Evidence of stratosphere–troposphere exchange during severe cyclones: a case study over Bay of Bengal, India

Mahesh Pathakoti, Sujatha P., Srinivasa Rao Karri, Sai Krishn S.V.S., Rao P.V.N., Dutt C.B.S., and Dadhwal V.K.

Atmospheric and Climate Sciences Group (ACSG), Earth and Climate Science Area (ECSA), National Remote Sensing Centre (NRSC), Indian Space Research Organization (ISRO), Hyderabad, India

ABSTRACT
The role of cyclones in atmospheric mixing and troposphere–stratosphere exchange of ozone and relative humidity (RH) is investigated for two severe cyclones PHAILIN and HUDHUD over the Bay of Bengal. Ozone concentration from Microwave Limb Sounder along with RH profiles obtained from Sounder for Probing Vertical Profiles of Humidity instrument aboard Meghatropiques platform, upon analysis at different pressure levels, revealed a rapid increase in RH and ozone concentration from lower troposphere to upper troposphere one day prior to landfall for both cyclones. The Weather Research and Forecasting model based simulations of convergence and divergence were used to estimate mass and momentum exchanges between troposphere and stratosphere which suggest the drastic increase in RH and ozone concentrations in UT due to high convective activity. Variations in the vertical profiles of ozone and RH during cyclonic period acts as a tracer for stratosphere–troposphere exchanges during peak cyclone intensity period.

1. Introduction

Atmospheric ozone (O₃) is primarily concentrated in the stratosphere, with about 10%–15% in the troposphere (Krupa & Manning 1988). Photolysis of O₃ is the primary source of the hydroxyl radical (OH) in the troposphere. An increase in O₃ will produce more OH, which decreases lifetime of many trace gases, such as methane (CH₄) and carbon monoxide (CO) (Finlayson-Pitts & Pitts 1993; Lin et al. 2014). Photodissociation of NO₂ (NO+NO₂, λ < 430 nm) by sunlight is the significant anthropogenic source of O₃ formation in the troposphere. CH₄ and CO contribute to ozone production in polluted atmosphere, particularly in the photochemical production of ozone in the free troposphere (Varotsos et al. 1994; Reid et al. 2008). Decrease in the stratospheric O₃ may be due to the updraft of O₃ destroying pollutants generated by both natural processes and by human activity (Krupa & Manning 1988). Studies investigating the transport of ozone and its precursors in the upper troposphere (UT) have accelerated in recent decades with the advent of satellite-based remote sensing and development of advanced chemical transport models. Contamination from long-range transportation, and the transport of air into/from the stratosphere play an important role in identifying the O₃ transport in the UT (Mahlman 1997; Kaskaoutis et al. 2012). A decrease in the stratospheric O₃ concentrations brought about by reaction with various pollutants mixed into the...
stratosphere due to stratosphere—troposphere exchanges (STE) results in a greater incidence of harmful ultraviolet at the earth’s surface (Krupa & Manning 1988).

Several researchers have also studied tropical cyclones and their effect in transporting contaminants, such as ozone and CO (Thompson et al. 1997; Fadnavis et al. 2011; Midya et al. 2012). Severe cyclones may extend up to the upper layer of troposphere due to large quantity of water vapour and the influence of the tropical convective systems (Mitra 1996). Variation in total columnar ozone due to tropical cyclones has been studied by Midya et al. (2012) in the period leading up to, during and after, landfall of tropical cyclone. The physical processes behind the transport of gases from the planetary boundary layer into the free troposphere are crucial towards understanding air pollution problems at local and global scales as well as climate issues (Leiivelde and Crutzen 1990; Fadnavis et al. 2011). Dickerson et al. (2007) showed the role of cyclone in transporting pollutants into the UT from lower troposphere (LT) and reported the vertical exchange of ozone from lower stratosphere to UT. The tropopause height (TH) is also an important meteorological parameter that separates the troposphere from the stratosphere (Wirth 2001). During convective systems, it has an advantage when considering the exchange of mass or constituents across the tropopause (Wirth & Egger 1999). The sensitivity of deep tropical convective systems on ozone budget studied by Thompson et al. (1997) using Goddard Cumulus Ensemble and Tropospheric Chemistry models explained that ozone formation can be enhanced when deep convection injects boundary layer pollutants into the free troposphere.

Tropical cyclones occur when low-pressure regions formed from weak pressure waves propagating from east to west lead to the formation of low-level convergence under favourable conditions. If the sea is warm enough and there is sufficient upper level divergence, i.e. the air mass rising from the low-pressure region is blown away at higher levels, then the decreased pressure at the surface due to the removal of the overlying air mass leads to increasing convergence. Low-level convergence coupled with upper level divergence gives rise to vertical motion taking the air mass through an in-up-out pattern. Air flows into the storm centre at low levels of the atmosphere bringing in heat and moisture from the ocean surface and is expelled at higher levels. The deep convective processes, thus associated with cyclones are thus responsible for transport of water vapour and ozone from the lower to upper levels of the atmosphere.

In this study, we have analysed variations in ozone and RH during the PHAILIN (2013) and HUDHUD (2014) cyclones which occurred over the Bay of Bengal (BoB). PHAILIN, which was the most intense cyclone to occur after the Odisha super cyclone of October 1999, devastated most of coastal Odisha and parts of coastal Andhra Pradesh. HUDHUD (7–14 October 2014) was even more intense than PHAILIN with wind speeds in excess of 180 kpmh recorded over the west central BoB along Andhra Pradesh coast. It crossed northern coast of Andhra Pradesh at Visakhapatnam (VSK) between 1200 and 1300 hr on 12 October 2014 with the same wind speed (IMD report 2013 and 2014). The BoB is relatively more polluted region as it is more strongly influenced by surrounding continental emissions than the Arabian Sea (Leiivelde et al. 2001; Kunhikrishnan & Lawrence 2004; Kunhikrishnan et al. 2004). Here, we report ozone exchange from lower stratosphere to UT based on vertical distribution of ozone at different pressure levels (215, 146 and 100 hPa) during high intensity of cyclones on 12 October 2013 and 2014 over BoB.

2. Data and methodology

The Aura Microwave Limb Sounder (MLS) instrument aboard Aura satellite (http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&project=MLS), measures vertical profiles of mesospheric, stratospheric and upper tropospheric temperature, ozone, sulphur dioxide (SO2) and CO from limb scans (Levett et al. 2006). In this study, we utilized the MLS standard product for ozone derived from radiance measured by the 240 GHz radiometer (Schoerbel et al. 2007). Vertical distribution of ozone has been shown over BoB during severe cyclones occurring in October 2013 (PHAILIN) and October 2014 (HUDHUD). Ozone for the cyclonic region has been shown 3 days
before and after the landfall to see the cyclone effect on ozone in the atmosphere. Daily averaged relative humidity (RH) profiles at six levels (1000–880 hPa, 850–700 hPa, 700–550 hPa, 550–400 hPa, 400–250 hPa and 250–100 hPa) were obtained from a Sounder for Probing Vertical Profiles of Humidity (SAPHIR) microwave humidity sounder and a radiometer of Meghatropiques to infer the STE.

2.1. Study area and meteorological conditions during cyclone

The PHAILIN and HUDHUD (a very severe cyclonic storm; VSCS) formed in BoB, India during 9–14 October 2013 and 7–14 October 2014, respectively. In this study, the cyclone affected region is considered 10–25°N latitude and longitude 80–95°E.

2.1.1. PHAILIN

From satellite observations, intense to very intense convection was seen over Andaman Sea and adjoining area between latitude 8.50°N to 14.50°N and longitude 88.50°E to Tenasserim coast (13.0°N, 98.75°E) on 8 October 2013 (figure 1(a)). According to Dvorak’s intensity scale, the intensity of the system was T 1.5 (IMD, October 2013 cyclone report). The system showed shear pattern with convection shifted to the west of low-level circulation centre. A deep depression formed on the morning of 9 October which intensified into a cyclonic storm (CS), ‘PHAILIN’ by evening. Moving north-westwards, it further intensified into a severe cyclonic storm (SCS) in the morning and into a VSCS in the forenoon of 10 October 2013 with wind speed >115 knots over east central BoB. Light green circle with star marks indicates the VSCS with pressure of 998 hPa as shown in figure 1(a). The cyclone traversed the BoB from 9 to 14 October 2013 and dissipated after landfall on 11 October 2013. This was the most intense cyclone which struck the Indian coast after the Odisha super cyclone of 29 October 1999.

2.1.2. HUDHUD

A VSCS developed from a low-pressure area over the Tenasserim coast and adjoining North Andaman Sea in the morning of 6 October 2014. The low-pressure system concentrated into a depression in the morning of 7 October 2014 over the North Andaman Sea and further intensified into a CS in the morning of 8 October 2014. It moved further into BoB and continued to move west-by-north-westwards. It continued to intensify while moving north-westward and reached maximum intensity (figure 1(b), thick blue circle with pressure of 994 hPa) in the early morning of 12 October 2014 with a maximum wind speed of 100 knots over the west central BoB off Andhra Pradesh coast. HUDHUD is the first cyclone that crossed VSK coast in the month of October after 1985.

Figure 1. (a) PHAILIN cyclone track from 9 to 14 October 2013. (b) HUDHUD from 7 to 14 October 2014.
2.2. Model details

Weather Research and Forecasting (WRF) is a non-hydrostatic model, which includes several options of dynamic cores and physical parameterizations so that it can be used to simulate atmospheric processes over a wide range of spatial and temporal scales (Skamarock et al. 2005). In this study, the WRF model with advanced research WRF (ARW) core was initialized with the National Centre for Environmental Prediction Final Analysis data at 1° × 1° resolution for every 6 hourly intervals (http://dx.doi.org/10.5065/D6M043C6). Model was integrated for 3 days starting from 00 UTC of 10 October 2013 and 2014 for PHAILIN and HUDHUD cyclones, respectively. Details of physical processes and parameterization scheme used for this experiment are given in table 1.

3. Results

3.1. Relative humidity levels during cyclonic periods

Figures 2(a) and (b) show variation in vertical profiles of RH between 1000 and 200 hPa obtained from SAPHIR microwave sounder during the period of study for both cyclones. A gradual decrease in the vertical profile of RH occurred until landfall for both cyclones with minimum RH observed on the day of landfall, accompanied by a considerable increase in RH along vertical profile in the days after landfall. The decrease in RH before and on day of landfall is observed to be more significant for HUDHUD as compared to that of PHAILIN as HUDHUD, being the more severe cyclone, caused more precipitation (IMD report, October 2013 and 2014). The difference values in RH of other days against the day before landfall as shown in table 2. In general, RH has considerable difference in the upper part of the troposphere and minimum near the surface. Maximum difference observed during PHAILIN (HUDHUD) is approximately 45% (55%) at level 4 (550–400 hPa) compared to normal days which, indicates strong vertical convection during high intensity of severe cyclones. Further investigations were made to understand the mass or air pollutants exchange between troposphere and stratosphere.

Table 1. WRF model physical processes and parameterizations schemes.

| S. No. | Physical process       | Parameterization scheme |
|--------|------------------------|-------------------------|
| 1      | Micro Physics          | WSM5                    |
| 2      | Long-wave radiation    | RRTM                    |
| 3      | Short-wave radiation   | Goddard                 |
| 4      | Boundary layer         | YSU                     |
| 5      | Cumulus parameterization | Grell-3               |
| 6      | Land surface process   | Noah                    |

Figure 2. Vertical distribution of relative humidity during (a) PHAILIN and (b) HUDHUD.
3.2. WRF model simulated convergence and divergence

The WRF model simulated convergence and divergence along with circulation for cyclones HUD-HUD and PHAILIN are shown in figure 3. Intense convergence formed at lower level (925 hPa), which transports water vapour and gases into middle and UT around primary and secondary convergence zones. Furthermore, this transportation has been maintained and enhanced by intense divergence at upper level (200 hPa), which helps in well mixing of convected moisture and gases to the UT and lower stratosphere. In the middle troposphere (500 hPa), model simulations show belts of weak convergence and divergence pattern embedded on each other. The cyclonic motions of convergence and divergent at higher and lower pressure levels, respectively, which are accompanied by bands of subsidence motions around the deeply convective eye walls (Willoughby 1988) are illustrated in figure 3.

| Pressure levels (hPa) | 9 October 2013 (9 October 2014) | 10 October 2013 (10 October 2014) | 12 October 2013 (12 October 2014) | 13 October 2013 (13 October 2014) | 14 October 2013 (14 October 2014) |
|-----------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Level-1 (1000–850)    | −0.21                            | 0.28                             | −5.01                            | −2.22                            | 0.81                             |
| Level-2 (850–700)     | (−8.05)                          | (−3.00)                          | (−5.10)                          | (−7.93)                          | (−7.19)                          |
| Level-3 (700–550)     | 13.16                            | 5.62                             | 14.56                            | 21.50                            | 17.69                            |
| Level-4 (550–400)     | 22.58                            | 10.54                            | 21.69                            | 33.37                            | 23.37                            |
| Level-5 (400–250)     | 28.30                            | 11.65                            | 28.73                            | 44.82                            | 44.80                            |
| Level-6 (250–100)     | −7.32                            | −9.78                            | 4.26                             | 7.38                             | 17.48                            |

Table 2. RH difference from the day before landfall.

Figure 3. Convergence and divergence ($10^{-7}$ s$^{-1}$) during PHAILIN and HUDHUD.
3.3. Tropopause height

The TH obtained from Constellation Observation System for Meteorology, Ionosphere and Climate (COSMIC)—Radio Occultation (RO) database, which is a repository of 1-DVAR wet profile data of temperature, pressure and water vapour (http://cdaac-www.cosmic.ucar.edu/cdaac/index.html). The data were examined at 0.1 km vertical resolution (Peethani et al. 2014; Mahesh et al. 2015) over a $3^\circ \times 3^\circ$ region with eye of cyclone as its centre for the VSCS, PHAILIN. It could not be examined for HUDHUD cyclone event due to non-availability of COSMIC-RO data for the same region. Figures 4((a) and (b)) explain the TH variation during perturbed (11 October 2013) and relatively unperturbed (5 October 2013) atmosphere. The cold-point temperature (CPT) during unperturbed and perturbed atmospheric conditions was 192.94 K and 187.77 K, respectively. Positive vertical gradient in tropopause temperature of 5.5 K was observed during server cyclonic day compared to normal day. Drop in tropopause temperatures could be due to more water vapour transported to (figures 2 and 3) UT because of strong convection on high intensity of cyclone. It is observed that during high phase of cyclone the TH (16.7 km, ~100 hPa) shifted by 300 m from the normal day (16.4 km, ~100 hPa). The maximum positive deviation of CPT was observed to be 5.5 K which points to updraft of UT due to high convection. During cyclonic periods, Wirth (2001) also reported the large deviations in the TH.

3.4. Vertical distribution of ozone during very severe cyclones

Figures 5((a) and (b)) illustrate the vertical distribution of ozone during PHAILIN and HUDHUD CSs over a $15^\circ \times 15^\circ$ study region over the BoB and surrounding area. During the high phase of both cyclones, a decrease in ozone concentrations was observed in the LT accompanied by an
increase in the UT and a drop in concentration in the lower stratosphere. During the severe cyclonic period preceding landfall, the strong vertical convection which drives RH variations (figures 2(a) and (b)) also significantly contributes towards lifting of ozone to upper level of the atmosphere as shown in figures 5(a) and (b). The ozone concentration at 146 hPa is greater than at 215 hPa during the period of peak cyclonic activity, thus implying a strong exchange of ozone between the UT and lower stratosphere. This exchange may also be due to downward transport of ozone mixing ratios from the lower stratosphere to UT.

4. Summary and conclusions

In this case study, we have analysed variations in ozone and RH at different pressure levels during the VSCSs of PHAILIN and HUDHUD which occurred off the eastern coast of India between 9–14 October 2013 and 7–14 October 2014, respectively, over the BoB. We observed a marked decrease in the vertical profile of tropospheric RH along with a shift in the peak ozone concentration from the lower stratosphere to UT subsequent to the day of landfall for both cyclones. The decrease in upper atmospheric concentrations of both RH and ozone after landfall for both cyclones occurs due to weakening of convective activity caused by collapse of convergence after landfall of cyclone. Our observations strongly support the presence of stratosphere–troposphere mixing during severe cyclones as reported by Baray et al. (1999) and Fadnavis et al. (2011).

Acknowledgments

We would like to thank NASA’s Giovanni and Mirador web portal for providing the data of Aura/MLS satellite. The authors also thank IMD for providing the information about cyclone track. We also acknowledge team MOSDAC (mosdac.gov.in) for providing the Meghatropiques data. We also thank the editor and anonymous referees for their comments/suggestions, which have certainly improved the quality of manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Mahesh Pathakoti obtained BTech in physical sciences from Indian Institute of Space Science and Technology (IIST) in 2011 and currently working as a scientist in Atmospheric and Climate Sciences Group (ACSG) of National Remote Sensing Center (NRSC) at Hyderabad, India. His area of research is in the field of atmospheric trace gases and their impact on climate system.

Sujatha P. pursuing PhD from Andhra University, Visakhapatnam, India. She is currently working in NRSC as a senior research fellow. Her area of experience is in analysis of long term COMIC RO data towards understanding the impact of tropopause and boundary layer height over Indian region.

Srinivasa Rao Karri is currently working as scientist in NRSC. His research focuses on running the weather research and forecasting (WRF) and WRF-Chem to understand the hot spots of atmospheric trace gases and their impact on regional climate change.

Sat Krishn S.V.S. obtained BTech in physical sciences from IIST in 2011 and is currently working as a scientist in ACSG of NRSC at Hyderabad, India. His current research interests include energy balance at the surface and studies of atmospheric boundary layer dynamics through micrometeorological tower based measurements.

Rao P.V.N. is a deputy director of Earth and Climate Science Area (ECSA) and programme director of National Information System for Climate and Environment Studies (NICES) at NRSC, Hyderabad. His area of expertise is in microwave remote sensing.

Dutt C.B.S. was a former deputy director of ECSA of NRSC at Hyderabad. He was responsible for implementing ECSA activities at NRSC with special emphasis on ocean, atmosphere, land surface processes products analysis using satellite and in-situ data.
Dadhwal V.K. is a distinguished scientist and director, NRSC, Indian Space Research Organisation (ISRO), Hyderabad. His research interests are crop modeling, remote sensing applications in agriculture, terrestrial carbon cycle, land cover land use change modeling, and land surface processes.

References

Baray JL, Ancialet G, Randriambelo T, Baldy S. 1999. Tropical cyclone Marlene and stratosphere—troposphere exchange. J Geophys Res (1984—2012). 104:13953—13970.

Dickerson RR, Li C, Li Z, Marufu LT, Stehr JW, Mc Clure B, Yang J. 2007. Aircraft observations of dust and pollutants over northeast China: insight into the meteorological mechanisms of transport. J Geophys Res (1984—2012). 112, D24S80, 1—13.

Fadnavis S, Beig G, Buchunde P, Ghude SD, Krishnamurti TN. 2011. Vertical transport of ozone and CO during super cyclones in the Bay of Bengal as detected by Tropospheric Emission Spectrometer. Environ Sci Pollut Res. 18:301—315.

Finlayson-Pitts BJ, Pitts Jr. JN. 1993. Atmospheric chemistry of tropospheric ozone formation: scientific and regulatory implications. Air Waste. 43:1091—1100.

Kaskaoutis DG, Kosmopoulos PG, Nastos PT, Kambezidis HD, Sharma M, Mehdi W. 2012. Transport pathways of Sahara dust over Athens, Greece as detected by MODIS and TOMS. Geomat Nat Haz Risk. 3:35—54.

Krupa SV, Manning WJ. 1988. Atmospheric ozone: formation and effects on vegetation. Environ Pollut. 50:101—137.

Lelieveld J, Crutzen PJ, Ramanathan V, Andreae MO, Brenninkmeijer CAM, Campos T, Williams J. 2001. The Indian Ocean experiment: widespread air pollution from South and Southeast Asia. Science. 291:1031—1036.

Levelt PF, vanden Oord, GH, Dobber RM, Malkki A, Visser H, de Vries J, Saari H. 2006. The ozone monitoring instrument. IEEE Trans Geosci Remote Sens. 44:1093—1101.

Reid N, Yap D, Bloxam R. 2008. The potential role of background ozone on current and emerging air issues: an overview. Air Qual Atmos Health. 1:19—29.