Response to Referee #1's Comments

Influence of tropical cyclones on tropospheric ozone: possible implication By Das et al.
This paper presents ozonesonde observations in southern India for two tropical cyclonecases. For both cases, 5-6 ozonesonde profiles during 5-9 days show an ozoneenhanced layer that (seems to have) descended from the upper troposphere to lowertroposphere during the observation period at the rate of about 1 km/day. As additionalsources of information, numerical simulations using the WRF model and microwavesatellite tropospheric humidity data are also presented. The authors conclude that theenhanced ozone layer was originated from the stratosphere in association with thetropical cyclone activity.The ozone observation results are very interesting, and the hypothesis that the observed ozone layer was associated with the tropical cyclone activity is also very interesting.However, I think that the authors need more data analysis to confirm that theirconclusions are really supported by all the available data and information. I do notthink that in the current manuscript, the hypothesis has been proved correct.

Response : We would like to sincerely thank the anonymous referee for very positive evaluation and constructive comments/suggestion for the improvement of the manuscript.

Point-by-point responses on how we have addressed each recommendations/suggestions are given below. Please note that manuscript is also altered in view of reviewer - 2 and 3's comments and suggestions.

In thefollowing, I write the key questions.
(1) In Introduction, the authors just cite some papers that discuss possible roles of tropicalcyclones in the stratosphere-troposphere exchange. Add more specific discussion,based on previous works (including those discussing the dynamical and thermodynamicalstructure of tropical cyclones), how tropical cyclones could work for transport oflower stratospheric air into the troposphere. ***What is a horizontal scale of such a transport****?At the core (or the eye) of the tropical cyclones, there might exist a net downwardtransport. But, what the ozone observations showed might be of much larger horizontalscale, including the outer region of a tropical cyclone, and thus related to other flowstructures of the tropical cyclones. Also, does the descent rate of 1 km/day correspondto, for example, the subsidence in non-convective tropical region by radiative cooling?*

Response : Introduction is elaborated in view of

- **(i) dynamical and thermodynamical structure of tropical cyclone with references**
- **(ii) Mechanism for transport of lower stratospheric air into the troposphere**
- **(iii) We do not have many observations to comments on its horizontal scale. However, using simulation it was found that the horizontal scale is about 50 km X 250 km (Das et al., 2011).**
- **(iv) We do not have observations of stratospheric intrusion during non-convective days for estimating descend rate.**

(2) Reanalysis data and numerical simulation data can be used to make trajectorycalculations. I think that trajectory calculations are necessary to show the origin ofthe ozone enhanced layer and to prove that the layers at different altitudes in differentsoundings are actually an identical layer.

Response : We thank referee for the suggestion. We have tried to do the back trajectories (ARL/NOAA HYSPLIT) analysis but could not able to capture event. This may be due to the poor temporal and spatial resolution of the reanalysis data (input).

(3) It seems to me that the dates of the numerical simulation results shown in Figure 3 and of the satellite humidity data shown in Figure 4 do not correspond well to those for ozonesonde observations shown in Figure 2. For example, for the Nilam case in 2012,ozonesonde data are from 30 October to 7 November, while the

numerical simulationresults are on 30 October for a snapshot and from 27 October to 2 November for the time series. The satellite data are shown on 25 October, with the time series for15 October to 10 November. I am puzzled at the choice of these dates. Therefore, the question about whether the layers at different altitudes in different soundings areactually an identical layer or not cannot be readily answered.

Response : The ozonesonde observation for Nilam is from 30 October to 7 November 2012. The time-series for Nilam showing in (right panel) Fig.3(c) and 3 (d) (RH) is from 27 October to 2 November 2012, which is well within the observations. To minimized the number of similar figure, we have only shown one set of figure (Figure 3(a) and 3(b)) on 30 October 2012 over the ozonesonde observation site (Trivandrum).

Similarly, the ozonesonde observations for Phailin are from 11-15 October 2013. The time-series for Phailin in shown in Figure 4(c) and 4(d) are from 7-12 October 2013, which is well within the observation period. In addition we have shown one example of height-latitude cross-section on 10 October 2013 over Trivandrum.

Similar methodology is adapted for satellite observations. To avoid the confusion, we have split the Fig.3 and 4 (old manuscript) in two different parts.

(4) The surface ozone actually showed a step-like change in the behavior in Figure 2.However, there are several factors that control the surface ozone (as the authors haveacknowledged), and I think that more discussion is needed to attribute the elevatednight-time ozone and elevated daytime ozone to the ozone transport from the above.For example, after the passage of a tropical cyclone, stronger sunshine and higherhuman activities might lead to elevated daytime surface ozone, and prevailing oceanicair-mass following the cyclone might lead to weaker destruction of surface ozone atnight-time. I think there are several previous publications that discuss diurnal variationsof surface ozone around the tropical coastal regions, which would be helpful for the interpretation of the current results.

Response : Thank you for the suggestions.
We have discussed the changes in sunshine in the revised manuscript. Along with the surface-ozone variation, we have show the time series of ground-reaching total solar radiation (Please see the Figure below). This shows that there was not much change in the radiation among the days 11-13 and 14-17 October 2013. Thus, this indicates that the observed enhancement was not due to change in sunshine. At the Trivandrum station, ozone remains to its daytime value even after evening hours until the onset of land-breeze (David and Nair, 2011) and do not increase in the evening hours. Interestingly, the enhancement observed on 14 October is during evening hours (16-17 hours) where solar radiation is very low or even zero. (Discussion with the reference including the diurnal variability of surface ozone is made in the revised manuscript).
Over the site, land-breeze prevails during night-time. The change in night-time ozone depends on the precursor gas (e.g. NO) concentration in land-breeze, which has dependency on local precursor gas emission/human activity. Change in human activity during 11-17 October would not have happened considerably and these may not be Bio-mass burning due to rain associated with cyclone. However, the possibility of change of human activity cannot be denied fully. The day-to-day variability of surface ozone over Trivandrum is ~ 9.5 ppbv (1-sigma standard deviation). The observed enhancement of about 10 ppbv in the day-time and 10-15 ppbv in the nigh-time is above the day-to-day variability which is attributed due to the transport from the UTLS region. However, other possibility of this enhancement cannot be fully ruled out.

There are few studies which clearly proven the enhancement of surface ozone due to intrusion of stratospheric into the troposphere associated with severe weather condition (*Stohl et al*., 2000; *Jiang et al*., 2015).

Minor comments.

Technical description is also necessary for the IMD's ozonesonde. Also, are there any intercomparison results between the ECC ozonesonde and IMD ozonesonde?

Response : We thank referee for the suggestion. Now we have incorporated in the revised manuscript.

For the WRF simulations, is the domain for 60 km horizontal resolution from 1S to 25N and 60E to 100E? How about the domain for 20 km horizontal resolution? Also, is the 20 km horizontal resolution appropriate for a tropical cyclone simulation? Cite some papers to discuss the ability and limitation with this setting for a tropical cyclone simulation.

Response : The model domain has been configured with two nested domains of 60 and 20 km horizontal resolution. The inner domain is 20 km and thus it is the horizontal resolution for 1°S to 25°N and 60°E to 100°E. To see the gross-features, 20 km horizontal resolution is appropriate. We have earlier carried out with two nested domains of 81 km and 27 km (Das et al., 2011; Pan et al., 2015).

References :

Das, S.S., Sijikumar, S., Uma, K.N., 2011.: Further investigation on stratospheric air intrusion into the troposphere during the episode of tropical cyclone: Numerical simulation and MST radar observations, Atmos. Res., 101, 928-937.

Jiang, Y. C., Zhao, T. L., Liu, J., Xu, X. D., Tan, C. H., Cheng, X. H., Bi, X. Y., Gan, J. B., You, J. F., and Zhao, S. Z., 2015: Why does surface ozone peak before a typhoon landing in southeast China?, Atmos. Chem. Phys., 15, 13331-13338, doi:10.5194/acp-15-13331-2015.

Stohl, A., Wernli, H., Bourqui, M., Forster, C., James, P., Liniger, M. A., Seibert, P., and Sprenger, M., 2003.: A new perspective of stratosphere-troposphere exchange. Bull. Am. Met. Soc. 84, 1565-1573.70, doi: http://dx.doi.org/10.1175/BAMS-84-11-1565.

Pan, L.L. et al., 2015.: Thunderstorms enhance tropospheric ozone by wrapping and shedding stratospheric air, Geophy. Res. Lett., 41, 7785-7790, doi : 10.1002/2014gl061921.

Response to Referee #2's Comments

The paper "Influence of tropical cyclones on tropospheric ozone: possible implication" by Das. S. S. et al. discusses the role tropical cyclones may play in controlling tropospheric ozone level. The paper is based on the analysis of ozone and humidity measurements in the vicinity of two tropical cyclones which occurred in the Bay of Bengal in 2012 and 2013. The paper also takes advantage of a series of WRF simulations which describes the dynamical field in the vicinity of the cyclones. Understanding the role of tropical convection in the stratosphere to troposphere exchange is certainly a scientific question which falls well within the scope of ACP. This is made even more interesting by the impact these processes could have on near surface conditions. Although studies of this kind are not knew the authors present results of two cyclones which could potential add relevant information on these exchange processes. Das S. et Al. also appear to reach quite substantial conclusions by the end ofthe paper (pages 19315 lines 4-+9920) but these don't seem to be fully supported by the evidences presented in the paper. In particular I don't think the paper demonstrates to a sufficient level:

Response : We would like to sincerely thank Dr.C.Buontempo for reviewing the manuscript and for his constructive comments/suggestion and accepting the conceptual view.

Point-by-point responses on how we have addressed each recommendations/suggestions are given below. Please note that manuscript is also altered in view of reviewer - 1 and 3's comments and suggestion.

1) that the ozone enhancement is attributable entirely to a stratospheric intrusion and not to local source (e.g. lightning), tropospheric advection, or anthropogenic origin.

Response : During the period of observations, the sky was fully cloudy, raining and the possibility of anthropogenic activities are negligible during rain event. Moreover, the enhancement observed in ozone is at much higher height i.e. middle and upper troposphere.

There were lightning event all around the Indian region not specifically over the cyclone area as observed from satellite measurements. However, we agree with referee that we cannot fully rule out the thunderstorm.

There may be possibility of advection which is already discussed and also attributed due to cyclone. Now we have modified / revised the manuscript accordingly.

2)that the intrusion in the troposphere would add as a significant stratospheric sink assuggested in line 7-10 on page 19307

Response : Yes, we agree with the referee but the amount is too low as that of stratospheric ozone which cannot be traceable.

3) how significant such exchange process is for the overall ozone budget of the troposphere and what its possible impact on the living organisms could be (page 19307 line 27 and page 19308 line 15-19).

Response : Ozone budget and its impact on living organism are now discussed in the revised manuscript (*National Research Council*, 1991)**.**

4)whether the tropical cyclones in the bay of Bengal could be considered representative of the tropical cyclones in other part of the tropics.

Response : Probably yes. We have come across few latest literatures which proved that thunderstorms enhance tropospheric ozone [*Pan et al.*, 2014]. More discussion is made in the revised manuscript with references.
There are few studies which clearly proven the enhancement of surface ozone due to intrusion of stratospheric into the troposphere associated with severe weather condition (*Stohl et al.*, 2000; *Jiang et al.*, 2015)

5) what is the extent of the area for which the ozone enhancement area has been recorded.

Response : It is very difficult to say the extent of the area as there is no much observational (ozonesonde) evidence and satellite passes are very limited in time and space. However, with the numerical simulations it is found that the entire band of the cyclone participated in the exchange process, i.e. 50 km x 250 km.

6) how significant the enhancement of surface ozone detected during the passage of the cyclones is when compared to the normal level of variability at the station.

Response : The variability at the station depends on the synoptic meteorological condition in addition to changes in local anthropogenic activity. The variability (i.e. 1-sigma standard deviation) is ~9.5 ppbv during the month of October. Thus, observed enhancement is of the order of normal variability at the station. Thus, it is possible that observed enhancement could be due to surface reaching intrusion effect but possibility of local/anthropogenic activity could not be fully ruled out.

7) how well the WRF-ARW is able to describe the dynamical field around the cyclone cyclones that exists.

Response : We have used different Physics schemes using WRF-ARW simulation and found one scheme is compared well with the observation of zonal, meridional and vertical winds (Das et al., 2011). Das et al. (2011) and Pan et al. (2015) have uses of WRF-simulation for Stratosphere to troposphere exchange during the passage of tropical cyclone.

8) I would think the paper would become significantly stronger if an estimate of the overall ozone mass exchange though cyclones would be attempted by the authors on the basis of the measurements they acquired and the number of tropical

Response : We agree with the referee but we have only two cases of tropical cyclone where we have few ozonesonde observations and it is not extensive enough to allow us to estimate the ozone flux. In near future we will definitely estimate of the overall ozone mass exchange with more number of cyclone cases and simultaneous observations of ozonesonde at different locations. We thank referee for the suggestion.

Detailed comments:
Page 19306 Line 18 : at least one of the many references should be mentioned here.

Response : Now reference is included.

Page 19306 Line 18 : I would think the properly of Ozone as GHG don't depend so much on its location in the atmosphere

Response : Corrected.

Page 19306 Line 24 : I don't think that categories such as "bad" and "good" are particularly useful for the discussion here especially because it is not clear to whom such change would be good or bad.

Response : Following the reviewer's comments, entire sentence is removed in the revised manuscript.

Page 19308 lines 9-10: at least at the first order the amount of radiation that reach the surface should not depend on the specific vertical profile of ozone as much as on its total column amount.

Response : Sentence is modified in the revised manuscript.

Page 19313 line 14: I don't think it can be safely assumed that tropical cyclones have no lightning for example: http://journals.ametsoc.org/doi/abs/10.1175/MWR-D-11-00236.1

Response : We thank referee for raising this important point. Now we have revised the statements in this version of manuscript.

Page 19314 line 24: I think the provides only once piece of evidence in support of the thesis the authors suggest rather than a demonstration similarly I would be more cautious in the conclusion c.

Response : Now we have elaborated the discussion in this context.

Page 19315 lines 11-14: I don't think this statement is fully supported by the evidences presented by the authors. The enhancements the authors suggest (which I assume can only be local) is probably offset by a slow ascent happening on the large scale. Understanding the balance between these two competing processes would be the only way to the long-term impact tropical cyclones may have on the ozone concentration of the troposphere.

Response : With the limited observations of ozonesonde along with numerical simulation we have tried to established the stratospheric intrusion associated with the passage of tropical cyclone.

References :

Pan, L.L. et al., 2015.: Thunderstorms enhance tropospheric ozone by wrapping and shedding stratospheric air, Geophy. Res. Lett., 41, 7785-7790, doi : 10.1002/2014gl061921.

Jiang, Y. C., Zhao, T. L., Liu, J., Xu, X. D., Tan, C. H., Cheng, X. H., Bi, X. Y., Gan, J. B., You, J. F., and Zhao, S. Z., 2015: Why does surface ozone peak before a typhoon landing in southeast China?, Atmos. Chem. Phys., 15, 13331-13338, doi:10.5194/acp-15-13331-2015.

Stohl, A., Wernli, H., Bourqui, M., Forster, C., James, P., Liniger, M. A., Seibert, P., and Sprenger, M., 2003.: A new perspective of stratosphere-troposphere exchange. Bull. Am. Met. Soc. 84, 1565-1573.70, doi: http://dx.doi.org/10.1175/BAMS-84-11-1565.

National Research Council (1991), Rethinking the Ozone Problem in Urban and Regional Air Pollution, 1051 Committee on Tropospheric ozone formation and measurement, Natl. Acad. Press, Washington, D.C.

Response to Referee #3's Comments

Review for "Influence of tropical cyclones on tropospheric ozone: possible implication" by Das et al. The authors present an interesting study where two cases of tropical cyclones enhance tropospheric ozone levels. The two cyclones Nilam and Phailin are discussed with data from ozone dropsondes, surface ozone measurements and relative humidity derived from satellite scans. Furthermore, numerical simulations are used to get a more complete picture of the dynamics of the events. All in all, the argumentation is clear enough and the data support the main statements. However, there are also some concerns which need some consideration before the manuscript is ready for publication.

Response : We would like to sincerely thank the anonymous referee for very positive evaluation and constructive comments/suggestion for the improvement of the manuscript.

Point-by-point responses on how we have addressed each recommendations/suggestions are given below. Please note that manuscript is also altered in view of reviewer - 1 and 2's comments and suggestion.

Major concerns:
1. In its present state, the introduction is not very well structured and at several places remains rather unspecific.
• For instance, it is written that Appenzeller and Davies (1992) attribute the stratospheric intrusion to "disturbed weather conditions over mid-latitude". This is not specific enough!

Response : We have rewritten the introduction section.

• Furthermore, I would not agree that stratospheric intrusions are generally a slow process, as written in P19307,L10. See for instance recent studies by Bourqui and Trepanier (2010), Skerlak et al (2014) or the review by Stohl et al. (2003) with its particular focus on the synoptic scale of STE (see below). In short, a more careful review of current literature seems to be appropriate.

Response : Now the sentence is revised in view of recent literature survey and more references are added in this version of manuscript.

• The first paragraph starts with some very general statements about ozone in the atmosphere. I wonder whether this could be considerably shortened and the focus brought much faster to the main topic of the study, i.e., how tropical cyclones influence the tropospheric ozone levels.

Response : We feel general introduction is necessary to make the reader comfortable. However, we have revised these introductory sentences taking in account of all the reviewer's comments.

• At L19307,L8-9 it is written that stratospheric intrusions "... also decreases the stratospheric ozone, which in principle enhances the penetration of UV to reach the Earth's surface." In principle yes, but I doubt that it is of practical importance. Is there a reference for this statement?

Response : As per our knowledge there are no such literatures which have shown quantatively the amount of decreasing stratospheric ozone and its effect in enhancing the penetration of UV radiation to Earth's surface. However, this sentence is well accepted and mentioned in many literatures (e.g. *Baray et al*., 1999 and *Cairo et al*., 2008)

• The last sentence of the introduction repeats statements from before. There is no need to 'complete' the introduction with such a summarizing statement.

Response : Now the sentence is omitted in the revised manuscript.

• In P19308,L8-10 the effect of humidity on ozone is discussed. But it remains unclear how, in the context of the paper's research topic, this fits in. The sentence looks a little 'out-of-context'!

Response : This sentence is omitted. Introduction is rewritten in the revised manuscript.

• The aim of the study is only handled in one single sentence near the end of the introduction: "The present study addresses the influence of tropical cyclones quantitatively on enhancement of tropospheric ozone by stratospheric intrusion." First, the sentence structure looks a little strange to me, second, I would appreciate when the aim of the studied is presented in some greater detail.

Response : This sentence is revised accordingly.

2. Some physical arguments remain unclear, or can be critically questioned.
• In Figure 2 the surface ozone measurements for Phailin are shown. There is a nice shift in background ozone levels from 14 to 15 October 2013. The authors attribute this increase to air descending within a stratospheric intrusion. In the same line they mention other processes which influence ozone levels (P19313, photochemical reactions, biomass burning and lightning). However, they state that given the cyclones' characteristics, the impact of any of the three mechanisms will be very low. If this is the case, where does the diurnal cycle in the surface ozone measurement coming from? In short, I am not fully convinced that the other processes are really negligible. Note also that on 16 October the surface ozone measurement reaches very low ozone mixing ratios, although the stratospheric intrusion already 'took place'.

Response : By the statement "given the cyclones' characteristics, the impact of any of the three mechanisms (photochemical reactions, biomass burning and lightning) will be very low", we wanted to say that changes in these mechanisms would be low. We agree that the diurnal variability in surface ozone is influenced by photochemical processes under the presence of precursor gases like NOx, CO, etc (David and Nair, JGR, 2011). But the enhancement in ozone is observed in the middle and upper troposphere and as the day progresses the enhancement height of ozone decreases. If the enhancement is due to local activities e.g. biomass burning then initially we might have observed ozone enhancement in the surface or lower troposphere which is in contrast to our observations. Considering the variability in the surface ozone at which is ~9.5 ppbv (i.e standard deviation during month of October), the observed enhancement (~10 ppbv) fall under the day to day variations. Thus, in the view of this, it is possible that observed enhancement could be due to surface reaching intrusion effect but possibility of local/anthropogenic activity could not be fully ruled out.

There are few studies which clearly proven the enhancement of surface ozone due to intrusion of stratospheric into the troposphere associated with severe weather condition (*Stohl et al.*, 2000; *Jiang et al.*, 2015).

• As a 'proof' that stratospheric air is really coming down, it is written that " Enhanced potential vorticity 0.5–1.5 PVU is also observed vertically down from the stratosphere to the surface, overlapping the downdraft regions." There is indeed a clear PV maximum discernible in Figure 3, at about mid-tropospheric levels. But one might argue that this is diabatically produced PV, due to condensational heating, which therefore is not of stratospheric origin. This option should clearly be discussed in the manuscript.

Response : We thank referee for the suggestion. Now we have incorporated in the revised manuscript.

• Some of the formulations are not careful enough. For instance, (P19313,L25) "The potential temperature contours indicate the presence of unstable atmosphere at this location". I do not see any sign of an unstable air column. Possibly, what is meant is that the stability is reduced?!

Response : Corrected in the revised manuscript.

Minor concerns:
- P19309,L3: There is no need to repeat at several places that it is a very severe cyclonic storm'. The text seem here, and other places, a little repetitive.

Response : Corrected in the revised manuscript.

- P19309: I am not familiar with ozone analysis. What does "1% linearity" mean?

Response : The surface ozone analyser was calibrated by applying known mixing ratios of ozone in the measurement range (i.e. 0 to 70 ppbv). The calibration constant is fixed based multipoint calibration (i.e. based on linear fit between know values of ozone and those measured by the analyser). The analyser

shows linear behaviour, however it deviates from linearity by ±1%. Thus, ozone mixing ratios may have deviation of ±1% of its measured value. Note that our ozone measurement range is from few ppbv to 30 ppbv, ±1% correspond to 0.3 ppbv which is very small in the context of observed enhancement (i. e. ~10 ppbv).

- P19309,L23: "This data is also used to do the qualitative analysis of stratospheric air." What do you mean with 'qualitative analysis of stratospheric air'?

Response : Sentence is removed from the revised manuscript.

- Section 3. The last paragraph of section 3.2 would better be placed in the introduction to the whole section 3. It applies to both cases and already refers to the images in Figure 1.

Response : Following the reviewer's suggestion, we have moved this sentence to the whole section 3.

- Section 4: I strongly suggest to rename section 2 into "campaign details and data" (or something in this direction). Then, the description of section 4 could be added to this new section. At the moment, section 4 with all the technical details of the NWP simulation looks rather out of place. It distracts the reader from the physical discussion.

Response : Following the reviewer's suggestion, we have moved the section under 'Numerical Simulation' to the section 2.

- Figure 1: Mention in the caption what the blue star refers to!

Response : Added in the figure caption.

- Figure 2: Describe in caption, what the mean ozone profile refers to. It's discussed in the text, but not in the figure caption.

Response : Added in the figure caption.

- Figure 3: The position of the height-latitude cross-section could be shown in Figure 1.

Response : It is very difficult to accommodate this information in Fig.1 (a) as it is already very crowded. We hope reviewer will kindly accept not to incorporate this particular suggestion.

Reference

David, L. M., and Nair, P.R. 2011.: Diurnal and seasonal variability of surface ozone and NOx at a tropical coastal site: Association with mesoscale and synoptic meteorological conditions,116, D10303, doi : 10.1029/2010JD015076.

Jiang, Y. C., Zhao, T. L., Liu, J., Xu, X. D., Tan, C. H., Cheng, X. H., Bi, X. Y., Gan, J. B., You, J. F., and Zhao, S. Z., 2015: Why does surface ozone peak before a typhoon landing in southeast China?, Atmos. Chem. Phys., 15, 13331-13338, doi:10.5194/acp-15-13331-2015.

Stohl, A., Wernli, H., Bourqui, M., Forster, C., James, P., Liniger, M. A., Seibert, P., and Sprenger, M., 2003.: A new perspective of stratosphere-troposphere exchange. Bull. Am. Met. Soc. 84, 1565-1573.70, doi: http://dx.doi.org/10.1175/BAMS-84-11-1565.

Influence of the Tropical Cyclones on Tropospheric Ozone: Possible Implication

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Abstract. The present study examines the role of tropical cyclones in the enhancement of tropospheric ozone**.** The most significant and new observation is the increase in the upper tropospheric (10-16 km) ozone by 20-50 ppbv, which has extended down to the middle (6-10 km) and lower troposphere (< 6 km).The descending rate of enhanced ozone layer is found to be ~1 km/day. Enhancement of surface ozone concentration by ~ 10 ppbv in day-time and 10-15 ppbv in the night-time is observed during cyclone. Numerical simulation of potential vorticity, vertical velocity and potential temperature, reproduced the key feature of observations. Simulation study indicates the downward transport of stratospheric air in to the troposphere. Space borne observations of relative humidity indicate the presence of sporadic dry air in the upper and middle troposphere over the cyclonic region. These observations constitute quantitatively an experimental evidence of enhanced and redistribution of tropospheric ozone during cyclonic storms.

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[**Key words:** Stratosphere-troposphere exchange processes, tropopause, ozone, water vapour]

1. Introduction

Stratospheric ozone (O_3) maximum around 25-30 km altitude, regulates the amount of ultraviolet radiation coming from the Sun to the Earth's surface. There are ample studies indicating depletion of stratospheric ozone since 1890's and its consequences of impairing the entire ecological system (e.g. *Forster et al*., 2007). Ozone is an important greenhouse gas, which acts as an oxidant in the troposphere and have an important role in climate forcing (*Forster et al*., 2007; *Pan et al*., 2015). The tropopause is a layer that separates the troposphere and the stratosphere, and plays a key role in controlling the mixing of minor constituents, *viz*., ozone and water vapour between these two layers. One of the major consequences of the tropospheric ozone enhancement is on the living organism, as it acts as a toxic agent among the air pollutants (*National Research Council*, 1991).

Owing to the importance of ozone chemistry and its implication for air quality and climate change, studies focusing on the origin of ozone enhancement in the troposphere, its trends and distributions need immediate consideration. Increase in the tropospheric ozone is considered to be due to (1) in-situ photochemical formation associated with lightning, advection, anthropogenic (e.g., *Jacobson*, 2002 and references therein), and (2) stratospheric flux (*Wild*, 2007 and reference therein; *Skerlak et al*., 2014). Increase of the ozone downward flux from the stratosphere to the troposphere not only increases the tropospheric ozone, but also decreases the stratospheric ozone, which in principle enhances the penetration of UV radiation to reach the Earth's surface.

In general, downward flow of air masses from the stratosphere to the troposphere, i.e. stratospheric intrusion is a middle and higher latitude phenomenon linked with synoptic scale disturbances (*Holton et al*., 1995). This downward flow is attributed to the dissipation of extra-tropical planetary and gravity waves in the stratosphere (*Stohl et al*., 2003 and references therein). *Liang et al*. (2009) have described the time scale of stratospheric ozone

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Formatted: Font: Italic, Complex Script Fon Italic intrusion that occurs in 3 steps, and takes about three months to reach from stratosphere to lower troposphere. In extra-tropic there is a continuous downward flow from the stratosphere to the troposphere (*Stohl et al.*, 2003; *Bourqui and Trepanier*, 2010). In the global ozone budget, 25-50 % of tropospheric ozone source is from middle latitude stratospheric intrusion (*Bourqui and Trepanier*, 2010). *Appenseller and Davies* (1992) have also discussed that exchange between the stratosphere and the troposphere (both directions) is highly episodic due to the perturbation of tropopause associated with strong mesoscale convective systems. A global climatology of STE was established by *Skerlak et al.* (2014) using ERA-Interim reanalysis data. The authors have estimated fluxes of mass and ozone across the tropopause. Maximum ozone forms over the tropics, moves upward and then pole-ward by Brewer-Dobson circulation, which further descends to the lower stratosphere and troposphere at high latitudes. There is much observational evidence supporting the slow intrusion of stratospheric air into the troposphere during cut-off lows (*Vaughan and Price*, 1989), high/low pressure systems (*Davies and Schuepbach*, 1994), the tropopause folds (*Sprenger and Wernli*, 2003) and in a rapid episodic manner which generally triggered by overshooting convection, like a tropical cyclones (*Loring et al.*, 1996; *Baray et al.*, 1999; *Cairo et al.*, 2008; *Das*, 2009, *Das et al.*, 2011, *Zhan and Wang*, 2012; *Jiang et al.*, 2015).The tropical cyclones are the synoptic-scale disturbances of organised convective systems which weaken the tropopause by overshooting convection and enhancing the stratosphere-troposphere exchange (STE) in a spontaneous manner. In addition, turbulence caused due to wind shear (*Shapiro*, 1976) and breaking of gravity wave (*Langford et al.*, 1996) can also be the causative mechanisms for the occurrence of stratospheric intrusion. Recent study by *Pan et al.* (2015) have shown the enhancement of tropospheric ozone is associated with thunderstorm event (*Pan et al.*, 2014). Slow stratospheric intrusion is reasonably well

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Formatted: Font: Italic, Complex Script Fo Italic understood and is a regular phenomenon, whereas the rapid intrusion needs to be understood in detail.

The intrusion of the stratospheric air into the troposphere has been demonstrated by *Hocking et al.* (2007) for mid-latitude condition and *Das* (2009) for low latitude during cyclone using high power radar system (VHF radar). Subsidence of stratospheric air is generally observed in the vicinity of cyclone (*Baray et al.*, 1999; *Cairo et al., 2008; Leclair De Bellevue et al.*, 2006, 2007*; Das*, 2009, *Das et al.,* 2011). *Appenzeller and Davies* (1992) have shown the intrusion of the stratospheric air into the troposphere due to disturbed weather condition over mid-latitude, combining weather prediction model and satellite observations.

Stratospheric intrusion can bring ozone rich air from stratosphere to the troposphere which further affects the surface ozone concentration (*Bourqui and Trepanier*, 2010). Earlier studies using aircraft measurement shows that the perturbation of the tropopause associated with deep convective thunderstorm can transport ozone from the stratosphere to the troposphere (*Dickerson et al.*, 1987; *Poulida et al.*, 1996; *Stenchikov et al.*, 1996; *Pan et al.*, 2015). *Stohl et al*. (2000) have shown that episodic stratospheric intrusion is associated with severe weather condition which enhanced the surface ozone concentration. A recent study by *Jiang et al*. (2015) have shown that high surface ozone by 21-42 ppbv and the nocturnal surface ozone level exceeding 70 ppbv over the southeastern coast of China during the passage of tropical cyclone (before land fall).

A tropical cyclone is a heat engine of hot cumulus towers, areas of low pressure and is characterized by cyclonic tangential and inflowing radial winds. The tropical cyclone circulation consists of (a) the rotational air flow in the horizontal direction, (b) the in-up-out-down overturning flow in the vertical direction, (c) out-flow at in the vicinity of UTLS region and (d) subsiding nature in the periphery (*Jiang et al*., 2015). The eye (centre of the tropical cyclone) is about tens of kilometre and it is the core of downdraft with relatively no cloud

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Formatted: Font: Italic, Complex Script For Italic with calm wind structure. The bands of the tropical cyclone have intense vertical extended cumulus cloud up to UTLS region. These regions are accompanied with updrafts, whereas downdrafts are encounter between these bands. The eyewall region is characterised by local maximum equivalent potential temperature, whereas minimum is found in the middle to upper troposphere. The eyewall and radius of maximum winds increases with height. The low pressure core extended to UTLS region and the horizontal pressure gradient decreases with height (*Koteswaram*, 1967). *Mitra* (1996) and *Das* (2009) reported the weakening of the tropopause due to a tropical cyclone. Detail study on the dynamical and thermo dynamical structure of tropical cyclone can be found in *Hence and Houze* (2012) and review article on clouds in the tropical cyclone can be found in *Houze* (2010). Thus, the tropical cyclones have influence on stratosphere-troposphere exchange process which causes air mass and energy transports in the troposphere and redistribution of tropospheric ozone (e.g. *Jiang et al*., 2015). A complete review on the effect of the tropical cyclones on the upper troposphere and lower stratosphere can be found in *Cairo et al*. (2008). Inspite of many observational and modelling studies, the exchange of air mass from the stratosphere to the lower troposphere in short-time scale associated with tropical cyclones is still unclear and further studies are needed.

The present study addresses the influence of the tropical cyclones quantitatively on enhancement of tropospheric ozone by stratospheric intrusion. This ozone intrusion observed in the lower troposphere not only acts as a pollutant but also cool the stratosphere and warm the troposphere, hence plays a vital role in the Earth’s radiation budget.

2. Campaign details and data analysis

An intense campaign, named as ‘Troposphere-Stratosphere Exchange-Cyclone (TSE-C)’ under the Climate And Weather of Sun-Earth System (CAWSES)-India phase-II programme was conducted during two cyclone events. Under this campaign, a series of ozonesondes were launched from Trivandrum (8.5^{o}N, 76.5^{o}E) during the intense period of cyclonic storm

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Nilam from 30 October to 7 November 2012 and a very-severe cyclonic storm Phailin from 11 to 15 October 2013.The ozonesondes used are EN-SCI (USA) make, which were integrated with the GPS based radiosondes of i-met make. These standard ozonesonde are made up of the Electrochemical Concentration Cell (ECC) (*Komhyr et al*., 1995). The uncertainty in the ozone measurements is 5-10 %. Table 1 also provides the details of ozonesonde measurements conducted during the passage of cyclonic storm Nilam and Phailin. Ozonesonde data was obtained at a fixed height resolution by down sampling at 100 m height resolution by linear interpolation method. The India Meteorological Department (IMD) also conduct 1-2 IMD-ozonesonde launches per month. The background profiles (non-convective day at least for 3 days) is constructed by averaging the ozone data (23 profiles) obtained from the IMD combined with our observations from 1995-2013 for the month October over Trivandrum. The IMD-ozonesonde used Brewer bubbler electrochemical sonde developed in the Ozone Research Laboratory of the IMD. These IMD ozone sonde were compared with ECC sondes and found that it is underestimated by 5-10 % in the troposphere (*Kerr et al*., 1994; *Deshler et al.*, 2008), which is about <2 ppbv of the observed mean value. Detail system description of IMD-Ozonesonde can be found elsewhere (*Sreedharan*, 1968; *Alexander and Chatterjee*, 1980). There is no ozonesonde launch by IMD in campaign mode (daily one launch) during the low pressure system. The measurements of near-surface ozone are carried out using the online UV photometric ozone analyser (Model AC32M) of Environment S.A, France. This ozone analyser works on the principle of UV absorption of ozone at the wavelength 253.7 nm. The instrument has a lower detection limit of 1 ppbv and 1% linearity. The data is sampled with an interval of 5 min.

The SAPHIR (Sondeur Atmospherique du Profild' Humidite Intertropical par Radiometrie) onboard Megha-Tropiques satellite is a multichannel passive microwave humidity sounder, measuring brightness temperatures in six channels located close to the

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183.31GHz water vapor absorption line (±0.15,±1.20, ±2.80,±4.30, ±6.60and, ±11.0,GHz). These channels allow retrieving the integrated relative humidity respectively between the levels of 1000–850 hPa, 850–700 hPa, 700–550 hPa, 550–400 hPa, 400–250 hPa, and 250–100 hPa. The radiometer has a cross-track scan of ±43°, providing a swath of 1705 km and a 10 km resolution at nadir. This data is also used to do the qualitative analysis of stratospheric air. The detail instrumentation can be found in *Raju* (2013), and retrieval algorithm and validation can be found in *Gohil et al*. (2012); *Mathur et al.* (2013) and *Venkat Ratnam et al*. (2013); *Subrahmanyam and Kumar* (2013), respectively.

Apart from the ozonesonde observations, a high resolution numerical simulation using the Advanced Research Weather Research and Forecast (WRF-ARW) model version 3.6 has also been carried out for both cases of cyclones. The model domain has been configured with two nested domains of 60 km and 20 km horizontal resolution, and covers an area extending from 1°S to 25°N and 60°E to 100°E. The innermost domain has been used for the present study. The initial and lateral boundary conditions have been taken from ERA-Interim reanalysis on 0.75° x 0.75° continuously at every 6 hours. The present simulation was carried out with the model Physics options :(i) New Simplified Arakawa-Schubert (NSAS) (*Han and Pan*, 2011), (ii) Yonsei University (YSU) boundary layer scheme (*Hong et al*., 2006), (iii) Rapid Radiative Transfer Model (RRTM) long wave radiation scheme (*Mlawer et al*., 1997), (iv) WRF Single Moment (WSM) 5 class microphysical scheme (*Hong et al*., 2004), and (v) NOAA land-surface scheme (*Smirnova et al*., 2000).

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3. Meteorological background

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The present experiments were conducted during the passage of the (1) cyclonic storm '**N**ilam**'** from 28 October to 1 November 2012 and (2) very severe cyclonic storm 'Phailin**'** from 4-14 October 2013 over the Bay of Bengal (BOB). The track of each tropical cyclones and outgoing long wave radiation (OLR) images (date and time are stamped) are shown in

Figures 1a and 1b, respectively. The detailed bulletin can be found in www.imd.gov.in. During these campaigns, several ozonesondes were launched from Trivandrum, whenever the intensity of cyclones is maximum and the path/eye was close to the launching site. The details of each of the tropical cyclone used for present analysis are as follows:

3.1 Case-1 (Nilam)

A depression formed over the southeast of BOB (~9.5^{0}N, 86.0^{0}E) at 11:30 IST of 28 October 2012. It moved westwards and intensified into a deep-depression on the morning of 29 October 2012 over southwest BOB, about ~550 km south-southeast of Chennai. It continued to move westwards and intensified into a Cyclonic Storm, 'Nilam**'** in the morning of 30 October 2012 over southwest BOB. Then it moved north-northwest, crossed the north Tamilnadu coast near Mahabalipuram (12.6^{0}N, 80.2^{0}E), south of Chennai in the evening hours of 31October 2012. After the landfall the cyclonic storm, Nilam moved west-northwest and weakened gradually into a deep depression and then into a depression in the morning hours of 1November 2012.

3.2 Case-2 (Phailin)

A low pressure system was formed over Tenasserim coast (~12.^{0}N, 96^{0}E), on early morning of 6 October 2013. It intensified into a depression over the same region on 8October and then moved towards the west-northwestwards. It further intensified into a deep depression on early morning of 9 October 2013 and then into a cyclonic storm, 'Phailin' in the evening hours. Moving northwestwards, it finally converted into a severe cyclonic storm in the morning hours of 10 October 2013 over east central BOB. The very severe cyclonic storm continued to move northwestwards and crossed Andhra Pradesh and Odisha coast near Gopalpur (19.2^{0}N, 84.9^{0}E) in the late evening of 12 October 2013. It further continued to move north-northwestwards after the landfall for some time and then northward and finally north-northeastwards up to southwest Bihar. The system weakened gradually into a cyclonic

Formatted: Normal, Indent: First line: 0.2" No bullets or numbering storm from 13 October 2013 and finally the intensity decreased to a low pressure system on 14 October 2013.

4. Results and Discussion

Figure 2 (a-b) shows the profiles of ozone mixing ratio (OMR) and relative humidity (RH) from ozonesonde measurements during the passage of the tropical cyclones Nilam (top panels) and Phailin (bottom panels). The background ozone profile is obtained by averaging individual profile (23 profiles) over Trivandrum of October from 1995-2013 and shown by dotted lines in Figure 2. During the passage of Nilam on 30 October 2012, enhancement in tropospheric ozone (marked by horizontal arrows) from background by 40-50 ppbv was observed in the height region between 8-9 km (~1 km width) and 11-14 km (~3 km width). These enhancements persisted till 31 October 2012 but at the height region reduced 6-7 km with a reduced width. However, the enhancement of about ~40 ppbv was still observed on 2 November 2012 but the height region decreased to 5-6 km. After two days, we had again observations from 5-7 November 2012. The height of enhancement in the ozone profiles were reduced to ~4, ~3 and ~1.5 km by 40, 30, and 20 ppbv on 5, 6 and 7 November 2012, respectively. The present observation reveals that the downward propagation of the enhanced upper tropospheric ozone into the lower troposphere occurs in episodic manner. The descending rate of the ozone rich layer from the upper troposphere to the boundary layer during Nilam is approximately estimated to be ~875 m/day. It is also noted that the corresponding relative humidity profiles during Nilam did not decrease with increasing ozone mixing ratio except on 2 November 2012. A significant sudden decrease in relative humidity is observed on 2 November 2012 at ~6 km, where the maximum enhancement (~ 70 ppbv) of tropospheric ozone is observed. This is due to the presence or accumulation of dry air, which is believed to have been originated from the stratosphere. A similar phenomenon is also

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The track of each tropical cyclones and outgoing long wave radiation (OLR) images (date and time are stamped) are shown in Figures 1a and 1b, respectively. The detailed bulletin can be found in www.imd.gov.in. During these campaigns, severa ozonesondes were launched from Trivandrum (8.5°N, 76.5°E), whenever the intensity of cyclone were maximum and the path/eye was close to the launching site. ¶

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Apart from the radiosonde/ozonesonde observatio a high resolution numerical simulation using the Advanced Research Weather Research and Foreca (WRF-ARW) model version 3.6 has also been carried out for both cases of cyclones. The model domain has been configured with two nested domains of 60 km and 20 km horizontal resolutio and covers an area extending from 1°S to 25°N an 60°E to 100°E. The innermost domain has been us for the present study. The initial and lateral bound conditions have been taken from ERA-Interim reanalysis on 0.75° x 0.75° continuously at every hours. The present simulation was carried out wit the model Physics options :(i) New Simplified Arakawa-Schubert (NSAS) (*Han and Pan*, 2011), (ii) Yonsei University (YSU) boundary layer sche (*Hong et al*., 2006), (iii) Rapid Radiative Transfer Model (RRTM) long wave radiation scheme (*Mlawer et al*., 1997), (iv) WRF Single Moment (WSM) 5 class microphysical scheme (*Hong et al* 2004), and (v) NOAA land-surface scheme (*Smirnova et al*., 2000). ¶

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As discussed in the introductory section, significant perturbation in the tropopause due to deep convection will lead to the transport of ozone rich stratospheric air in to the troposphere. Figure 3 shows variation in the cold point tropopause height (CPT-H) and cold point tropopause temperature (CPT-T) derived from the temperature measurement by ozonesonde launched during passing of the tropical cyclones **(a)** Nilam and **(b)** Phailin over Trivandrum. Significant perturbation in the tropopause is observed for both the cyclone cases. The CPT-H gradually decreased from 17.8 km on 30 October to 16.7 km on 2 November 2012 for Nilam. Afterwards, the CPT-H gradually increased and reached to 17. 5 km. Similarly for Phailin, the CPT-H decreases from 16.5 km on 11 October 2013 to 15.8 km on 12 October 2013 and then gradually increases. In both the cyclone events, CPT-T show anti-correlation with CPT-H as expected. The height above the tropopause (i.e. stratosphere) is in radiative equilibrium, whereas the height below the tropopause (i.e. troposphere) is in convective equilibrium. Thus, turbulent mixing is taking place below the tropopause and above it (i.e. stratosphere), the air is highly stable and of subsidence in nature. On 30 October 2012, when the tropopause height is at 17.8 km the turbulent mixing is taking place below 17.8 km and the mixing height decreased following the tropopause height and reached as low as 16.7 km on 2 November 2012. When the tropopause height increased after 1 November 2012, the turbulent mixing height also increased but the stratospheric air still remained in the

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troposphere as it cannot follow the spontaneous increase in the tropopause height. During this process (i.e. increasing height of the tropopause), the stratospheric air get mixed with tropospheric air by the mean of turbulent mixing and it further intrude down to the lower troposphere due to the presence of downdrafts as observed in the simulation (discussed later).

In addition to the profiling of ozone, we have surface measurement of ozone and solar flux during the Phailin. Figure 4 shows the time series of near-surface ozone mixing ratio along with solar irradiation from 11 to 19 October 2013. As expected, clear diurnal variability is observed in the time-series of ozone. In general there are three main mechanisms for the production of ozone in the atmospheric boundary layer: (1) photochemical reaction via NOx and CO channel, (2) Bio-mass burning /fossils fuel, and (3) lightning. However, *David and Nair* (2011) have shown the diurnal pattern of surface ozone observed over Trivandrum is due to the mesoscale circulation, i.e., local sea and land breeze and the availability of NOx. From 11 to 14 October the maximum and minimum average peak of ozone are observed to be 24 and 1 ppbv, respectively, whereas from 14 to 18 October 2013, the maxima and minima is observed to be 35 and 10 ppbv, respectively. Even though there was no solar radiation in the evening hours, there are enhancements in surface ozone concentration (indicated by vertical arrows) on 14-15, 16-17, 18-19 October 2013. The upper and lower average is indicated by horizontal solid and dash lines respectively. The ozone profiles obtained from ozonesonde measurements also show that enhanced ozone layer propagates downward from the upper troposphere starting during 11-15 October 2013. It is well expected the enhanced ozone layer further propagates downward to near-surface which is observed as enhanced as surface ozone even there is a cut-off in solar radiation. Time-series of solar irradiation shows that there was not much change in the radiation among the day11-13 and 14-17 October 2013.This indicates that the observed enhancement was not due to change in sunshine. At Trivandrum, ozone remains to its daytime value even after evening hours. Interestingly, the enhancement

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observed on 14 October 2013 is during evening hours (16-17 hours) where solar radiation is very low or even zero. Over the observation site, land-breeze prevails during night-time. The change in night-time ozone depends on the precursor gas (e.g. NO) concentration in land-breeze, which has dependency on local precursor gas emission/human activity. Due to the cyclonic condition over Trivandrum, change in human activity during 11-17 October 2013 would not have happened considerably and Bio-mass burning may not be possible due to rain. The day-to-day variability of surface ozone over Trivandrum is ~ 9.5 ppbv (1-sigma standard deviation).The observed enhancement of about 10 ppbv in the day-time and 10-15 ppbv in the nigh-time is above the day-to-day variability which is attributed due to the transport from the UTLS region. In a recent study by *Jiang et al.* (2015), increase of surface ozone by 21-42 ppbv and surface nocturnal surface ozone levels exceeding 70 ppbv is observed in the region Xiamen and Quanzhou over the southerneastern coast of China before the Typhoon Hagibis landing. However, there are possible of influence of lightening associated with cyclone and thus other possibility of this surface ozone cannot be fully ruled out.

Further, to support the present observations of stratospheric intrusion into the troposphere and further to surface, dynamical analysis is carried out using WRF-ARW simulation. *Das et al.* (2011) and *Pan et al.* (2015) have shown ability of WRF simulation during the tropical cyclone. Figure 5 shows the height-time cross-section of (a) vertical velocity along with potential vorticity (magenta line) and potential temperature (black line) contours, and (b) relative humidity along with equivalent potential temperature (black line) and zonal wind (grey line) for Nilam (left panels) and Phailin (right panels) over Trivandrum using WRF simulation. Figure 5 (a) shows the presence of strong updrafts (red) and downdrafts (blue) marked with rectangle box at UTLS regions. Enhanced potential vorticity 0.5-1.5 PVU is also observed vertically down from the stratosphere to the troposphere overlapping the

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Height-time cross-section of relative humidity shown in Figure 5 (b) indicates presence of dry air from UTLS region to the 2-4 km. The equivalent potential temperature contours in Figure 5 (b) indicate that from surface to ~8 km it is highly unstable for vertical motion and favourable condition for the convection to take place during 29-31 October 2012 (Nilam) and 9-11 October 2013 (Phailin). During the same periods, from 10 km to the tropopause level, the vertical motion is suppressed and the atmosphere is found to be statically stable to the unstaturated atmosphere. The present condition indicates the presence of statically stable stratospheric air in the upper and middle troposphere. In addition, strong wind shear is also observed at UTLS region.

Similarly, Figure 6 shows the height-latitude cross-section of (a) vertical velocity along with potential vorticity (magenta line) and potential temperature (black line) contours, and (b) relative humidity cross-section along with equivalent potential temperature (black line) and zonal wind (grey line) at 79^{o}E at 18 GMT on 30 October 2012 for Nilam (left panels) and 18 GMT on 10 October 2013 for Phailin (right panels) using WRF simulation. The vertical velocity profiles shows the presence of downdraft (blue) followed by updraft (red) between 8-17^{o}N at the UTLS region in both the cyclone cases. Enhanced potential vorticity 0.5-1.5 PVU is also observed vertically down from the stratosphere to the lower troposphere, overlapping the downdraft regions. It is also true that enhanced potential vorticity may be also associated with diabatically by condensational heating but the enhancement is only observed with the presence of downdraft at UTLS region. Thus, in the present study, enhancement in the potential vorticity indicates the presence of stratospheric air in the troposphere. The potential temperature contours indicate the presence of reduced stability of the atmosphere at this location and noticed that stable stratospheric air penetrated downward

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at 12-14^{o}N for Nilam and 16-18 ^{o}N for Phailin. Relative humidity profiles indicate the presence of dry air at ~ 8^{o}N which is in the vicinity of ozonesonde observational site. The equivalent potential temperature contours in Figure 6 (b) indicate that from surface to 10 km it is highly unstable for vertical motion and favourable condition for the convection to take place at 6-12^{o}N for Nilam and 12-18 ^{o}N for Phailin. In the same latitude regions from 10 km to the tropopause level, the vertical motion is suppressed and the atmosphere is found to be statically stable to the unstaturated atmosphere for both Nilam and Phailin. The present condition indicates the presence of statically stable stratospheric air in the upper and middle troposphere in the latitudinal cross-section at79^{o}E at 18 GMT on 30 October 2012 and 10 October 2013. Numerical simulation reproduced the key features and confirms the presence of stratospheric intrusion in to the troposphere.

To get further insight, relative humidity derived from SAPHIR onboard the Megha-Tropiques satellite is used. The relative humidity (daily mean) shown is an average over 12-14 passes per day. Figure 7 shows the height-time intensity plot of daily mean relative humidity during the passage of the cyclones: Nilam (left panel) and Phailin (right panel). The grid is averaged from 4-8^{o}N and 83-88^{o}E. Strong dry air intrusion originated from lower stratosphere is observed between 23-27 October 2012 (Nilam) and 12-18 October 2013 (Phailin). In both cyclones, dry air (low humidity region) reached down to the height of 8 km. For the perception of spatial distribution of relative humidity, latitude-longitude plot of relative humidity averaged over different height level is shown in Figure 8. The low value of relative humidity i.e., the presence of dry air on the same day of enhanced ozone mixing ratio in between 5 and 10 km prove that the dry air present in the upper and middle troposphere is of stratospheric origin. The present observations show the influence of the tropical cyclone on the air mass exchange from the stratosphere to the lower troposphere and redistribution of

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tropospheric ozone. Further analysis is required to quantify the amount of mass exchange taking place between the stratosphere and the troposphere.

5. Summary and Conclusions

Important results brought out in the present analysis during the passage of a cyclonic storms Nilam (2012) and Phailin (2013):

a) enhancement of upper tropospheric ozone by 20-50 ppbv from its climatological mean is observed

b) The upper tropospheric ozone propagates downwards to the lower troposphere with a rate of 0.8-1 K/day

c) About 10 ppbv in the day-time and 10-15 ppbv in the night-time enhancement of surface ozone is noticed

d) Perturbation of the tropopause is also noticed

e) Numerical simulation shows the presence of stable dry ozone rich stratospheric air in the upper and middle troposphere over the cyclone prone area

The present observation emphasizes the influence of the tropical cyclones in redistribution of the tropospheric ozone and enriched surface ozone. The study clearly reveals that cyclone plays a vital role in changing the atmospheric composition apart from general weather phenomena.

Acknowledgments

Results reported in this manuscript are from the experimental campaign, TSE-C, conducted under the CAWSES-India Phase-II program, which is fully funded by the Indian Space Research Organisation (ISRO), Government of India and authors sincerely acknowledge the same. The authors would like to thank all the technical and scientific staff of the Space Physics Laboratory (SPL) who participated in this STE-C campaign. The India Meteorological Department (IMD) is highly acknowledged for providing the climatological

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<#>Enhanced ozone in the upper troposphere descend down to surface and the descent rate is found to be 0.87-1 km/day¶
Presence of dry air in the upper and middle troposphere during the period of enhancement ozone in the middle/lower troposphere, which of stratospheric origin is also been reported in both the cases.

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ozonesonde data. K.V. Suneeth and S. Aneesh are thankful to ISRO for providing doctoral fellowship during the study period.

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Figure Captions

Figure 1. (a)Track of cyclones Nilam and Phailin (top panels) and (b) its Outgoing Long wave Radiation (OLR) wave radiation at 14:30 GMT on 30 Oct. 2012 (Nilam) and 9:00 GMT on 10 Oct. 2013 (Phailin). In each panels, date and time is mentioned along the track. In first panel, 18-1/11 indicates 18 GMT of 1 November 2012 and similarly followed for others. Blue star in Fig.1(a) indicates the Ozonesonde launching site Trivandrum.

Figure 2. (a) Profiles of ozone mixing ratio (OMR) (dark black line) and relative humidity (grey line) for individual days during passing of tropical cyclones (a) Nilam and (b) Phailin. The mean ozone mixing ratio profile for non-convective days (as control day) is shown in dotted line. Mean profile is obtained by averaging ozone data over Trivandrum for the month of October from 1995-2013. Horizontal arrows indicate the height of enhanced ozone.

Figure 3. Variation of cold point tropopause height (CPT-H) and cold point tropopause temperature (CPT-T) derived from temperature measurement by ozonesonde launched during passing of tropical cyclones (a) Nilam and (b) Phailin over Trivandrum.

Figure 4. Time series of surface ozone mixing ratio along with solar radiation from 00 IST on 11 October 2013 to 23:55 IST on 19 October 2013. Solid and dotted horizontal lines indicate the mean maximum and minimum surface ozone. The vertical arrows indicate the nocturnal enhancement of surface ozone. The data is collected every 5 min.

Figure 5. Height-time cross-section of (a) vertical velocity along with potential vorticity (magenta line) and potential temperature (black line) contours, and (b) relative humidity along with equivalent potential temperature (black line) and zonal wind (grey line) for Nilam (left panels) over Trivandrum (8.5oN,76.9oE) from 27 October to 2 November 2012 and Phailin (right panels) from 7 to 12 October 2013. Rectangle boxes indicate the presence of strong updrafts and downdrafts and the dry air between stratosphere and troposphere. The above parameters are obtained from WRF simulation.

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Figure 6. Height-latitude cross-section of (a) vertical velocity along with potential vorticity (magenta line) and potential temperature (black line) contours, and (b) relative humidity cross-section along with equivalent potential temperature (black line) and zonal wind (grey line) at 79oE at 18 GMT on 30 October 2012 for Nilam (left panels) and 18 GMT on 10 October 2013 for Phailin (right panels). The above parameters are obtained from WRF simulation.

Figure 7. Pressure-time cross-section of relative humidity obtained from SAPHIR onboard Megha-Tropiques satellite during the cyclones Nilam (left panel) from 15 October to 10 November 2012 and Phailin (right panel) from 2 to 22 October 2013. The data is averaged over from 4oN to 8oN and 83oE to 88oE.

Figure 8. Latitude-longitude distribution of relative humidity derived from SAPHIR onboard Megha-Tropiques at different pressure levels (stamped on each panel) for Nilam (25 October 2012) and Phailin (14 October 2013). The data is averaged for one day which is about 12-14 passes at different timings and arrows indicate the presence of dry air.

Table Captions

Table 1. Details of ozonesonde launched from Trivandrum including the historical data for control day analysis.

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Figure 4. (a) Pressure-time variation of relative humidity obtained from SAPHIR onboard Megha Tropiques satellite during the cyclones Nilam (lef panel) and Phailin (right panel). **(b)** Latitude-longitude distribution of relative humidity derived from same satellite at different pressure levels (stamped on each panel) for Nilam (25 Oct. 2012)

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