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Case study of deep STE event of ozone at a low latitude Indian station using simultaneous balloon borne ozonesonde and surface ozone measurements

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सार – क्षोभमंडल में ओज़ोन की मात्रा को प्रभावित करने वाले महत्वपूर्ण कारक ओज़ोन का समतापमंडल क्षोभमंडल में परस्पर विनिमय (STE) का होना है। यह सर्वमान्य बात है कि निम्न अक्षांशों पर समतापमंडल क्षोभमंडल विनिमय (STE) अपेक्षाकृत असामान्य होता है। इसलिए इस शोध पत्र में ओजोन सौंदे, उपग्रह एवं पराबैंगनी प्रकाशमिक ओज़ोन विश्लेषक आंकड़ों का उपयोग करते हुए भारत के निम्न अक्षांश पर स्थित ऊष्ण कटिबंधीय ओज़ोन के समतापमंडल क्षोभमंडल विनिमय (STE) की घटना का गहराई से अध्ययन किया गया है।

ABSTRACT. Stratosphere Troposphere Exchange (STE) of ozone is an important factor influencing the budget of ozone in the troposphere. It is well established that STE is relatively uncommon at low latitudes. Therefore a case study of deep STE event of ozone at a low latitude tropical coastal site of India is presented in the paper using ozonesonde, satellite and UV photometric ozone analyzer data.

Key words – Stratospheric intrusion, Ozone, Deep STE, Potential vorticity, Vertical pressure velocity, Relative humidity.

1. Introduction

Stratospheric ozone plays a beneficial role by absorbing most of the biologically damaging ultraviolet (UV) radiation. Decrease in stratospheric ozone will result in an increase in UV-B radiation, which will have negative impacts on human health such as suppressed immune system, serious sunburn, cataracts, reduced vitamin D synthesis, skin cancer and also cause deterioration of synthetic materials like plastics. However, as ozone is toxic to the living system, intense exposure to surface ozone may result in persistent decrease in lung function, pneumonia, influenza, asthma, decrease in crop yield and also cause the temperature of the atmosphere to rise as it is a green house gas. Transport of ozone from the stratosphere to the troposphere will result in a decrease in stratospheric ozone and corresponding increase in tropospheric ozone which can have serious consequences for life on earth.

Surface ozone at any location depends on the amount of its supply from the stratosphere, rate of photochemical production (Kirchhoff, 1988), transport from other regions and the rate of its destruction on the earth's surface either due to dry deposition or photochemical loss mechanisms (Junge, 1962; Crutzen, 1974; Van Dop *et al*., 1977). The mechanisms leading to Stratosphere Troposphere Exchange (STE) are tropopause folds, cut-off lows, and quasi adiabatic transports along isentropic surfaces (Holton *et al*., 1995; Vaughan, 1988). Shallow exchange events are partially reversible in nature and produce compositional changes in the tropopause region. However, deep STE events are largely irreversible and have a highly significant impact on atmospheric chemistry. Rapid and deep STE events are associated with severe weather (Browning and Reynolds, 1994; Browning and Golding, 1995; Georing *et al*., 2001) and cause ozone peaks at the surface (Stohl *et al*., 2000; Stohl *et al*., 2003). When compared with photo chemically induced high ozone episodes produced *in situ* near the Earth's surface, relatively little attention has been paid in India to the surface episodes which have their origin in downward transport from the lower stratosphere. Although these episodes are relatively uncommon, they have been reported to produce transient peak ozone concentrations of around 100 ppbv at sea-level and concentrations in excess of 250 ppbv in mountain regions (Davies and Schuepbach, 1994). STE of ozone at Thiruvananthapuram using ozonesonde and rocket measurements have been reported by Indian scientists in the past (Mandal *et al*., 1998; Mohankumar, 2008; Ganguly and Tzanis, 2011). However, study of deep STE of ozone at

Fig. 1. Map of India depicting the measurement site

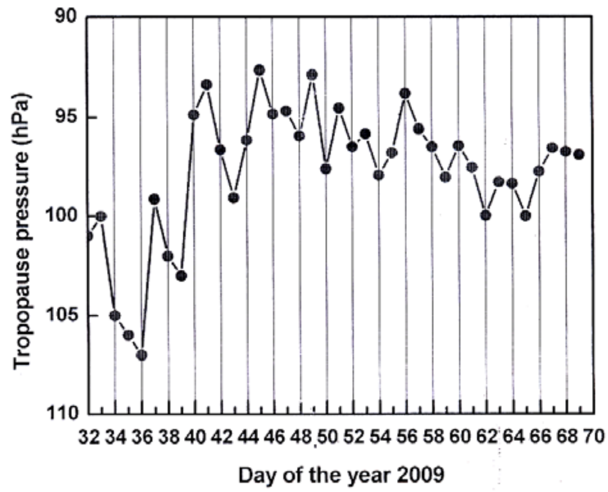


Fig. 2. Tropopause pressure observed at Thiruvanthapuram from 1 February 2009 - 10 March 2009. Tropopause weakening is observed on several occasions during February 5, 8, 12, 19, 23, 28 and during March 3 and 6 (*Source* : NCEP Reanalysis)

Thiruvananthapuram using simultaneous balloon borne ozonesonde and surface ozone measurements is being reported for the first time to my knowledge. Ganguly and Tzanis (2011) have observed that STE events at Thiruvananthapuram were found to occur more frequently during winter and the occurrence of shallow STE is higher compared to deep STE. As Thiruvananthapuram is located in the tropical coastal region, and is devoid of any large scale industrial activity, any abnormal increase in surface ozone level is either due to photochemical production in presence of high dose of solar radiation, or long range transport of ozone and its precursors or intrusion of ozone from the stratosphere. In the light of these observations, a rare case study of deep STE of ozone, which occurred on 25 February, 2009 is presented using ozone sonde, satellite and UV photometric ozone analyzer data.

2. Experimental site

Thiruvananthapuram (8.5° N, 76.9° E), the capital of the state of Kerala is situated by the sea shore on the west coast, near the southern tip of mainland India (Fig. 1). It is bounded by Arabian Sea to its west and the Western Ghats to its east. The city spans over an area of around 250 km^2 and has an elevation of 16 ft above sea level. Ozone sonde launches of India Meteorological Department (IMD) and measurements of near surface ozone were carried out at a site within the city at an altitude of 60 m from mean sea level. The site is devoid of any large scale industrial activity.

3. Data and its analysis

The vertical temperature and ozone profiles from 1973 - 2009 at Thiruvananthapuram were obtained from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC). These profiles were measured by IMD at all standard pressure levels (from 1000 hPa to 1 hPa with an accuracy of 0.5 hPa). The pressure levels for 25 February, 2009 ozone profile were equated to their equivalent altitude in km. The ozonesonde used for the vertical sounding was Electrochemical Concentration Cell and data were taken during the ascent of the balloon. Sounding was performed at 0510 hr IST (Indian Standard Time). Cold point tropopause was identified from ozonesonde temperature data. Continuous measurement of near surface ozone was carried out by using online UV photometric ozone analyzer, which is based on the principle of absorption of UV light by the ozone molecules at a wavelength of 254.7 nm. Calibration of the instrument is done regularly. The lower detection limit of the instrument is 1.0 ppbv. The instrument takes measurements at intervals of 10 seconds, and data averaged at 5 min intervals were used in the present study. The 5 day back trajectories and potential vorticity at different pressure levels were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF). Vertical pressure velocity and relative humidity at different pressure levels in the troposphere and tropopause

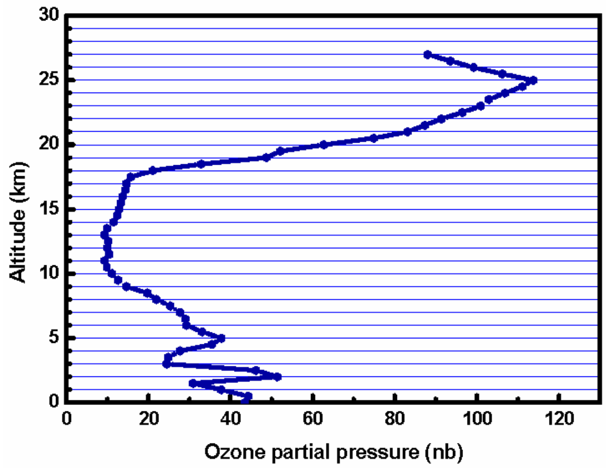
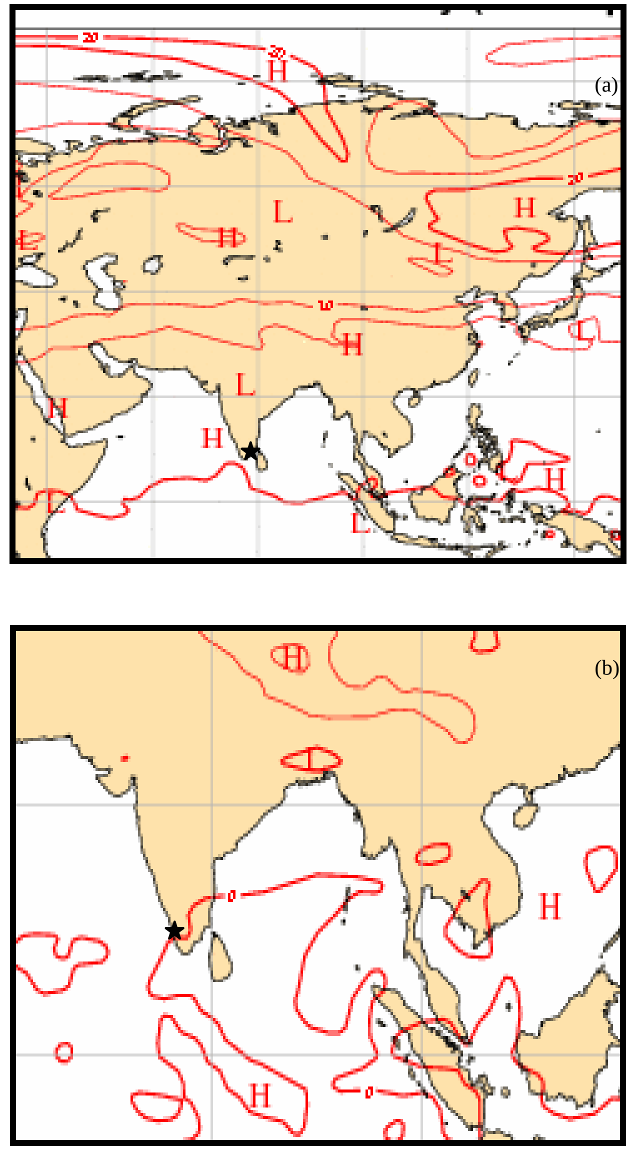


Fig. 3. Vertical ozone profile at Thiruvananthapuram on 25 February, 2009; 0510 hrs IST (*Source of data* : India Meteorological Department and WOUDC)



Figs. 5(a&b). Potential vorticity at (a) 100 hPa and (b) 300 hPa pressure levels (at 0600 UTC) on 25 February, 2009 (*Source* : ECMWF)

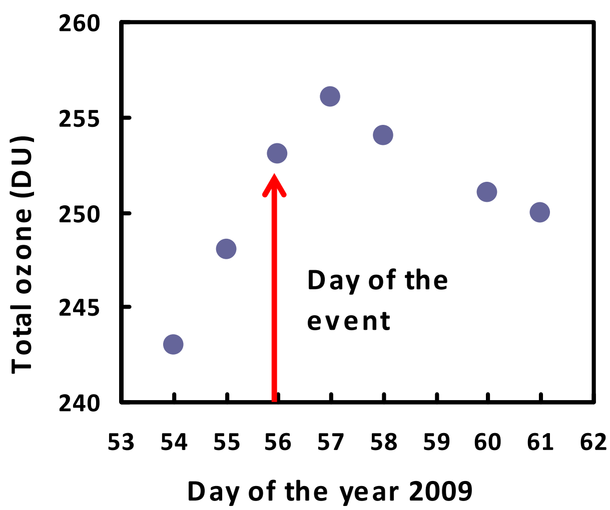
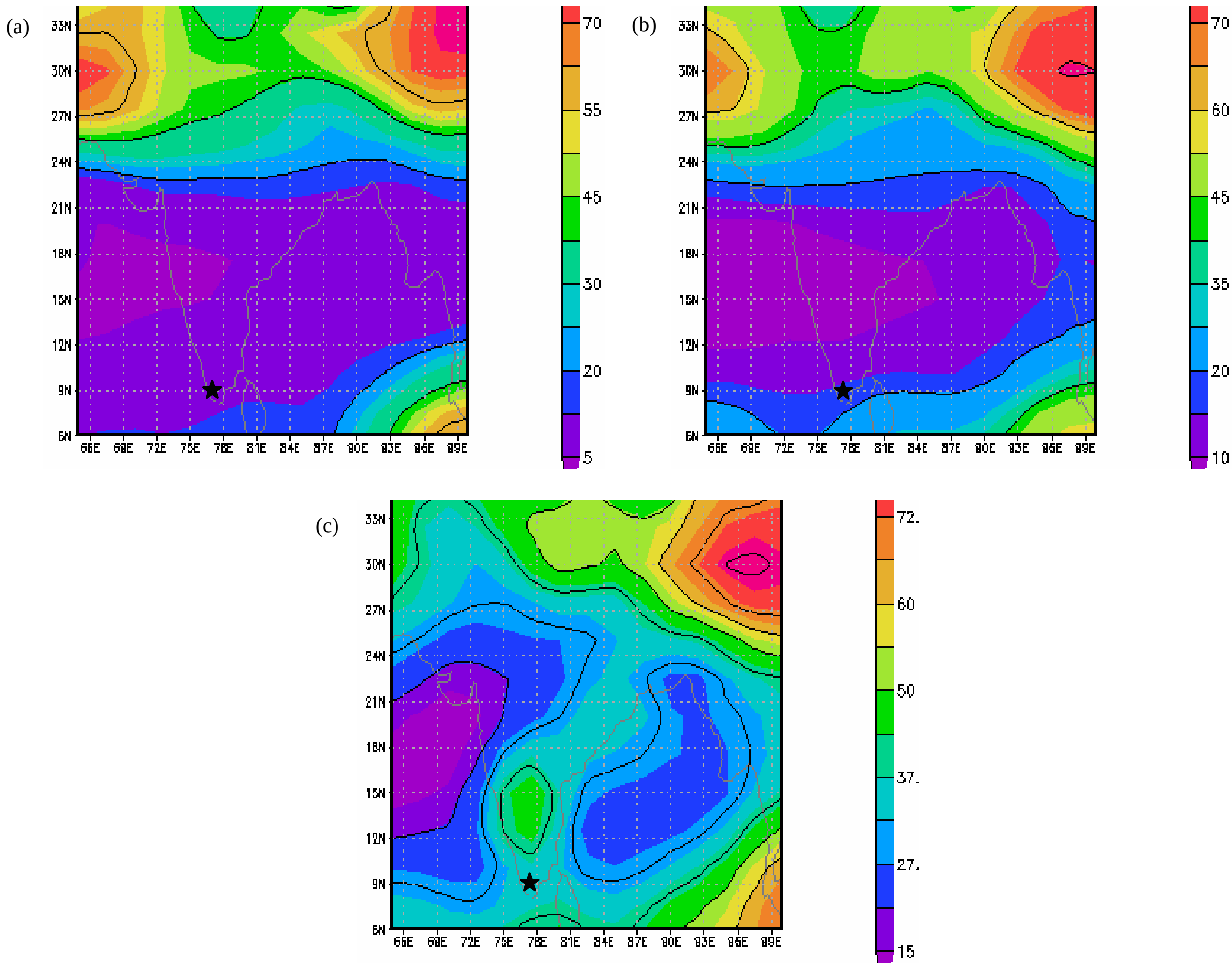


Fig. 4. Total ozone observed at Thiruvananthapuram from 23 February 2009 – 2 March 2009 (*Source* : Ozone monitoring instrument)

pressure was retrieved from NCEP/NCAR Reanalysis (Kalnay *et al.*, 1996). Tropospheric Carbon monoxide (CO) and Methane (CH_4) data were obtained from TES (Tropospheric Emission Spectrometer) on NASA's EOS (Earth Observing System) spacecraft and total ozone and nitrogen dioxide (NO_2) column data was obtained from Ozone monitoring instrument (OMI).

4. Discussion of results

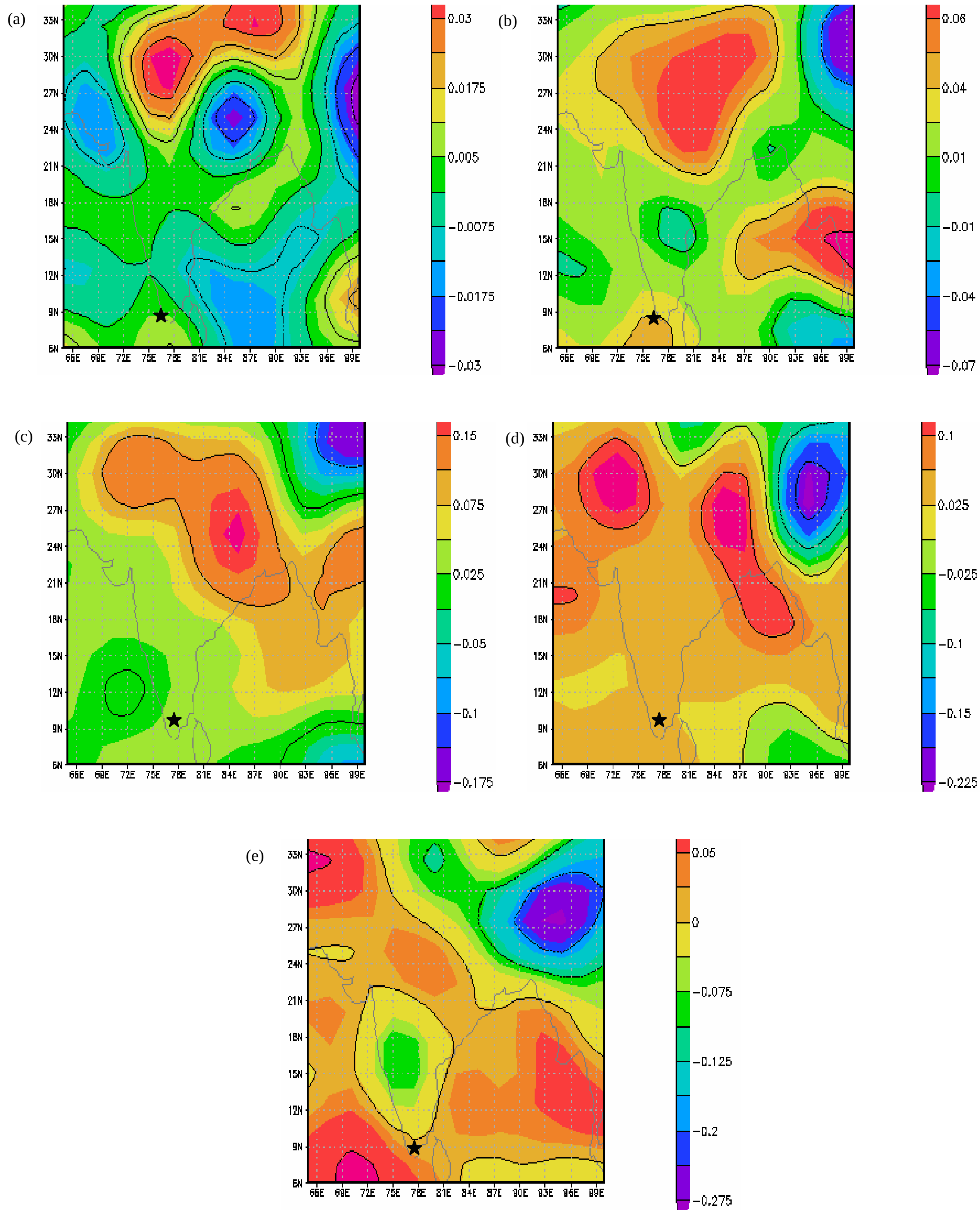
As pressure decreases with altitude, higher values of tropopause pressure indicate lower tropopause height. The Indian ozonesonde profiles from 1973-2009 indicated that the average cold point tropopause height at Thiruvananthapuram is at around 95.5 hPa pressure level (around 16.5 km from the earth's surface). An examination of tropopause pressure during the period from 1 February to 10 March 2009 from NCEP reanalysis (Fig. 2), indicated tropopause weakening on several occasions during February 5, 8, 12, 19, 23, 28 and March 3 and 6. Rosenlof (1995) reported that the mass flux across stratosphere during STE was largest between December and February and smallest between June and August.



Figs. 6(a-c). Relative humidity (%) at (a) 500 hPa, (b) 600 hPa and (c) 700 hPa pressure levels on 25 February, 2009 (*Source* : NCEP Reanalysis)

The vertical ozone profile measured at 0510 hrs (IST) on 25 February 2009 indicates a layer of high ozone partial pressure (around 52 nb) at an altitude of 2 km from the earth's surface (Fig. 3). The increase in ozone partial pressure was accompanied with a small increase in total ozone content (from 243 DU on 23 February to 256 DU on 26 February; Fig. 4). The possible causes for this enhanced ozone concentration were examined in detail.

Potential vorticity is a measure of the spin of air. Stratospheric air is characterized by high potential vorticity (PV> 1.6) and low relative humidity (RH < 60%) [WMO definition; Cristofanelli *et al.*, 2010]. In the present study, potential vorticity at 100 hPa and 300 hPa pressure levels were high [Figs. 5(a&b)] and relative humidity at 500, 600 and 700 hPa pressure levels on 25 February were 10%, 15% and 37% respectively [Figs. 6(a-c)], indicating the presence of air masses having stratospheric origin. The vertical pressure velocity (Pa s^{-1}) was examined to confirm the downward transport of ozone from the stratosphere. As pressure decreases with altitude, positive values of vertical pressure velocity indicate sinking motion and negative values indicate rising motion in the atmosphere. The positive values of vertical pressure velocities (Pa s^{-1}) at all pressure levels from the tropopause (100 hPa) to 600 hPa confirmed the downward transport of ozone from the stratosphere [Figs. 7(a-e)]. In the remote troposphere, ozone formation is sustained by the oxidation of CO and CH_4 through OH. In order to check the possibility of the layer of high ozone partial pressure being influenced by polluted air or biomass burning plumes, the CO, CH_4 and NO_2 concentration at Thiruvananthapuram and along the path of back trajectories were examined. The 5 day back trajectories at 925, 850 and 700 hPa pressure levels were examined to determine the place from where the air parcels had originated (Fig. 8). This information was in turn used to check the possibility of horizontal transport of ozone and its precursors from these areas. It was observed from the back trajectories that the air parcels from 700 - 925 hPa



Figs. 7(a-e). Vertical pressure velocity (Pa S^{-1}) at (a) 100 hPa, (b) 200 hPa, (c) 300 hPa, (d) 600 hPa and (e) 850 hPa pressure levels on 25 February, 2009 (*Source* : NCEP Reanalysis)

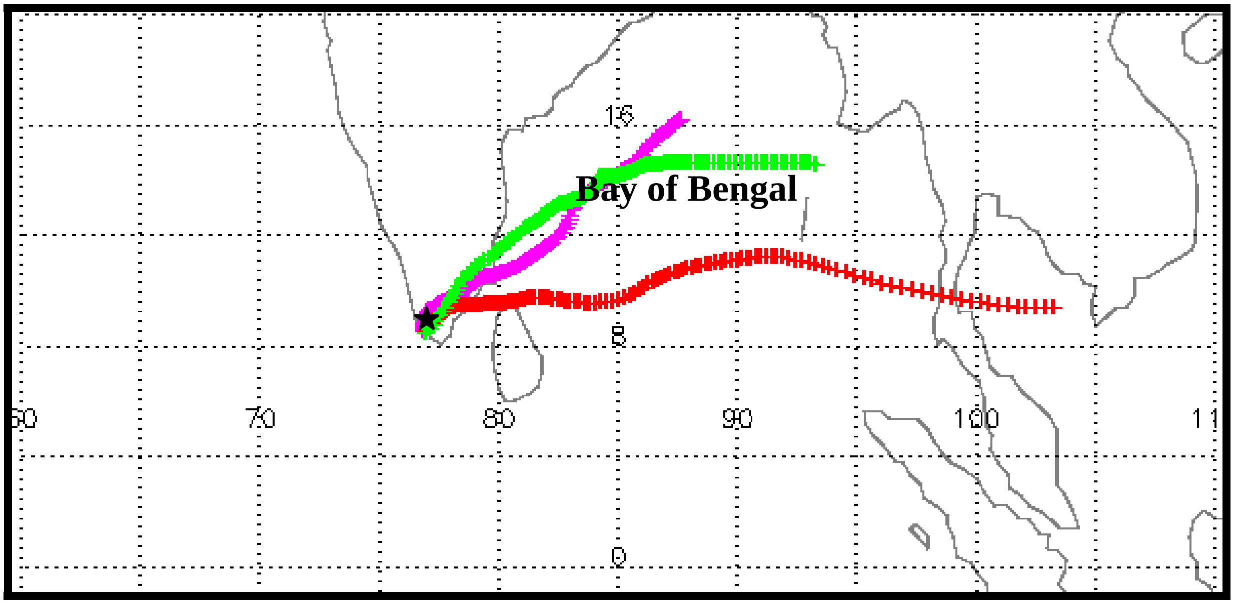


Fig. 8. Five (5) day back trajectories at 925 (pink), 850 (red) and 700 (green) hPa pressure levels (*Source of data* : ECMWF)

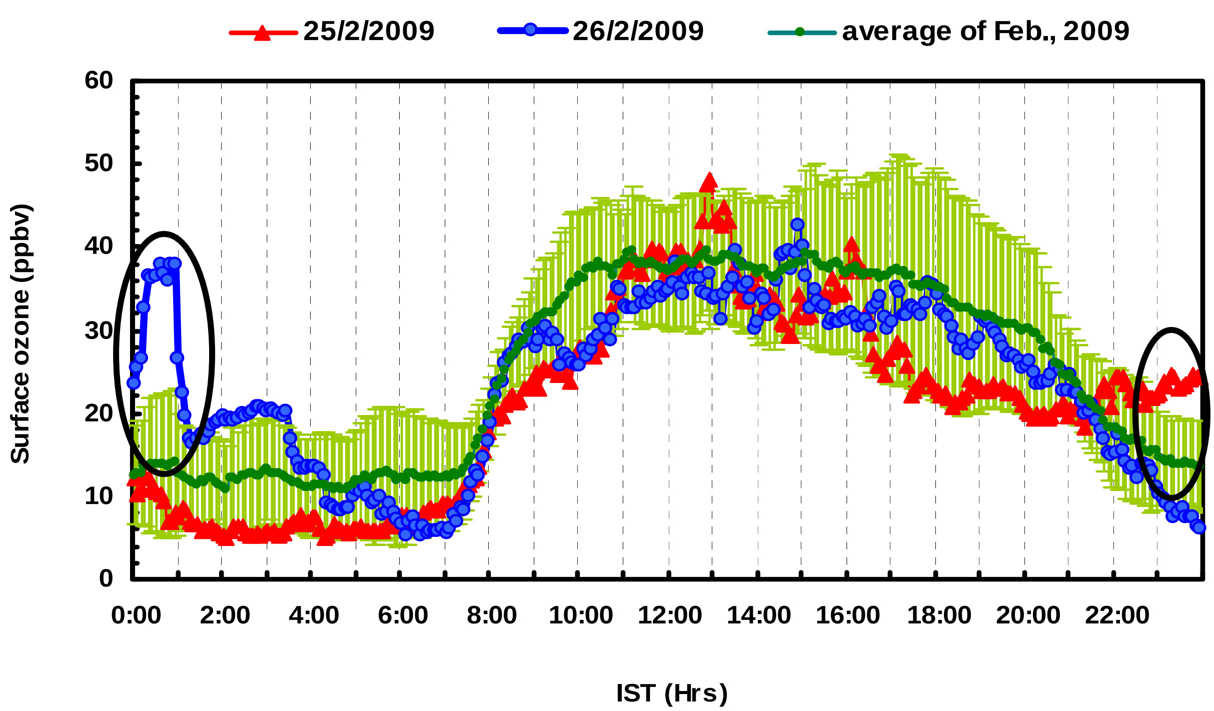


Fig. 9. Comparison of monthly mean diurnal variation of surface ozone during February 2009 with the diurnal variation of surface ozone measured on 25 and 26 February, 2009 at Thiruvananthapuram. Bars indicate ± one standard deviation. The enhanced surface ozone is highlighted inside the black oval shape

pressure levels at Thiruvananthapuram had originated from regions in the Bay of Bengal, having nearly same CH_4, CO, ozone and NO_2 levels as at Thiruvananthapuram. Since high insolation and humidity destroys ozone and its precursors (Roelofs and Lelieveld, 2000), the air parcels passing over sea / ocean in the present study are not expected to contribute to the observed enhanced ozone in this study. This suggests that the enhanced ozone layer observed at an altitude of 2 km at 0510 hrs IST on 25 February may be due to intrusion of ozone from the stratosphere during the events of tropopause weakening on February 19 and 23.

The diurnal variation of surface ozone for all available days (20 days) in the month of February 2009 was averaged and compared with the diurnal variation of ozone on 25 and 26 February for any abnormal variations in surface ozone (Fig. 9) on these days. The monthly mean surface ozone concentration at Thiruvananthapuram in February 2009 was observed to be low (15 ppbv) at sunrise [up to 0730 hrs (IST)]; increase gradually to a maximum (40 ppbv) around 1200 hrs (IST), remain high up to around 2000 hrs IST and thereafter decrease to reach a minimum (15 ppbv) at night similar to that observed by David and Nair (2011). However, it was observed that the surface ozone level on 25 February was higher than the monthly mean value by around 10 ppbv at 2300 hrs (IST), continued to increase sharply thereafter, reaching a maximum of 38 ppbv (higher than the monthly mean value by around 25 ppbv) around 0030 – 0100 hrs (IST) on 26 February and decreased to the normal value around 0430 hrs (IST) (Fig. 9). The vertical pressure velocities (Pa s^{-1}) from 600 - 850 hPa (altitude of 4 - 1.5 km from earth's surface) pressure levels indicated downward transport of air parcels on 25 February. In absence of photochemical production of ozone at night, relatively constant values of CH_4, CO and NO_2 at Thiruvananthapuram over the past five days and absence of transport from surrounding regions, the only possibility for the observed enhanced surface ozone at around 2300 hrs (IST) on 25 February - 0100 hrs (IST) on 26 February may be due to the descent of the enhanced ozone observed at an altitude of 2 km at 0510 hrs (IST) on 25 February, 2009. The time taken by the air parcel to reach the ground from an altitude of around 2 km is approximately 18 - 20 hrs in the present study. As the tropopause height at Thiruvananthapuram is around 16.5 km, this observed time interval justifies the observation that the enhanced ozone layer observed at an altitude of 2 km on 25 February may be due to intrusion of ozone from the stratosphere during the events of tropopause weakening on February 19 and 23. However, as no other vertical ozone profile could be obtained during 15 - 24 February 2009 at Thiruvananthapuram, the exact time taken by the air parcel to descend from the tropopause to the surface could not be ascertained.

5. Conclusions

A case study of a deep STE event of ozone, which is very rare at Thiruvananthapuram, a tropical coastal site of India, is presented in the paper. It is observed that STE is a very slow phenomenon.

Acknowledgments

The ozone and temperature profiles measured at India Meteorological Department was retrieved from the World Ozone and Ultraviolet Radiation Data Centre. The 5 - day back trajectories and potential vorticity at different pressure levels were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF). Tropospheric CO and CH_4 data were obtained from TES on NASA's Earth Observing System (EOS) spacecraft and total ozone and nitrogen dioxide (NO_2) column data was obtained from Ozone monitoring instrument (OMI). The vertical pressure velocities, tropopause pressure and relative humidity were retrieved from NCEP Reanalysis.

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