Influence of tropical cyclones on tropospheric ozone: possible implications

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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 reported 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 descent rate of enhanced ozone layer during the passage of tropical cyclone is 0.8–1 km day\(^{-1}\), which is three times that of a clear-sky day (non-convective). Enhancement of surface ozone concentration by ~10 ppbv in the daytime and 10–15 ppbv in the night-time is observed during a cyclone. Potential vorticity, vertical velocity and potential temperature obtained from numerical simulation, reproduces the key feature of the observations. A simulation study indicates the downward transport of stratospheric air into 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 quantitatively constitute experimental evidence of redistribution of stratospheric ozone during cyclonic storms.

1 Introduction

The stratospheric ozone (O\(_3\)) layer, found around 25–30 km altitude regulates the amount of ultraviolet radiation coming from the Sun to the Earth’s surface. Ozone is an important greenhouse gas, which acts as an oxidant in the troposphere and has an important role in climate forcing (Forster et al., 2007; Pan et al., 2015). One of the major consequences of the tropospheric ozone enhancement is on living organisms, as it acts as a toxic agent among air pollutants (National Research Council, 1991). Increase in the tropospheric ozone is considered to be due to (1) in situ photochemical formation associated with lightning, advection, anthropogenic activities (e.g. Jacobson, 2002, and references therein), and (2) stratospheric flux (Wild, 2007, and reference therein; Škerlak al., 2014). The tropopause, which acts a barrier between the troposphere and the stratosphere, plays a key role in controlling the flow of minor constituents from one layer to other. The increase of the ozone downward flux from the stratosphere to the troposphere not only increases the tropospheric ozone, but also decreases the stratospheric ozone. The ozone presence in the troposphere (intruded from the stratosphere) further reacts with tropospheric water vapour and the tropospheric ozone is destroyed. In principle, the total columnar ozone decreases and thus there will be an enhancement in the penetration of UV radiation to the Earth’s surface.

In general, stratospheric-air intrusion into the troposphere is observed over the middle and higher latitudes, which are linked with synoptic scale disturbances (e.g. Stohl et al., 2003). This downward flow is attributed to the dissipation of extra-tropical planetary and gravity waves in the stratosphere (Holton et al., 1995). Stohl et al. (2003) and Bourqui and Trepanier (2010) have reported the continuous downward flows from the stratosphere to the troposphere in a much smaller timescale over the extratropics. In the global ozone budget, 25–50 % of tropospheric ozone sources
are from middle-latitude stratospheric intrusion (Bourqui and Trepanier, 2010). Appenzeller and Davies (1992) have also discussed that exchange between the stratosphere and the troposphere (both directions) is highly episodic. 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 is generally triggered by overshooting convections, such as tropical cyclones (Loring Jr. 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; Venkat Ratnam et al., 2016). Overshooting convections associated with tropical cyclones can weaken the tropopause stability, which plays a key role in the stratosphere–troposphere exchange. In addition, turbulence caused due to wind shear (Shapiro, 1976) and breaking of gravity waves (Langford et al., 1996) can also be causative mechanisms for the occurrence of stratospheric intrusion. A recent study by Pan et al. (2015) has shown the enhancement of tropospheric ozone associated with the thunderstorm event. Subsidence of stratospheric air is generally observed in the vicinity of the cyclone (Appenzeller and Davies, 1992; Baray et al., 1999; Cairo et al., 2008; Leclair De Bellevue et al., 2006, 2007; Das, 2009; Das et al., 2011; Venkat Ratnam et al., 2016). Slow stratospheric intrusion is reasonably well understood and is a regular phenomenon, whereas rapid intrusion needs to be understood in detail.

The increase in surface ozone is also linked with stratospheric intrusion (e.g. Bourqui and Trepanier, 2010). Earlier studies have also shown, using aircraft measurements, that stratospheric-air intrusion into the troposphere is associated with deep convections by tropopause perturbation (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 conditions which enhanced the surface ozone concentration.

The bands of the tropical cyclone have intense vertical extended cumulus cloud up to the UTLS region. These bands of cloud are accompanied with updraughts, whereas down-draughts are encountered between these bands. The eyewall region is characterised by local maximum equivalent potential temperature, whereas the minimum is found in the middle to upper troposphere. The eyewall and radius of maximum winds increase with height. The low-pressure core extended to the UTLS region and the horizontal pressure gradient decreased with height (Koteswaram, 1967). Mitra (1996) and Das (2009) reported the weakening of the tropopause during the passage of a tropical cyclone. A detailed study on the dynamical and thermodynamical structure of a tropical cyclone can be found in Hence and Houze Jr. (2012) and the review article on clouds in the tropical cyclone can be found in Houze Jr. (2010). Thus, the tropical cyclones have an influence on the stratosphere–troposphere exchange process which causes air mass and energy transports in the troposphere and redistribution of stratospheric 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). In spite of many observational and modelling studies, the exchange of air mass from the stratosphere to the lower troposphere in a short timescale, associated with tropical cyclones, is still unclear and further studies are needed. The present study addresses the influence of the tropical cyclones quantitatively on the enhancement of tropospheric ozone by the stratospheric intrusion.

### 2 Campaign details and the data analysis

An intense campaign, named Troposphere-Stratosphere Exchange-Cyclone (TSE-C) under the Climate and Weather of the Sun Earth System (CAWSES) India phase II pro-
gramme (Pallamraju et al., 2014), was conducted during two
cyclone events. Under this campaign, a series of ozoneson-
des were launched from Trivandrum (8.5°N, 76.5°E) during the
intense period of cyclonic storm 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 made by
EN-SCI (USA), which were integrated with the GPS-
based radiosondes (i-Met). These standard ozonesonde
are made up of the Electrochemical Concentration Cell (ECC)
(Komhyr et al., 1995). The uncertainty in the ozone mea-
surements is 5–10 %. Table 1 also provides the details of
ozonesonde measurements conducted during the passage of
these cyclonic storms. Ozonesonde data was obtained at a
fixed height resolution by down sampling at 100 m height
resolution by the linear interpolation method. The India Me-
teorological Department (IMD) also launches ozonesondes
every fortnight. The background profiles (non-convective
day for at least three days) is constructed by averaging
the ozonesonde data (23 profiles) obtained from the IMD,
combined with our observations from 1995 to 2013 for the
month October over Trivandrum. The IMD ozonesonde used
a Brewer-Mast electrochemical sonde (bubblor) developed in
the Ozone Research Laboratory of the IMD. These IMD
ozonesondes were compared with ECC sondes and under-
estimations of 5–10% were found in the troposphere (Kerr
et al., 1994; Deshler et al., 2008), which is about ≈2 ppbv of the
observed mean value. Detailed system descriptions of the
IMD ozonesonde can be found elsewhere (Sreedharan, 1968;
Alexander and Chatterjee, 1980). There is no ozonesonde
launch by IMD in this campaign. The measurements of near-
surface ozone are carried out using the online UV photomet-
ic ozone analyser (Model AC32M) from Environment S.A.
France. This ozone analyser works on the principle of UV
absorption of ozone at the wavelength 253.7 nm. The instru-
ment has a lower detection limit of 1 ppbv and 1 % linearity.
The data has a sample interval of 5 min.

The SAPHIR (Sonde Atmosphérique du Profil
d’Humidité Intertropicale par Radiométrie) on board the
Megha-Tropiques satellite is a multichannel passive
microwave humidity sounder, measuring brightness tem-
peratures in six channels located close to the 183.31 GHz
water vapour absorption line (±0.15, ±1.20, ±2.80, ±4.30,
±6.60 and ±11.0 GHz). These channels allow for retrieving
the integrated relative humidity in the ranges of 1000–850,
850–700, 700–550, 550–400, 400–250 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 for the qualitative analysis of the stratospheric
air. A detailed instrumentation can be found in Raju (2013)
and retrieval algorithm in Gohil et al. (2012) and Mathur et
al. (2013). Venkat Ratnam et al. (2013) and Subrahmanyam
and Kumar (2013) have validated relative humidity data
obtained from SAPHIR with other satellite and radiosonde
observations.

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 cyclones. The model do-
main has been configured with two nested domains of 60
and 20 km horizontal resolution, and covers an area ex-
tending from 1° S to 25° N and 60 to 100° E. The inner-
most domain has been used for the present study. The ini-
tial and lateral boundary conditions have been taken from
the ERA-Interim reanalysis on 0.75° × 0.75° continuously
at every 6 h. The present simulation was carried out with
the model physics options: (i) New Simplified Arakawa–
Schubert (NSAS) (Han and Pan, 2011), (ii) Yonsei Uni-
versity (YSU) boundary-layer scheme (Hong et al., 2006),
(iii) rapid radiative transfer model (RRTM) long-wave radia-
tion scheme (Mlawer et al., 1997), (iv) WRF single-moment
(WSM) 5-class microphysics scheme (Hong et al., 2004)
and (v) National Oceanic and Atmospheric Administration
(NOAA) land-surface scheme (Smirnova et al., 2000).

3 Meteorological background

The present experiments were conducted during the passage of the (1) cyclonic storm Nilam from 28 October to 1 Novem-
ber 2012 and (2) very severe cyclonic storm Phailin from
4 to 14 October 2013 over the Bay of Bengal (BOB). The
track of each tropical cyclone and outgoing long-wave ra-
diation (OLR) images (date- and timestamped) are shown
in Fig 1a and b 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 was at maximum and the path/eye was
close to the launching site. The details of each of the tropical
cyclones used for present analysis areas are provided in the
following sections.

3.1 Case-1 (Nilam)

A depression formed over the south-east of BOB (~9.5° N,
86.0° E) at 11:30 IST (IST = UT+5.5 h) of 28 October 2012.
It moved westwards and intensified into a deep depression on
the morning of 29 October 2012 over south-west BOB, about
~550 km south-south-east of Chennai. It continued to move
westwards and intensified into a cyclonic storm, Nilam, in the
morning of 30 October 2012 over south-west BOB. Then it
moved north-north-west, crossed the north Tamil Nadu coast
near Mahabalipuram (12.6° N, 80.2° E), south of Chennai in
the evening hours of 31 October 2012. After the landfall, the
cyclonic storm Nilam moved west-north-west and weakened
gradually into a deep depression and then into a depression in
the morning hours of 1 November 2012.
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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 October 2012 (Nilam) and 09:00 GMT on 10 October 2013 (Phailin). In each panel, date and time are mentioned along the track. In the first panel, 18-1/11 indicates 18:00 GMT of 1 November 2012 and similarly followed for others. The blue star in (a) indicates the ozonesonde launching site Trivandrum.

3.2 Case-2 (Phailin)

A low-pressure system was formed over Tenasserim coast (∼12° N, 96° E), on the early morning of 6 October 2013. It intensified into a depression over the same region on 8 October and then moved towards the west-north-westwards. It further intensified into a deep depression in the early morning of 9 October 2013 and then into a cyclonic storm, Phailin in the evening hours. Moving north-westwards, 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 north-westwards and crossed Andhra Pradesh and the Orissa coast near Gopalpur (19.2° N, 84.9° E) in the late evening of 12 October 2013. It further continued to move north-north-westwards after the landfall for some time, then northward and finally north-north-eastwards up to south-west Bihar. The system weakened gradually into a cyclonic storm from 13 October 2013 and finally the intensity decreased to a low-pressure system on 14 October 2013.

4 Results and discussion

Figure 2a–b show 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 profiles (23 profiles) over Trivandrum in October from 1995 to 2013 and is shown by dotted lines in Fig. 2. During the passage of Nilam on 30 October 2012, enhancement in tropospheric ozone (marked by horizontal arrows) from the background by 40–50 ppbv was observed in the height region between 8 and 9 km (∼1 km width), and 11 and 14 km (∼3 km width). These enhancements persisted until 31 October 2012, but were observed between 6 and 7 km. However, the enhancement of about ∼40 ppbv was still observed on 2 November 2012. A significant sudden decrease in RH is observed on 2 November 2012 at ∼6 km, where the maximum enhancement (∼70 ppbv) of the tropospheric ozone layer is observed. This indicates the presence of accumulated dry air at 6 km. As the stratospheric air is dry and ozone rich, there may be a possibility that on...
Figure 2. (a) Profiles of ozone mixing ratio (OMR) (dark black line) and relative humidity (grey line) for individual days during the passage of tropical cyclones (a) Nilam and (b) Phailin. The mean ozone mixing ratio profile for non-convective days (as control days) is shown with a dotted line. The mean profile is obtained by averaging ozone data over Trivandrum for the month of October from 1995 to 2013. Horizontal arrows indicate the height of the enhanced ozone.

2 November 2012 the accumulated dry ozone-rich air at 6 km may be of stratospheric origin.

A similar phenomenon is also observed during the passage of Phailin. Intrusion from $\sim 14$ to 6 km (marked by horizontal arrows) is clearly observed in the ozone profiles from 11 to 15 October 2013. During Phailin, tropospheric ozone increases by 20–30 ppbv and the width of the enhanced ozone layer is larger than that observed during Nilam. During Phailin, the descent rate of enhanced ozone layer from the upper troposphere to the boundary layer is estimated to be $\sim 1000$ m day$^{-1}$. The descent rate in the tropical non-convective region, under the assumption of no vertical winds, may be inferred from the radiative heating rate in the tropical clear-sky regions. Gettelman et al. (2004) estimated tropical clear-sky radiative heating rates by using ozone and water-vapour sounding data together with the radiative transfer models and found $\sim -1$ to $\sim -2$ K day$^{-1}$ in the troposphere. If the temperature lapse rate is 6–10 K km$^{-1}$ in the upper troposphere, the descent rate is estimated to be 0.1–0.3 km day$^{-1}$. In the present observations, a 0.8–1 km day$^{-1}$ descent rate is estimated during the passage of tropical cyclones, which is three times that of clear-sky (non-convective) days with radiative subsidence. This may indicate that downward flow in association with the tropical cyclones (in their outer regions) enhanced the transport of ozone from the stratosphere to the lower troposphere.

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 into the troposphere. Figure 3 shows variation in the cold-point tropopause height (CPT-H) and cold-point tropopause temperature (CPT-T) derived from temperature measurement by ozonesonde launched during the passage of tropical cyclones (a) Nilam and (b) Phailin over Trivandrum.

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 the passage of tropical cyclones (a) Nilam and (b) Phailin over Trivandrum.
can be linked to the downward flow of upper-tropospheric ozone, even after the cut-off in solar radiation, surface ozone. The enhancement in radiative-convective equilibrium. The present observations of stratospheric intrusion into the troposphere and nearer to the surface, a dynamical analysis is carried out using WRF simulations. Das et al. (2011) and Pan et al. (2015) have shown the ability of WRF simulations during a 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 simulations. Figure 5a shows the presence of strong updraughts (red) and downdraughts (blue) marked with rectangular boxes in the UTLS regions. Enhanced potential vorticity of 0.5–1.5 PVU is also observed vertically down from the stratosphere to the troposphere overlapping the downdraught regions. The potential temperature contours indicate (Fig. 5a) the presence of reduced stability during 29–31 October 2012 (Nilam) and 9–11 October 2013 (Phailin).

Height-time cross section of relative humidity shown in Fig. 5b indicates the presence of dry air from 4 km to the tropopause level. The equivalent potential temperature contours in Fig. 5b indicate that from the surface to ~8 km, the atmosphere is highly unstable and favourable conditions for the convection took 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 compared to the unsaturated atmosphere. The present
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 (8.5° N, 76.9° E) from 27 October to 2 November 2012 and Phailin (right panels) from 7 to 12 October 2013. Rectangular boxes indicate the presence of strong updraughts and downdraughts and the dry air between stratosphere and troposphere. The above parameters are obtained from the WRF simulation.

Figure 6. Same as Fig. 5 but at 79° E at 18:00 GMT on 30 October 2012 for Nilam (left panels) and 18:00 GMT on 10 October 2013 for Phailin (right panels).

condition indicates the presence of statically stable stratospheric air in the upper and middle troposphere. In addition, strong wind shear is also observed in the UTLS region.

Similarly, Fig. 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° E at 18:00 GMT on 30 October 2012 for Nilam (left panels) and 18:00 GMT on 10 October 2013 for Phailin (right panels) using WRF simulations. The vertical velocity profiles show the presence of downdraught (blue) followed by updraught (red) between 8 and 17° N in the UTLS region in both cyclone cases. Enhanced potential vorticity of 0.5–1.5 PVU is also observed vertically down from the stratosphere to the lower troposphere, overlapping the down-
draught regions. High potential vorticity in the troposphere is also a signature of stratospheric air in the troposphere. It is true that enhanced potential vorticity can also be due to diabatic processes associated with condensational heating but the enhancement is only observed with the presence of downdraught in the UTLS region. The potential temperature contours indicate the presence of reduced stability of the atmosphere at this location and noticed that stable stratospheric air penetrated downward at 12–14° N for Nilam and 16–18° N for Phailin. Relative humidity profiles indicate the presence of dry air at ~ 8° N which is in the vicinity of ozonesonde observational site. The equivalent potential temperature contours in Fig. 6b indicate that from the surface to 10 km, the atmosphere is highly unstable and favourable conditions for the convection took place at 6–12° N for Nilam and 12–18° 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 unsaturated 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 at 79° E at 18:00 GMT on 30 October 2012 and 10 October 2013. Numerical simulation reproduced the key features supports the possibility of stratospheric-air intrusion into the troposphere during the passage of tropical cyclone.

To get further insight, relative humidity derived from SAPHIR on board 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 tropical cyclone.
the cyclones: Nilam (left panel) and Phailin (right panel). The grid is averaged from 4 to 8° N and 83 to 88° E. Strong dry-air intrusion originated in the lower stratosphere is observed between 23 and 27 October 2012 (Nilam), and 12 and 18 October 2013 (Phailin). In both the cyclones, dry air (low humidity region) reached down to an altitude of 8 km. For the perception of the spatial distribution of relative humidity, a latitude–longitude plot of relative humidity averaged over different pressure levels is shown in Fig. 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, indicates the possibility that dry air present in the troposphere is of stratospheric origin. The present observations provide strong evidence for the influence of the tropical cyclone on the air-mass exchange from the stratosphere to the lower troposphere and redistribution of stratospheric ozone. Further trajectory and chemical analyses are required to verify this and to quantify the amount of mass exchange taking place between the stratosphere and the troposphere.

5 Summary and conclusions

The important results brought out in the present analysis during the passage of cyclonic storms Nilam (2012) and Phailin (2013) are summarised below:

a. An increase in the upper-tropospheric ozone by 20–50 ppbv is observed from the climatological mean.

b. The upper-tropospheric ozone propagates downwards to the lower troposphere at a rate of 0.8–1 km day⁻¹.

c. An increase of about 10 ppbv in the daytime and 10-15 ppbv in the night-time is noticed in the surface ozone.

d. Significant variation in the cold-point tropopause altitude and temperature associated with tropical cyclones are noticed.

In the present study, the descent of stratospheric air into the troposphere has been deduced indirectly from a combination of ozone and meteorological observations and from modelling. The study clearly reveals that the cyclones play a vital role in changing the atmospheric composition apart from being general weather phenomena.

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