measurements. Bellevue et al. (2007) observed increase in ozone concentration in the upper troposphere during Tropical Cyclone (TC) event. Significant contribution of cyclones on hydration of the UT is reported by Ray and Rosenlof (2007) and injection of tropospheric air into the low stratosphere due to overshooting convection by cyclones is reported by Romps and Kuang (2009). Das (2009) and Das et al. (2016) have studied the stratospheric intrusion into troposphere during the passage of cyclone by using Mesosphere-Stratosphere-Troposphere (MST) Radar observations. Strong enhancement of ozone in the upper troposphere is observed during TCs over BoB (Fadnavis et al., 2011). The increased ozone levels in the boundary layer as well as near surface by as much as 20 to 30 ppbv due to strong downward transport of ozone in the tropical convection is also observed (Betts et al., 2002; Sahu and Lal, 2006; Grant et al., 2008). Cairo et al. (2008) reported that the colder temperatures are observed in the Tropical Tropopause Layer (TTL) region during cyclone Davina and also reported on the impact of the TCs ~~on~~ in the UTLS region on the regional scales. A detailed review on the effect of TCs on the UTLS can be found in same report. RavindraBabu et al. (2015) reported the effect of cyclones on the tropical tropopause parameters using temperature profile obtained from Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) Global Position System Radio Occultation (GPS-~~–~~RO) ~~data~~measurements. Many studies have been carried out on the role of extra tropical cyclones on the STE (for example Reutter et al., 2015 and references therein) though the quantitative estimates of STE provided by these case studies varied considerably. However, the vertical and horizontal variation of ozone and water vapor in the UTLS region and cross-tropopause flux quantification during cyclones over north Indian Ocean is not well investigated.

In the present study, we investigate the spatial and vertical variations of ozone and water vapor in the UTLS region for all the cyclones occurred over north Indian Ocean during 2007 to 2013 by using Aura- Microwave Limb Sounder (MLS) satellite observations. The effect of cyclones on the tropopause characteristics is also presented using COSMIC GPS-RO measurements. We also present the cross-tropopause mass flux estimated for each of the cyclones.

2. Data and Methodology

In the present study, we used Aura –MLS water vapor and ozone measurements (version 3.3) provided by the Jet Propulsion Laboratory (JPL). The version 3.3 was released in January 2011 and this updated version has change in the vertical resolution. The vertical resolution of the water vapor is in the range 2.0 to 3.7 km from 316 to 0.22 hPa and along track horizontal resolution varies from 210 to 360 km for pressure greater than 4.6 hPa. For ozone, vertical resolution is ~2.5 km and the along track horizontal resolution varies between 300 and 450 km (Livesey et al., 2011). The Aura MLS gives around 3500 vertical profiles per day and it crosses the equator at ~1:40 am and ~1:40 pm local time. For calculating the cross-tropopause mass flux, we used ERA-Interim winds obtained during cyclone period. (1)

We have taken the cyclone track information data from India Meteorological Department (IMD) best track data from year 2007-2013. During this period, around 50 cyclones have formed over the north Indian Ocean. Due to the considerable variability of cyclone life-cycles, for the present study we selected only 16 cyclones that lasted for more than 4 days. Table 1 shows the classification of the cyclones over the North Indian Ocean. The TCs over the north Indian ocean are classified in different categories by IMD based on their maximum sustained wind speed. There are classified as : ~~as~~ (1) low pressure when the maximum sustained wind speed at the sea surface is < 17 knots (~~/~~32 km/hr~~ph,~~), ~~as~~ (2) depression (D) at 17–27 knots ~~/~~(32–50 ~~kmph~~km/hr), (3) deep depression (DD) at 28–33 knots ~~/~~(51–59 km/~~p~~hr), (4) cyclonic storm (CS) at 34– 47 knots (~~/~~60–90 km/~~p~~hr), (5) severe cyclonic storm (SCS) at 48–63 knots (~~/~~90–110 km/~~p~~hr), (6) very severe cyclonic storm (VSCS) at 64–119 knots ~~/~~(119–220 km/~~p~~hr), and (7) super cyclonic storm (SuCS) at > 119 knots ~~/~~(220 km/~~p~~hr) ~~respectively~~ (Pattnaik and RamaRao, 2008). The Table 2 shows the different cyclones used in the present study and their maximum intensity, ~~maximum~~ sustained time ~~for cyclone period~~, ~~maximum~~ and sustained time for peak intensity period of the each cyclone. ~~and the total available MLS profiles for each cyclone with respect to corresponding season.~~ The mean sustained time for cyclones that occurred during pre-monsoon season is 85.5 ± 52.4 hours, for monsoon season is 122 ± 46.5 and for post-monsoon season is 112.6 ± 29.47 hours. Out of the 16 cyclones, 4 cyclones (CS-1, SCS-2 and VSCS-1~~-~~) formed during pre-monsoon season, 3 cyclones formed during monsoon season

(CS-1, VSCS-1 and SuCS-1) and 9 cyclones (CS-1, SCS-2, and VSCS-6) formed during post-monsoon season (Table 2). Depressions and deep depressions are not considered. The total available MLS profiles for each cyclone that are used in the present study are mentioned listed in the Table 2. We have 94 ± 21 mean MLS profiles for each cyclone used in thein the present study and when segregated season wise, there are 108±6, 99±21 and 88±23 during monsoon, pre-monsoon and post-monsoon season, respectively. The available total MLS profiles for each cyclone vary with respect to sustained period of the cyclone and over-all we have 1517 MLS profiles within 1000 km from the cyclone centre from all the16 cyclones. Since there are (temporal) limitations in the satellite measurements, thus we considered mean cross--tropopause flux is estimated only for the those cases of the cyclones that lasted for more than 4 days. However, our quantification of the cross--tropopause flux will not be affected by this limitation as earlier studies revealed that the maximum STE occurs during mature to peak stage of cyclone. Details on the selection of 16 cyclones are presented in Ravindra Babu et al. (2015). The tracks of all the cyclones used for the present study are shown in Figure 1 and different colors indicate different categories of the cyclones.

2.1. Tropopause characteristics observed during cyclones

As mentioned earlier, in the tropical region the amount of water vapor transported in tointo the lower stratosphere from the troposphere is controlled by the cold tropical tropopause temperatures present at the tropopause (Fueglistaler et al., 2009). Large convection around the eye and strong updrafts near the eye-walls transports large amount of water vapor in tointo the lower stratosphere through the tropopause. In this way, cyclones will affect the tropopause structure (altitude/temperature). Thus, before quantification of STE, we show the tropopause characteristics observed during the TCs. We used post-processed products of level 2 dry temperature profiles with vertical resolution around 200 m provided by the COSMIC Data Analysis and Archival Center (CDAAC) for estimating the tropopause parameters during cyclones period from 2007-2013. COSMIC GPS RO is a constellation of six microsatellites equipped with GPS receivers (Anthes et al., 2008). We also used CHAllengingMinisatellite Payload (CHAMP) GPS RO data that are available between the years 2002 to 2006 and COSMIC data from 2007-2013 for getting background climatology of tropopause parameters over the north Indian Ocean.

Climatological mean of all the tropopause parameters are obtained by combining GPS RO measurements obtained from CHAMP and COSMIC (2002-2013). The tropopause parameters include cold~~-~~ point tropopause altitude (CPH) and temperature (CPT), lapse rate tropopause altitude (LRH) and temperature (LRT) and the thickness of the tropical tropopause layer (TTL), defined as the layer between convective outflow level (COH) and CPH and are calculated for each profile of GPS RO collected during the above mentioned period. First, we separated the available RO profiles with respect to distance away from the cyclone centre around 1000 km for individual cyclone for each day of the respective cyclone. After separating, we calculated the tropopause parameters as mentioned above for each RO profile. Then we separated the tropopause parameters with respect to the different cyclone intensity. After ~~getting~~ estimating the tropopause parameters for all the 16 TCs with respect to different intensity, ~~we made finally~~ cyclone-centre composite of all tropopause parameters is obtained. After careful analysis, ~~we~~ it is found that there is no much variation in the tropopause parameters observed between D and DD, and between CS and SCS, and ~~in the depression (D) and deep depression (DD), cyclonic storm (CS) and severe cyclonic storm (SCS) and t~~thus ~~we~~ they are combined ~~them as~~to DD and CS, respectively. To ~~quantify the~~quantify the effect of the ~~TCs on~~TCs on the tropopause ~~parameter~~characteristics, ~~we subtracted~~ the climatological mean is removed from the individual tropopause parameters. The climatological mean t~~ from the climatological mean of t~~ropopause parameters is calculated estimated from the temperature profiles obtained by using GPS RO data from 2002-2013. We also calculated the difference of tropopause parameters for different cyclone intensities (Figures are not shown). Figure 2 shows the cyclone centered – composite of mean difference in the tropopause parameters (CPH, LRH, CPT, LRT, COH and TTL thickness) between climatological mean (2002-2013) and individual tropopause parameters observed during cyclones (irrespective of cyclone intensity) and the more detailed results on effect of TCs on the tropopause variations and mean temperature structure in UTLS region during TCs can be found in Ravindra Babu et al. (2015). We have reported that the CPH (LRH) is lowered by 0.6 km (0.4 km) in most of the areas within the 500 km radius from the cyclone centre and the temperature (CPT/LRT) is more or less colder or equal to the climatological values from the area around 1000 km from the cyclone centre. Note that effect of cyclone can be felt up to 2000 km but since the latitudinal variation also comes into picture when we consider 2000 km radius, we restrict our discussion related to variability within 1000 km from the cyclone centre. COH (TTL thickness) has increased (reduced) up to 2 km within 500 km from the cyclones in some areas up to 1000 km. Note that this decrease in TTL thickness is not only because of pushing up of the COH but also due to decrease of CPH. From the above results, we concluded that the tropical tropopause is significantly affected by the cyclones and the effect is more prominent within 500 km from the cyclone centre. These changes in the tropopause parameters are expected to influence the water vapor and ozone transported in the UTLS region during cyclones.

3. Results and discussion

3.1. Ozone variability in the UTLS region during cyclones

To see the variability and the transport of ozone during the passage of cyclones, we investigated the spatial and vertical variability of ozone in the UTLS region using MLS satellite observations. As mentioned in Section 2.1, we also separated the MLS profiles based on the distance from the TC centre for each day of the individual cyclone. From all the 16 cyclones cases, we separated the available MLS profiles with respect to distance from the cyclone centre around 1000 km and also we separated the MLS profiles with respect to different intensities of the cyclones. ~~The total available MLS profiles for each cyclone are mentioned in Table 2.~~ Figure 3 shows the normalized cyclone centered – composite of mean ozone mixing ratio (OMR) observed during cyclones (irrespective of cyclone intensity) at 82 hPa, 100 hPa, 121 hPa, and 146 hPa pressure levels during 2007-2013. Note that we have reasonable number of MLS profiles (1517) from 16 cyclones to generate the meaningful cyclone-centre composite of ozone. Black circles are drawn to show distances 250 km, 500 km, 750 km and 1000 km away from cyclone center. Since large variability in OMR is noticed from one pressure level to other, we normalized the values to the highest OMR value at a given pressure level. The highest OMR values at 82 hPa, 100 hPa, 121 hPa and 146 hPa pressure levels is 0.38 ppmv, 0.28 ppmv, 0.19 ppmv and 0.13 ppmv, respectively. Large spatial variations in the OMR are observed with respect to the cyclone centre. At 82 hPa, higher OMR (~0.4 ppmv) in the South-West (SW) side up to 1000 km and comparatively low OMR values (~0.2 ppmv) are noticed in the north of the cyclone centre. At 100 hPa, an increase in the OMR (~0.2 ppmv) near the cyclone centre within 500 km is clearly observed. This enhancement in OMR extends up to 146 hPa and is more prominent slightly in the western and eastern side of the cyclone. In general, the large subsidence located at the top of the cyclone centre is expected to bring lower stratospheric ozone to the upper troposphere. This might be the reason for the enhancement of ozone in the cyclone centre within 500 km. Earlier several studies have reported that the intrusion of the stratospheric air in to the troposphere due to the subsidence in the eye region (Penn, 1965; Baray et al., 1999; Das et al., 2009; Das et al., 2015). ~~Our~~ The present results also support~~s~~ this aspect that the detrainment of ozone reached to the 146 hPa might be due to strong subsidence. Interestingly, an enhancement in OMR in south east side at 121 hPa but is not either at 100 hPa or at 146 hPa can be noticed which need to be investigated further. Thus in general, higher ozone concentrations are observed in cyclone centre within 500 km and slightly aligned to the western side of the cyclone centre.

In order to quantify the impact of cyclones on UTLS ozone more clearly we have obtained anomalies by subtracting the mean cyclone-centered ozone observed during cyclones from the background climatology of UTLS ozone that is calculated by using the total available MLS profiles from 2007-2013. Figure 3 (e-h) shows the normalized mean difference of cyclone-centered ozone obtained after removing the background climatology values for different pressure levels shown in Figure 3 (a-d). The maximum difference in OMR for corresponding normalized value at 82 hPa, 100 hPa, 121 hPa and 146 hPa pressure levels is -0.089 ppmv, -0.19 ppmv, -0.09 ppmv and -0.06 ppmv, respectively. Enhancement in the OMR (~0.1 ppmv) up to 1000 km from the cyclone centre is observed at 82 hPa. Interestingly, at 100 hPa OMR is more or less uniform throughout 1000 km from the cyclone centre except ~500 km radius from the centre where significant increase of OMR (~0.2 ppmv) is observed. This increase in the OMR is within 500 km from cyclone centre and extends up to 121 hPa. However, enhancement in OMR at 146 hPa extends up to 1000 km but distributed towards eastern and western sides of cyclone centre. Thus, it is clear that the detrainment of lower stratospheric ozone will reach up to 146 hPa during cyclone period due to presence of strong subsidence in the cyclone centre. We also calculated the cyclone-centre composite of ozone based on different cyclone intensities such as DD, SCS and VSCS. After ~~carfully~~carefully going through them, we have found that this detrainment of ozone reaching up to 146 hPa is more in the higher intensity period of the TCs. We do not know what happens below this pressure level due to limitation in the present data, however, studies (Das et al., 2015; Jiang et al., 2015) have shown that LS ozone can reach low as boundary layer during cyclones. It will be interesting to see the variability in the water vapor as large amount of it is expected to cross the tropopause during the cyclone period and reach lower stratosphere.

3.2. Water vapor variability in the UTLS region during cyclones

As mentioned earlier, enormous amount of water vapor is expected to be pumped from lower troposphere to the upper troposphere and even it can penetrate into ~~up to the~~the lower stratosphere during cyclones. To see the linkage between tropopause variability and the transport of water vapor during cyclones, we investigated the horizontal and vertical variability of water vapor in the UTLS region using ~~same~~ MLS satellite observations. Figure 4 shows the normalized cyclone centered – composite of mean water vapor mixing ratio observed during cyclones (irrespective of cyclone intensity) at 82 hPa, 100 hPa, 121 hPa, and 146 hPa pressure levels observed by MLS during 2007-2013. Black circles are drawn to shown the 250 km, 500 km, 750 km and 1000 km away from cyclone center. The highest Water Vapor Mixing Ratio (WVMR) values for corresponding normalized value at 82 hPa, 100 hPa, 121 hPa, and 146 hPa pressure levels is 4.44 ppmv, 4.49 ppmv, 6.9 ppmv and 16.03 ppmv, respectively. Significantly higher WVMR values are noticed extending from 500 km up to 1000 km from the cyclone centre at 121 (~6.5 ppmv), 146 hPa (~15 ppmv) levels with more prominence in the eastern side of the cyclone centre. Comparatively low values are noticed in the centre of the cyclone, especially at 121 hPa. These results ~~match~~ comparing well with higher WVMR observed in the eastern side of cyclones over Atlantic and Pacific Oceans (Ray and Rosenlof, 2007). These results also ~~match~~ compare well with those reported by Ravindra Babu et al. (2015) where they used GPS RO measured relative humidity and found enhancement in RH in the eastern side of the centre in the upper troposphere (10-15 km) over north Indian Ocean. The higher WVMR values are observed in the eastern side of the cyclone centre might be due to the upper level anti-cyclonic circulation over the cyclones.

It is interesting to note that high WVMR lies not at the centre but extend from 500 to 1000 km from the centre of cyclone. The WVMR show high at 121 and 146 hPa than at 100 and 82 hPa. It seems less water vapor has been transported to 100 and 82 hPa from below. As we know, water vapor mostly origin from lower troposphere and decreasing with height. So vertical transport of water vapor from the lower troposphere to the UTLS may lead to water vapor enhanced at 121 and 146 hPa and some time it reaches to higher altitudes. The higher WVMR presented at 100 and 82 hPa levels show the signature of the tropospheric air entering even in to the lower stratosphere during cyclones.

In order to quantify the impact of cyclones on the UTLS water vapor more clearly, we have obtained anomalies by subtracting the mean cyclone-centered water vapor observed during cyclones from the background climatology mean of UTLS water vapor. Figure 4 (e-h) shows the normalized mean difference of the cyclone-centered WVMR obtained after removing the background climatology values for different pressure levels shown in Figure 4 (a-d). The maximum difference in WVMR for corresponding normalized values at 82 hPa, 100 hPa, 121 hPa, and 146 hPa pressure levels is -0.44 ppmv, -0.81 ppmv, -2.55 ppmv and -9.09 ppmv, respectively. More than 7 ppmv differences are observed at 146 hPa within the 1000 km from the centre and at 121 hPa difference of ~ 2 ppmv is noticed extending up to 2000 km (figure not shown) in the eastern side of the centre. At 100 hPa and 82 hPa levels, the increase in the WVMR is ~0.8 and ~0.6 ppmv, respectively, and the enhancement is more observed in the NE side of the cyclone centre. Thus, a clear ~~stratosphere–troposphere exchange (STE)~~STE is evident during the cyclone over north Indian Ocean where a clear enhancement in the water vapor (ozone) in the lower stratosphere (upper troposphere) is observed. For quantifying the amount of STE, we calculated the cross-tropopause mass flux for each cyclone by considering the spatial extent within the 500 km from the cyclone centre and results are presented in the following sub-section.

3.3. Cross tropopause flux observed during cyclones

We adopted method given by Wie (1987) to estimate the cross tropopause mass flux, F. F is defined as:

$$F = \frac{1}{g}\left(-\omega + V_h.\nabla P_{tp} + \frac{\partial P_{tp}}{\partial t}\right) = \left(-\frac{\omega}{g} + \frac{1}{g}V_h.\nabla P_{tp}\right) + \frac{1}{g}\frac{\partial P_{tp}}{\partial t} = F_{AM} + F_{TM} \qquad (1)$$

where ω is the vertical pressure-velocity, V_h is the horizontal vector wind, P_{tp} is the pressure at the tropopause, g is the acceleration due to gravity, F_{AM} is the air mass exchange due to horizontal and vertical air motions, F_{TM} is the air mass exchange due to tropopause motion.

The wind information is taken from ERA-Interim, and the tropopause temperature and pressure tropopause pressure and corresponding tropopuase temperature within 500 km from the cyclone centre is taken estimated from COSMIC GPS RO measurements (Ravindra Babu et al., 2015). These values are considered for the maximum intensity day for each of the 16 cyclones and calculated the respective cross tropopause flux is estimated. . Since the above mentioned results showed that the higher OMR values are observed in the west and NW side and more water vapor is located at the eastern side of the cyclone centre, we separated the area into 4 sectors with respect to cyclone centre as C1 (NW side), C2 (NE side), C3 (SW side), and C4 (SE side), respectively which areas shown in Figure 3(a). List of cyclones Table 3 presents the different cyclones used in the present study with their names, cyclone intensity (CI), centre latitude, centre longitude, minimum estimated central pressure on their peak intensify day are provided in Table 3. The total flux F (equation 1) depends on the air mass exchange due to horizontal and vertical air motion (F_{AM}), and the air mass exchange due to tropopause motion itself (F_{TM}). Since number of COSMIC GPS RO measurements are not sufficient to estimate the second term (F_{TM}) for each event, we calculated only the first part of the equation (F_{AM}) individually for each of cyclone with respect to different sectors mentioned above and the values are presented in Table 3. However, we roughly estimated the contribution of second term by assuming change in the tropopause pressure by 0.5 hPa increase (decrease) within 6 hr and could see cross-tropopause flux for CS is 0.25±0.07 x10^{-3} kg m^{-2} s^{-1}(-0.36±0.07x10^{-3} kg m^{-2} s^{-1}) and for VSCS it is -0.24±0.3x10^{-3} kg m^{-2} s^{-1} (-0.85±0.3x10^{-3} kg m^{-2} s^{-1}). If there is change in the tropopause pressure by 1 hPa increase (decrease), the flux for CS is 0.55±0.07x10^{-3} kg m^{-2} s^{-1} (-0.66±0.07x10^{-3}kg m^{-2} s^{-1}) and for VSCS it is 0.06±0.3x10^{-3}kg m^{-2} s^{-1} (-1.16±0.3x10^{-3} kg m^{-2} s^{-1}).

Figure 5 shows the cross-tropopause flux estimated in ~~the C1 (NW), C2 (NE), C3 (SW), and C4 (SE)~~ each sector~~s~~ from the centre of the cyclone for the different cyclone intensities (estimated based on the cyclone centre pressure). Red lines show the best fit. It clearly shows that the downward flux is always more in C1 and C3 sectors, ~~where as~~whereas C2 sector show more upward flux. The flux itself varies with the cyclone intensity and ~~we could see an~~it is found that the increase in ~~the~~ downward flux as the cyclone centre pressure decreases particularly ~~during~~ for C1 and C3 sectors. Whereas, in ~~the~~ C4 sector, increase in the upward flux is seen as the cyclone intensity increases but always upward in ~~the~~ C2 sector, irrespective of the cyclone intensity. The second term (in equation 1) itself corresponds the air mass exchange from the tropopause motion and generally during cyclone period there is an ~400 m difference in tropopause altitude (LRH) within 500 km from the centre of the cyclone (Figure 2). Thus, the spatial and temporal variation of the tropopause during the cyclones itself is very important for to decide the flux as downward or upward. Interestingly, C1 ~~(NW)~~ and C3 ~~(SW)~~ sectors of cyclone show dominant downward mean flux and C2 ~~(NE)~~ and C4 ~~(SE)~~ sectors show dominant upward mean flux with the values of 0.4±0.4×10^{-3} kg m^{-2}, 1.2±1.0×10^{-3}kgm^{-2}, 0.2±0.1×10^{-3} kg m^{-2} and 0.12±0.3x10^{-3} kg m^{-2}, respectively. These results strongly support our findings of higher ozone in the NW and SW sides and higher water vapor in the NE side of the cyclone centre. The mean flux is observed to vary with the intensity of the cyclone. Mean flux for the severe cyclonic storms (CS) is -0.05±0.29×10^{-3}kg m^{-2} whereas for very severe cyclonic storms (VSCS) it is -0.5±1.07×10^{-3}kgm^{-2}. Reutter et al.

(2015) reported the upward and downward mass fluxes across the tropopause are more dominant in a deeper cyclones compared to a less intense cyclones ~~for~~ over the North Atlantic~~-cyclones~~. Our results are ~~match~~ comparable~~fairly well~~ with their results with the averaged mass flux of the stratosphere to troposphere as 0.3×10^{-3} kg m^{-2} s^{-1} (340 kg km^{-2} s^{-1}) in the vicinity of cyclones over the North Atlantic Ocean. They also reported that the more transport across the tropopause occurred in the west side of the cyclone centre during intensifying and mature stages of the cyclones over the North Atlantic- region~~cyclones~~.

4. Summary and conclusions

In this study, we have investigated the vertical and spatial variability of ozone and water vapor in the UTLS region during the passage of cyclones occurred between 2007 and 2013 over the North Indian Ocean by using Aura- MLS satellite observations. In order to make quantitative estimate of the impact of cyclones on the ozone and water vapor budget in the UTLS region, we removed the mean cyclone-centre ozone and water vapor from the climatological mean calculated using MLS data from 2007 to 2013. We estimated the mean cross- tropopause flux for each of the cyclones on their peak intensity day. The ~~M~~main findings are summarized below.

1. Lowering of the CPH (0.6 km) and LRH (0.4 km) values with the coldest CPT and LRT (2–3 K) within a 500 km radius from the cyclone centre is noticed. Higher (2 km) COH leading to the lowering of TTL thickness (~3 km) is clearly observed (Ravindra Babu et al., 2015).
2. The impact of cyclones on ~~the~~ ozone and the tropopause (altitude/temperature) is more prominent within 500 km from the cyclone centre, whereas it is high from 500 km to 1000 km in case of water vapor.

3. Detrainment of ozone is highest in the cyclone centre (within 500 km from the centre) due to strong subsidence over top of the cyclone centre and this detrained ozone reaches as low as 146 hPa level (~13-14 km).
4. The detrainment of ozone is more in the higher intensity period (SCS or VSCS) of the cyclone compare to the low intensity (D or DD).
5. Interestingly, significant enhancement in the lower ~~stratosphere~~ stratospheric (82 hPa) water vapor is noticed in the east and ~~SE~~ southeast side from the cyclone centre.
6. Dominant downward [upward] cross-tropopause flux is observed in ~~the~~ C1 (NW) and C3 (SW)[C2 (NE) and C4 (SE)] sectors of the cyclone.

Figure 6 depicts above mentioned results in the form of the schematic diagram. The tropopause altitude (CPH) is lowered by 0.6 km within 500 km from the centre of the cyclone. The convective out flow level (COH) slightly pushes up (~2 km) with in 500 km from the centre of the cyclone but not exactly in the centre. Thus, a decrease of about 3 km in the TTL thickness is observed within the 500 km from the cyclone centre. Cyclone includes eye that extends from few km to 10's of kilometers. Strong convective towers with strong updrafts extending up to the tropopause ~~altitude~~ in the form of spiral bands extending from 500 to 1000 km are present. Strong water vapor transport in to the lower stratosphere (82 hPa) while pushing up the COH is observed around these spiral bands in the present study. Between these spiral bands equal amount of subsidence is expected with strong subsidence existing at the centre of the cyclone. Significant detrainment of ozone present above or advected from the surroundings is observed reaching as low as 146 hPa at the cyclones centre. Thus, it is clear that ozone reaches upper troposphere from lower stratosphere through the centre of the cyclone, whereas water vapor transport in to the lower stratosphere will happen from the 500 to 1000 km from the cyclones centre. Since more intense cyclones are expected to occur in a changing climate (Kuntson et al., 2010), the amount of water vapor and ozone reaching to the lower stratosphere and upper troposphere, respectively, is expected to increase thus affecting complete tropospheric weather and climate. Future studies should focus on these trends.

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Table:

Table1. IMD classification of cyclonic systems over the north Indian Ocean.

Intensity of the system	Maximum sustained surface winds (knots) at sea (1 knot =0.5144 m/s)
Low pressure area	<17
Depression	17–27
Deep depression (DD)	28–33
Cyclonic storm (CS)	34-47
Severe cyclonic storm (SCS)	48-63
Very severe cyclonic storm (VSCS)	64–119
Super cyclonic storm (SuCS)	>119

Table 2. Tropical cyclones occurred during different seasons, cyclone name, cyclone Intensity (CI), cyclone period, total sustained time, Sustained time with maximum intensity and total number of available MLS profiles.

Season	**Cyclone Name**	**Cyclone Intensity (CI)**	**Cyclone Period (days)**	**Total Sustained time**	**Sustained Time with maximum intensity**	**Total available MLS profiles**
Monsoon (JJA)	03B	CS	>4	75	6	104
	PHET	VSCS	>4	168	42	116
	Gonu	ScCS	>4	123	72	105
Pre-Monsoon (MAM)	Mahasen	CS	>4	24	24	119
	Aila	SCS	4	72	9	79
	Laila	SCS	4	96	27	82
	Nargis	VSCS	>4	150	87	118
Post-Monsoon (SON)	Nilam	CS	>4	102	36	52
	Jal	SCS	4	99	30	75
	Helen	SCS	4	78	30	72
	Giri	VSCS	4	66	15	65
	Phailin	VSCS	>4	147	66	111
	Leher	VSCS	>4	114	36	111
	SIDR	VSCS	>4	138	72	114
Winter (DJF)	Madi	VSCS	>4	150	36	104
	Thane	VSCS	>4	120	36	90

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Table 3. Cyclone name, cyclone Intensity (CI), centre latitude, centre longitude, estimated central pressure and estimated cross-tropopause mass flux with respect to cyclone centre for C1 (NW side), C2 (NE side), C3 (SW side) and C4 (SE side), respectively.

					Flux @500km			
Cyclone	CI	Centre Latitude	Centre Longitude	Estimated Central Pressure (hPa)	C1	C2	C3	C4
03B	CS	23.5	66	986 (25Jun2007)	-0.013	0.661	-0.603	-0.258
Aila	SCS	22	88	968 (25May2009)	1.90E-04	0.191	-0.299	-0.072
Helen	SCS	16.1	82.7	990 (21Nov2013)	0.025	0.216	-0.095	-0.11
Jal	SCS	11	84	988(6Nov2010)	0.025	0.384	-0.4	-0.218
Laila	SCS	14.5	81	986 (19May2010)	-0.012	0.123	-0.352	-0.299
Mahasen	CS	18.5	88.5	990 (15May2013)	-0.006	0.354	-0.473	-0.256
Nilam	CS	11.5	81	990 (31Oct2012)	0.016	0.313	-0.274	-0.097
Nargis	VSCS	16	94	962 (2May2008)	-0.828	0.094	-1.946	0.384
Giri	VSCS	19.8	93.5	950 (22Oct2010)	-0.518	0.022	-0.823	0.032
Gonu	SuCS	20	64	920 (4Jun2007)	-0.502	0.123	-2.563	0.37
Lehar	VSCS	13.2	87.5	980 (26Nov2013)	-0.55	0.119	-2.019	0.411
Madi	VSCS	13.4	84.7	986 (10Dec2013)	-0.375	0.054	-1.449	0.352
Phailin	VSCS	18.1	85.7	940 (11Oct2013)	-0.9	0.179	-2.576	0.479
Phet	VSCS	18	60.5	964 (2Jun2010)	-1.058	0.203	-2.698	0.559
SIDR	VSCS	19.5	89	944 (15Nov2007)	-0.493	0.066	-0.926	0.231
Thane	VSCS	11.8	80.6	970 (29Dec2011)	-1.272	0.356	-2.979	0.558

Figure captions:

Figure 1. Tropical cyclone tracks of different categories (cyclonic storm (CS, blue color), severe cyclonic storm (SCS, orange color), very severe cyclonic storm (VSCS, red color) and super cyclonic storm (SuCs, magenta color)) that occurred over North Indian Ocean during 2007 - 2013.

Figure 2. Cyclone centered – composite of mean difference in the tropopause parameters between climatological mean (2002~~7~~-2013) and individual tropopause parameters observed during cyclones(irrespective of cyclone intensity) in (a) CPH (km), (b) LRH (km), (c) CPT (K), (d) LRT (K), (e) COH (km) and (f) TTL thickness (km). Black circles are drawn to show the 250 km, 500 km, 750 km and 1000 km away from cyclone center.

Figure 3. Normalizedcyclone centered – composite of mean ozone mixing ratio observed during cyclones (irrespective of cyclone intensity) at (a) 82hPa, (b) 100hPa, (c) 121hPa, (d) 146 hPa levels by MLS during 2007-2013. (e) to (h) same as (a) to (d) but for normalized mean difference in the ozone mixing ratio between climatological mean (2007-2013) and individual events. Black circles are drawn to show the 250 km, 500 km, 750 km and 1000 km away from cyclone center. Sectors showing C1 (NW), C2 (NE), C3 (SW) and C4 (SE) are also shown in (a).

Figure 4. Same as Fig. 3, but for water vapor mixing ratio.

Figure 5. Cross-tropopause flux estimated in the (a) C1 (NW), (b) C2 (NE), (c) C3 (SW), and (d) C4 (SE) sectors from the centre of cyclone for different cyclone intensities (estimated based on cyclone centre pressure). Red lines show the best fit.

Figure 6. Schematic diagram showing the variability of CPH (brown color line) and COH (magenta color line) with respect to the centre of cyclone. Spiral bands of convective towers reaching as high as COH are shown with blue color lines. Light blue (red) color up

(down) side arrow shows the up drafts (downdrafts/subsidence). Thickness of the arrows indicates the intensity.

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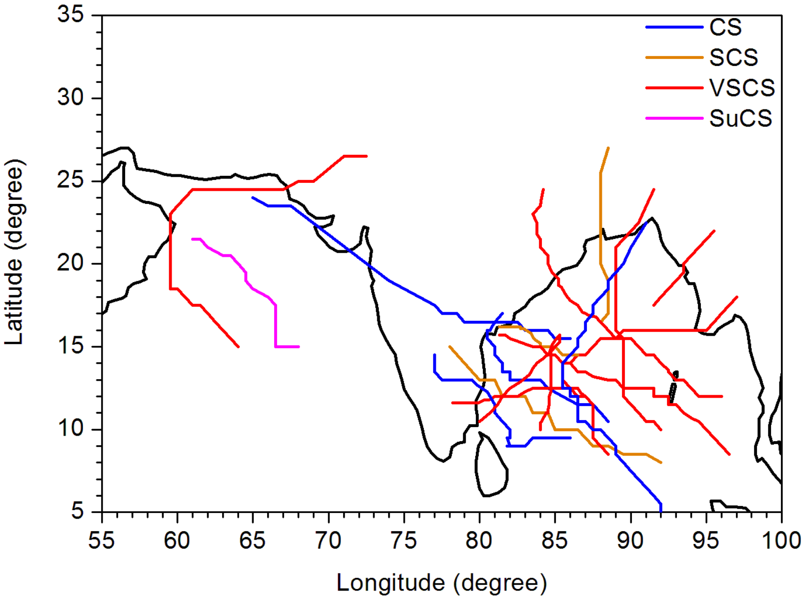
Figures:



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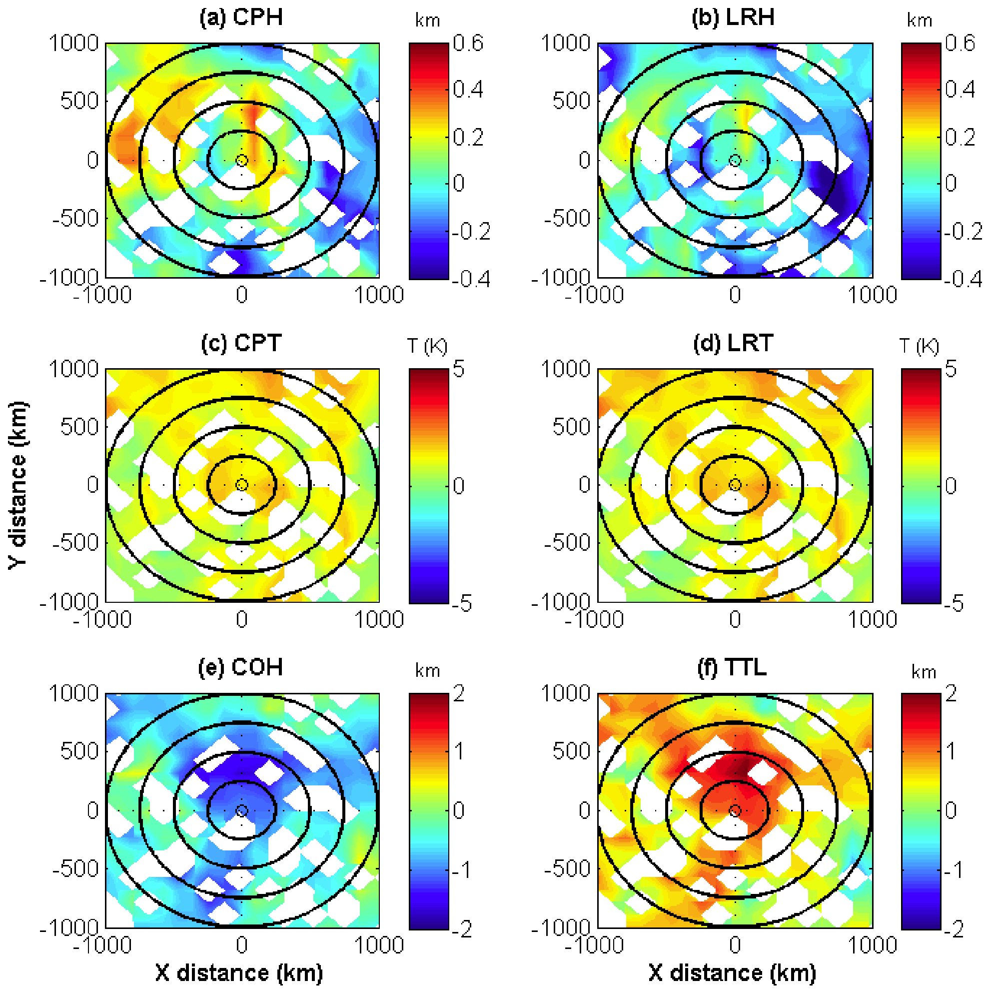

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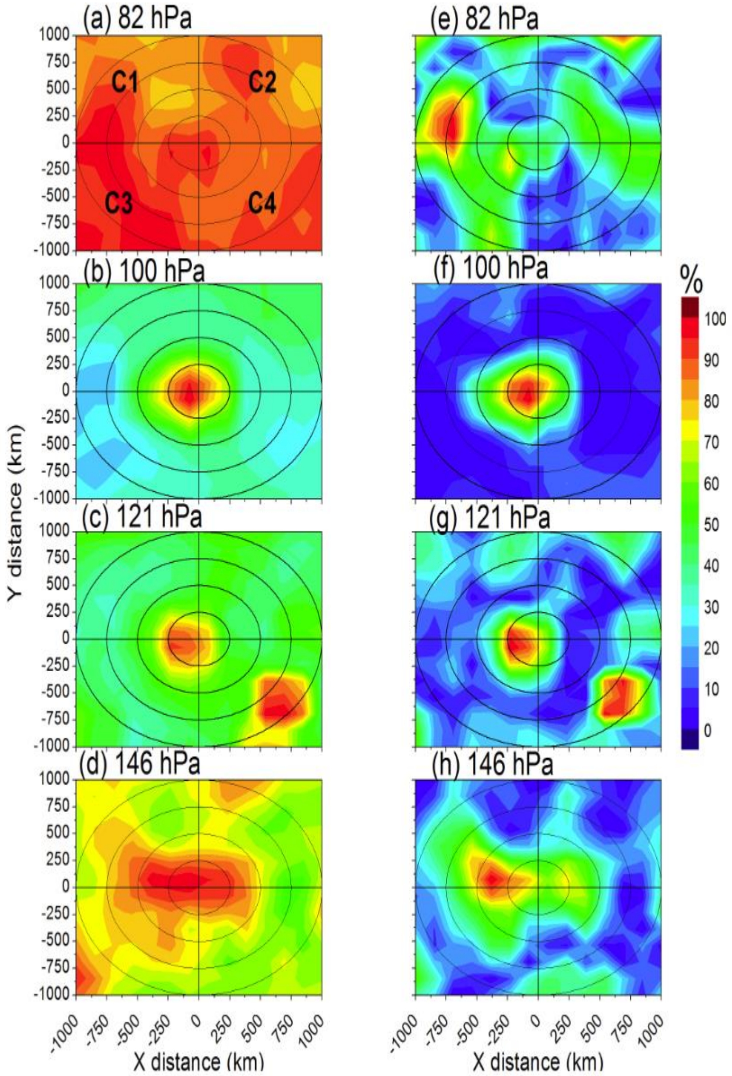

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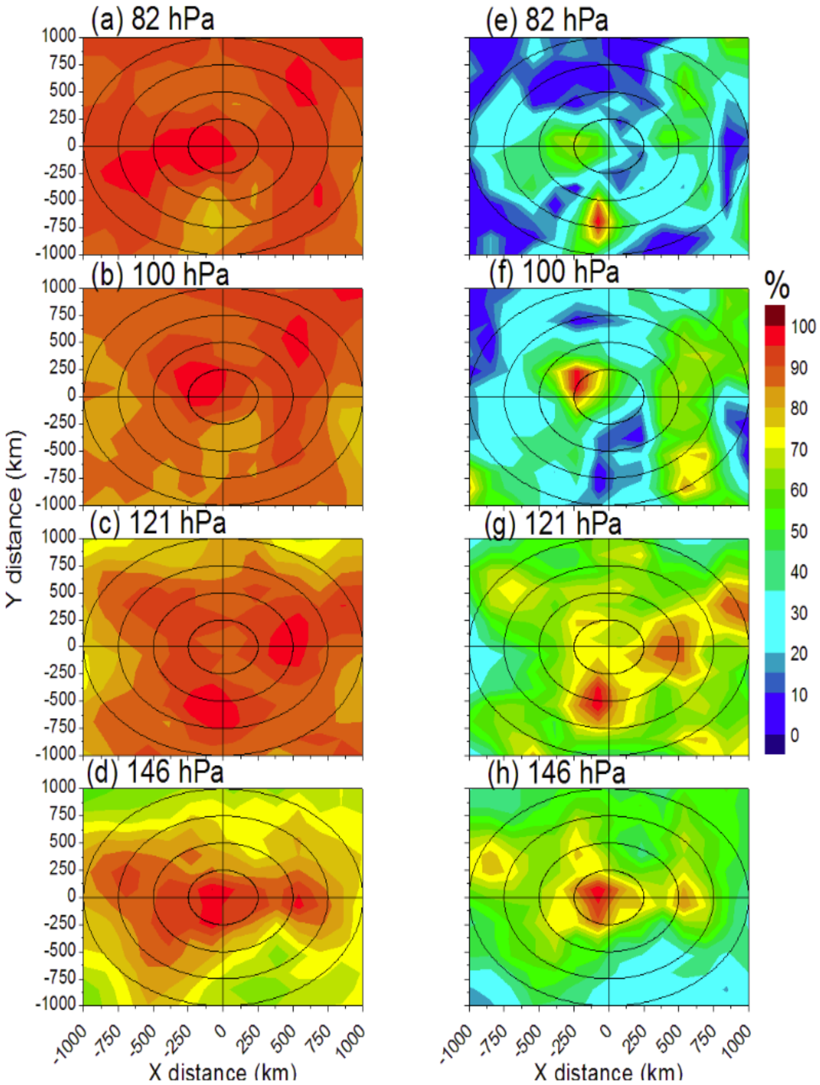

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1040 **Figure 4.**Same as Fig. 3, but for water vapor mixing ratio.

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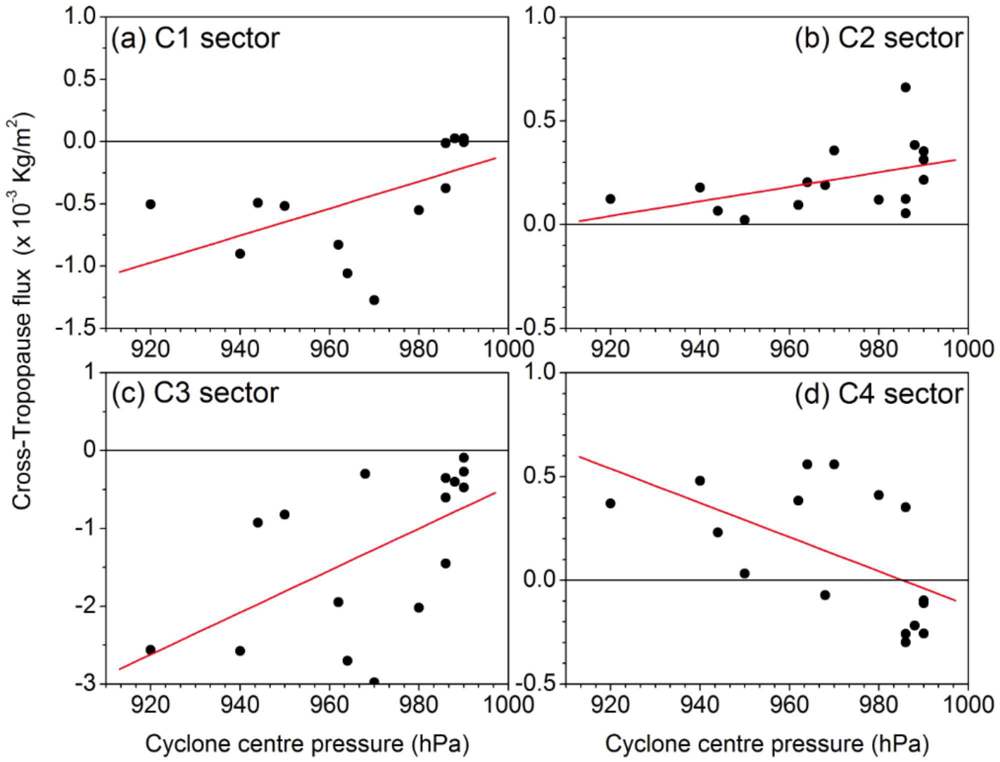

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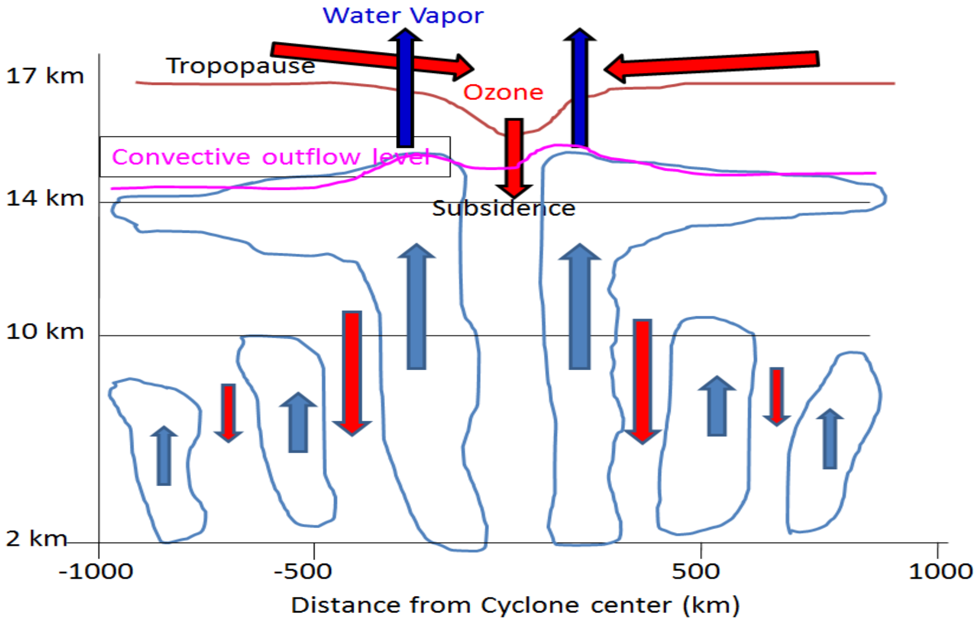

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