Can El Niño induce stratosphere–troposphere exchange of ozone?

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The possibility of stratosphere–troposphere exchange (STE) of ozone induced by El Niño has been studied over the Indian region for two events spanning the periods April 1997–May 1998 and August 2006–February 2007 using *in situ* and satellite-based measurements. The response of STE to El Niño was observed to be opposite in the tropics and extra tropics. In the tropics, lifting of polluted, ozone-rich surface air led to reduced lower tropospheric and enhanced upper tropospheric and lower stratospheric ozone during the El Niño period, indicating transport from the troposphere into the stratosphere. Conversely, in the extra tropics, sinking motion from the stratosphere into the troposphere resulted in higher upper tropospheric ozone concentration during the El Niño period. An increase in the middle and lower tropospheric ozone during the La Niña period immediately following the El Niño period suggests that the response of STE to El Niño did not manifest concurrently with the period of El Niño, but lagged by several months. El Niño southern oscillation (ENSO)-induced changes in total ozone are more prominent in the extra tropics of the northeast, compared to northwest India. However, as vertical ozone profiles are available for only two El Niño events, and the ozone variability between El Niño and La Niña events are relatively small, more detailed studies are needed to understand the dynamic influence of ENSO in producing ozone variability in India.

Keywords: Ozone, sea-surface temperature, stratosphere, troposphere, tropics and extratropics.

DURING an El Niño period, the trade winds weaken, allowing the warmer waters of the western Pacific to migrate eastwards. This change in sea surface water temperature causes large-scale shifts in the global circulation patterns in the troposphere and lower stratosphere, which in turn affects the transport of ozone in these regions. The coupled oceanic–atmospheric character of El Niño Southern Oscillation (ENSO) is represented by the Multivariate ENSO Index (MEI), wherein a negative index signifies La Niña (ocean cooling) and positive index signifies El Niño (ocean warming). Although El Niño is generally held responsible for almost any unusual climatic changes that happen anywhere[1,2], relationships between El Niño and rainfall, floods and droughts are well established[3–5]. The effect of El Niño on ozone variability is being studied globally[6–8], but more detailed studies are called for to understand the dynamic influence of ENSO in producing ozone variability, particularly in India[1]. In an El Niño period, the waters of the western Pacific warm up to above-normal values. This in turn causes additional convection to develop in the western Pacific Ocean, carrying large amount of warm and moist air upwards into the atmosphere. This warm moisture translates its energy into wind, yielding a stronger subtropical jet stream, which then flows eastwards, bringing about a change in the longitudinal structure of tropopause height[9]. The tropopause is subjected to significant gaps or breaks which are associated with jet streams[10]. Whenever this circulation accelerates, the ozone concentration increases in the lower stratosphere and when it weakens, ozone will decrease or remain constant depending upon its leakage into the troposphere. When El Niño takes place, the Brewer–Dobson circulation enhances the ozone transport in the stratosphere. Therefore, the total ozone increases in the extra tropics and decreases in the tropics[11]. The warm phases of ENSO are associated with an anomalous regional Hadley circulation. The descending motion over the Indian continent and ascending motion near the equator are sustained by the ascending phase of the anomalous Walker circulation in the equatorial Indian Ocean[12]. The stratosphere can strongly influence the interannual variability of tropospheric ozone, which increases following an El Niño event, due to enhanced stratosphere troposphere exchange (STE) of ozone. The changes in the dynamics, which affect the cross tropopause air-mass flux, may be an important factor driving the post-El Niño increase of ozone and tropospheric ozone abundances[7]. Zeng and Pyle[13] found that ENSO influenced tropospheric ozone through modulation of the net flux of stratospheric ozone into the troposphere. They have reported that the STE response was most prominent six months after the peak of the ENSO event and enhanced downward motion above the Indian Ocean brings higher amount of ozone-rich stratospheric air into the upper troposphere and lowers the tropopause height, while lifting of polluted ozone-rich surface air leads to reduced lower tropospheric and enhanced upper tropospheric ozone around 30°E. ENSO-induced changes of total ozone in India have been widely studied[14,15]. However, due to lack of vertical ozone profile measurements, these studies are unable to differentiate whether the changes are at the tropospheric or stratospheric altitudes, the amount and nature of change at different altitudes and latitudes, and the cause for the observed time lag.

In view of these considerations, the possible influence of ENSO on the vertical ozone distribution at tropical and extra-tropical Indian latitudes has been studied in this communication using *in situ* and satellite measurements.

The Indian subcontinent lies between 8–36°N lat. and 68–98°E long. New Delhi (28.4°N, 77.13°E;

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214.42 meters above sea level) located in the extra tropics, Pune (18.5°N, 73.5°E; 560 meters above sea level) in the tropics and Thiruvananthapuram (8.28°N, 76.56°E; 60 meters above sea level) in southern India close to the sea in the tropics have entirely different geographical morphology (Figure 1) and hence different local climatic conditions. New Delhi, the capital of India, is a densely populated, cosmopolitan city having high levels of pollution on account of sharp population growth accompanied by rapid industrialization. Pune is a hilly city located on the leeward side of the Western Ghats, which forms a barrier from the Arabian Sea. It is an important commercial centre having a temperate climate and is among the greenest urban areas in the country. Thiruvananthapuram, the capital city of Kerala, is situated by the seashore on the west coast, near the southern tip of mainland India adjoining the Indian Ocean on the southern side. It is bounded by Arabian Sea to its west and the Western Ghats to its east. The city is devoid of any large-scale industrial activity.

Vertical ozone profiles at New Delhi, Pune and Thiruvananthapuram spanning the period from April 1997 to July 2008 were obtained from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC), USA. These profiles were measured by India Meteorological Department (IMD) using balloon-borne electrochemical ozonesondes, flown bimonthly, from approximately 1000 to 1 hPa with a height resolution of 0.5 hPa. The ozone sonde used for the vertical sounding was electrochemical concentration cell and data were taken during the ascent of the balloon. The pressure levels were equated to their equivalent altitude in kilometres. Cold point tropopause was identified from the temperature data obtained from the ozonesonde profiles. The results obtained from ozonesonde profiles were supported with daily global 2.0° × 4.0° vertical ozone profiles obtained from TES (tropospheric emission spectrometer) on NASA's EOS (Earth Observing System) spacecraft. The geopotential height maps, vertical pressure velocities and relative humidity were retrieved from NCEP Reanalysis[16]. Potential vorticity was retrieved from MERRA, which is a NASA reanalysis for the satellite era using a new version (V5) of the Goddard Earth Observing System (GEOS), Data Assimilation System (DAS). The 3D monthly data have a resolution of 1.25° long. by 1.25° lat., with 42 vertical pressure levels. The vertical ozone profiles were arranged into four groups spanning the periods April 1997–May 1998 (strong El Niño); June 1998–April 2001 (strong La Niña); August 2006–February 2007 (moderate El Niño) and July 2007–July 2008 (moderate La Niña), and averaged over each group to study the variations in vertical ozone distribution during the El Niño and La Niña periods. Daily total ozone data were obtained from Earth Probe-Total Ozone Mapping Spectrometer (EP TOMS) and Ozone Monitoring Instrument (OMI). The stratospheric column ozone (SCO) and tropospheric column ozone (TCO) data at different Indian latitude belts (5–35°N) over the period from 1997 to 2004 were obtained using the convective cloud differential (CCD) method[17]. In this method total column ozone is derived from low reflectivity ($R < 0.2$) measurements and SCO from nearby column ozone measurements taken above the top of tropopause-level clouds under conditions of high reflectivity ($R > 0.9$). Above-cloud column amounts (in 5° × 5° bins) are first evaluated in the Pacific region where tropopause/near-tropopause-level clouds are common. SCO is then derived for every 5° latitude band for 120°E to 120°W using only the lowest values of above-cloud column amount. These SCO values from the Pacific region are then assumed to represent SCO at all other longitudes in a given latitude band. This assumption is based on the zonal characteristics of tropical SCO as inferred from the ozone data based on Stratospheric Aerosols and Gas Experiment (SAGE), Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) and Halogen Occultation Experiment (HALOE). TOMS version 8 level-2 footprint measurements were used to construct the data. Sigma uncertainty in these monthly measurements of both stratospheric and tropospheric column ozone is 2.5 DU (ref. 17).

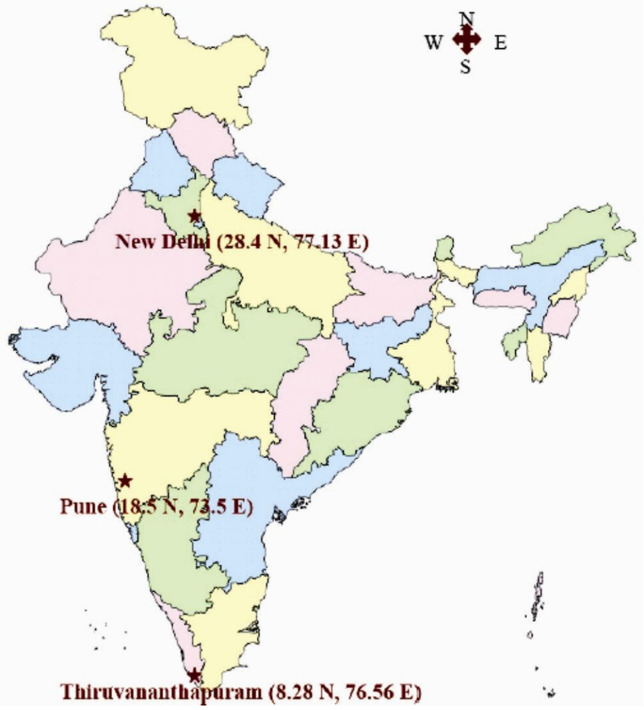

Figure 1. Map of India depicting the measurement sites.

Geopotential height approximates the actual height of a pressure surface above mean sea level. In the extra tropics, the geopotential height (m) maps at 700 hPa pressure level bend strongly to the south, indicating the presence of troughs during the April 1997–May 1998 El Niño (Figure 2 *a*), which extend up to the June

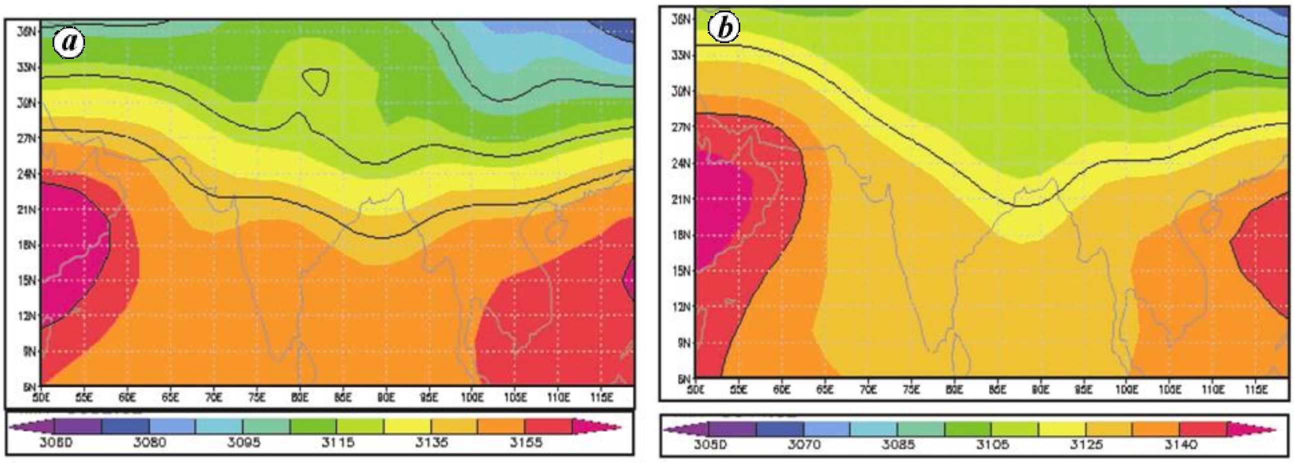

Figure 2. Geopotential height (m) map at 700 hPa pressure level during (***a***) April 1997–May 1998 strong El Niño period and (***b***) June 1998–April 2001 strong La Niña period (source: NCEP Reanalysis).

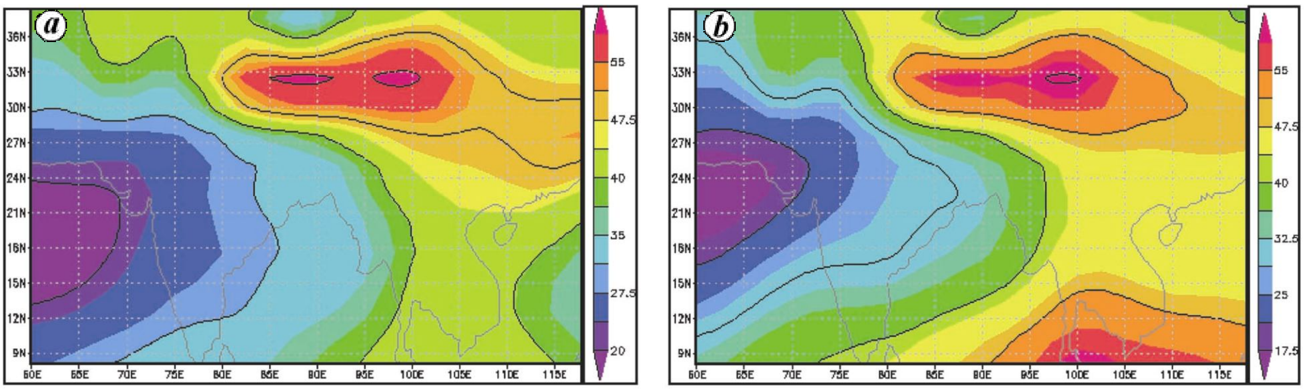

Figure 3. Relative humidity at 500 hPa pressure level during (***a***) April 1997–May 1998 strong El Niño period and (***b***) June 1998–April 2001 strong La Niña period (source: NCEP Reanalysis).

1998–April 2001 La Niña period (Figure 2*b*). Strong troughs are typically preceded by stormy weather and colder air at the surface. Stratospheric air is characterized by low relative humidity (RH < 60%)[18,19]. The relative humidity (at 500 hPa pressure level) at the extra tropics and some parts of the tropics in India is found to be low (< 45%) during the April 1997–May 1998 El Niño (Figure 3*a*), which extends up to June 1998–April 2001 La Niña period (Figure 3*b*), indicating the presence of stratospheric air masses. 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 vertical pressure velocity at 500 hPa pressure level indicates sinking motion at the extra tropics of western India and rising motion at all tropical latitudes and extra tropics of eastern India during the April 1997–May 1998 El Niño (Figure 4*a*). However, during the June 1998–April 2001 La Niña period, rising motion observed at all tropical latitudes and sinking motion observed at all extra tropical latitudes (Figure 4*b*) indicate a delayed response of STE to El Niño. Potential vorticity (PV) increases rapidly with altitude, reaching values greater 1.0 pvu (ref. 20) at the tropopause (where 1 pvu = 10^{-6} m^2 Kkg^{-1} s^{-1}). Stratospheric air is characterized by high PV values[21,22], exceeding 1.6 pvu, according to the WMO definition of dynamical tropopause[18]. In the extra tropics, potential vorticity at 150 hPa pressure level (~13.5 km) during the April 1997–May 1998 strong El Niño period and at 200 hPa pressure levels (~11.5 km) during the June 1998–April 2001 strong La Niña period are observed to be >1.6, indicating the presence of airmasses having stratospheric origin, whereas it is <1.6 in the tropics during these periods indicating the absence of stratospheric air masses.

Spatial distribution of total ozone over entire India obtained on a daily basis, was averaged for the periods April 1997–May 1998 (strong El Niño), June 1998–April 2001 (strong La Niña) and May

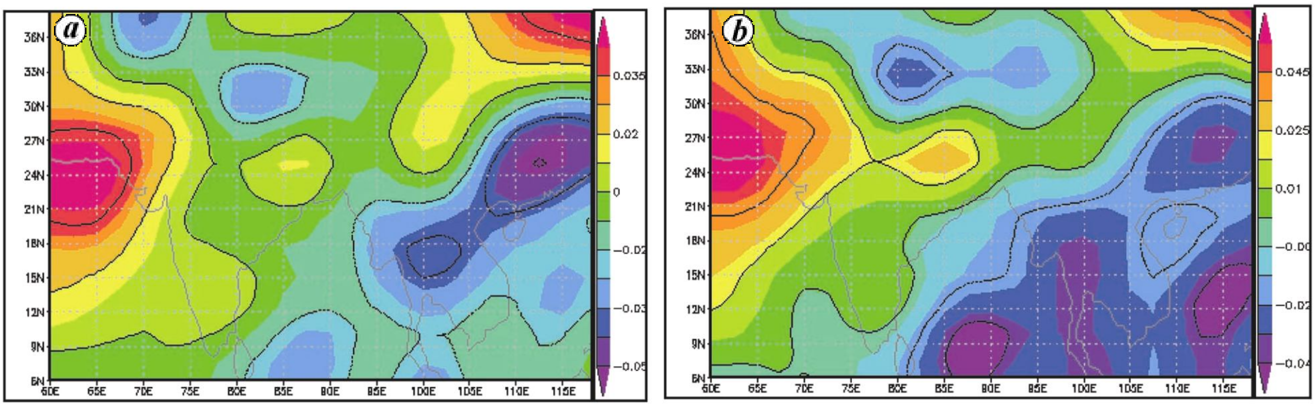

Figure 4. Vertical pressure velocity at 500 hPa pressure level during (***a***) April 1997–May 1998 strong El Niño period and (***b***) June 1998–April 2001 strong La Niña period (source: NCEP Reanalysis).

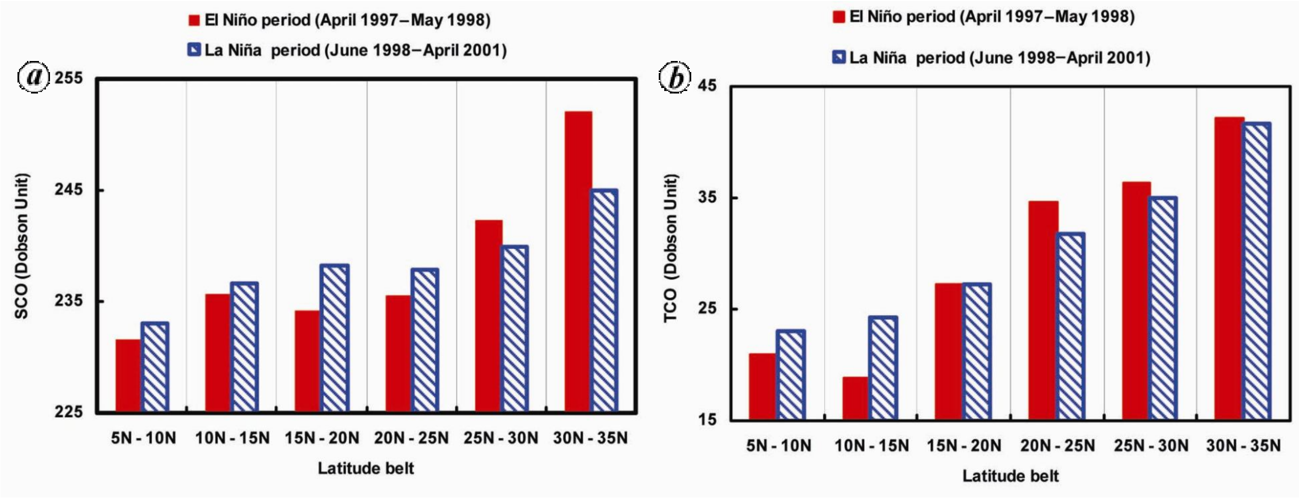

Figure 5. (***a***) Stratospheric column ozone (SCO) and (***b***) tropospheric column ozone (TCO) at different Indian latitude belts during the April 1997–May 1998 (strong El Niño) and June 1998–April 2001 (strong La Niña) period (source: Convective cloud differential method developed by Ziemke *et al.*[17]).

2001–December 2004 (normal period). The total ozone (~260–273 DU) did not vary significantly over these periods in the tropics (8–24°N). This may be because the difference between the total ozone values during the El Niño, La Niña and normal periods in the tropics is small compared to the resolution of the EP TOMS measurements.

In the extra tropics (25–36°N), a small change in total ozone distribution was observed over these periods. The total ozone (~273–300 DU) was higher compared to the tropics during the El Niño period. During the La Niña and normal periods, which followed thereafter, the total ozone in the northeastern part of India (~80–98°E; 25–33°N) decreased (~268–270 DU), while it continued to be high (~273–300 DU) in northwest India (68–80°E; 25–36°N). Similar results were observed in the tropics and extra tropics during the August 2006–February 2007 (moderate El Niño) and July 2007–July 2008 (moderate La Niña) periods. Thus ENSO-induced changes in total ozone were observed to be more prominent in the extra tropics of northeast India compared to northwest India.

The variation in SCO and TCO was studied making use of the ozone data obtained from the CCD method. TCO and SCO at different latitude belts of India (5–35°N) obtained on a monthly basis were arranged into two groups spanning the periods April 1997–May 1998 (strong El Niño) and June 1998–April 2001 (strong La Niña), and averaged over each group to study the variations in ozone distribution during the El Niño and La Niña periods (Figure 5).

It was observed that during the El Niño period, lifting of polluted, ozone-rich, tropical tropospheric air into the stratosphere combined with the horizontal advection of tropical stratospheric air into the extra-tropical stratosphere enhanced by Brewer–Dobson circulation resulted in reduced TCO and SCO in the tropics (5–25°N) and enhanced SCO in the extra tropics (25–35°N). Further, sinking motion from the extra-tropical stratosphere into

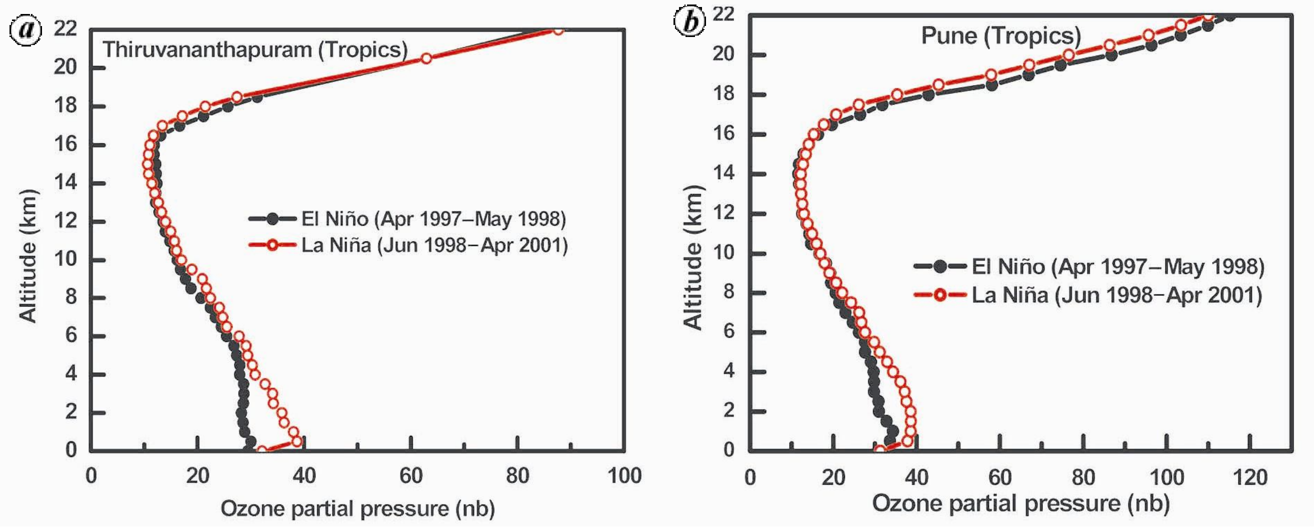

Figure 6. Vertical ozone profiles during the April 1997–May 1998 (strong El Niño) and June 1998–April 2001 (strong La Niña) periods at Thiruvananthapuram and Pune in the tropics (source: India Meteorological Department (IMD) and World Ozone and Ultraviolet Radiation Data Centre (WOUDC), USA.

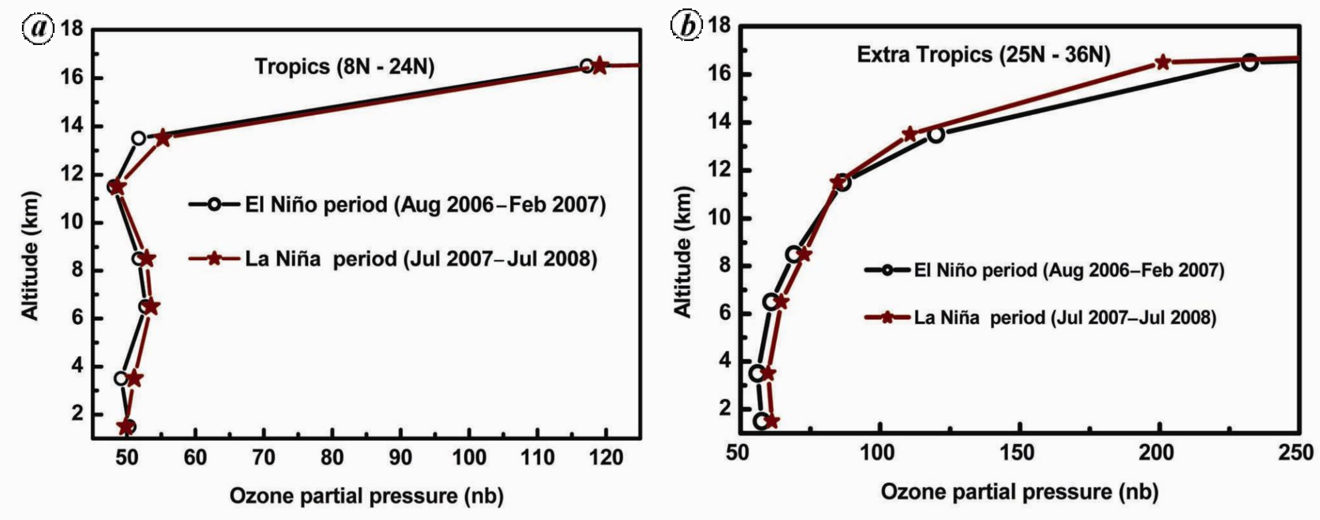

Figure 7. Vertical ozone profiles during the August 2006–February 2007 (strong El Niño) and July 2007–July 2008 (strong La Niña) periods at the tropics (8–24°N) and extra tropics (25–36°N; source: Tropospheric emission spectrometer).

the extra-tropical troposphere enhanced by Brewer–Dobson circulation, resulted in higher TCO during the El Niño period compared to La Niña period (Figure 5). The return drift of ozone-rich air from the extra-tropical troposphere to the tropical troposphere resulted in increasing TCO in 15–25°N lat. belts, thereby offsetting the decrease in TCO due to the lifting of polluted, ozone-rich, tropical tropospheric air into the stratosphere in these belts.

An examination of vertical pressure velocity at 500 hPa pressure level (Figure 4) and the vertical ozone profiles from ozonesonde measurements (Figure 6) in the tropics indicate the lifting of polluted, ozone-rich surface air, resulting in reduced lower tropospheric (from the Earth's surface to 8 km) and enhanced upper tropospheric and lower stratospheric (16–22 km altitude from the Earth's surface) ozone during the El Niño period from April 1997 to May 1998. Similar results were observed during the August 2006–February 2007 El Niño period (Figure 7) from satellite measurements. As the predominant transport of ozone was vertical (from the troposphere into the stratosphere) during the El Niño/La Niña period, the total ozone did not vary significantly over the El Niño, La Niña and normal periods in the tropics. The lifting of polluted, ozone-rich surface air in the lower troposphere was observed to be stronger during the April 1997–May 1998/June 1998–April 2001 strong and extended El Niño/La Niña phase, compared to the August 2006–February 2007/July 2007–July 2008 moderate and comparatively short El Niño/La Niña phase.

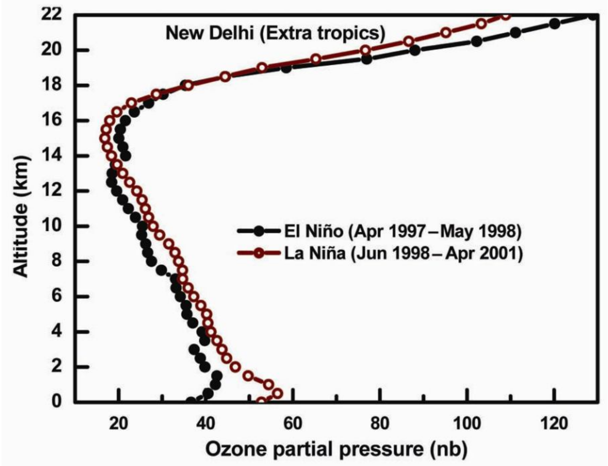

Figure 8. Vertical ozone profiles during the April 1997–May 1998 (strong El Niño) and June 1998–April 2001 (strong La Niña) periods at New Delhi in the extra tropics (Source: IMD and WOUDC).

An examination of vertical pressure velocity at 500 hPa pressure level (Figure 4 *a*) in the extra tropics indicates sinking motion over west India and rising motion over east India during the April 1997–May 1998 El Niño period. However, during the June 1998–April 2001 La Niña period, sinking motion was observed at all extra-tropical latitudes (Figure 4 *b*). Potential vorticity at 150 hPa pressure level (~13.5 km) during the April 1997–May 1998 strong El Niño period and at 200 hPa pressure levels (~11.5 km) during the June 1998–April 2001 strong La Niña period were observed to be >1.6, indicating the presence of air-masses having stratospheric origin. Thus, horizontal advection of ozone-rich tropical stratospheric air to the extra-tropical stratosphere enhanced by Brewer–Dobson circulation, combined with sinking motion from the extra-tropical stratosphere into the extra-tropical troposphere resulted in higher stratospheric and upper tropospheric ozone concentration (above 14 km altitude from the Earth's surface) during the El Niño period (April 1997–May 1998), compared to La Niña period (June 1998–April 2001) as observed from ozonesonde measurements in Figure 8. An increase in middle and lower tropospheric ozone (below 14 km altitude from the Earth's surface) is observed during the La Niña period (June 1998–April 2001) immediately following the El Niño period (April 1997–May 1998). Similar results were observed during the August 2006–February 2007 El Niño and July 2007–July 2008 La Niña phase (Figure 7) from satellite measurements. This is because enhanced downward motion brings ozone-rich stratospheric and upper tropospheric air into the middle and lower troposphere during the La Niña phase.

Thus the response of STE to El Niño did not manifest concurrently with the period of El Niño, but lagged by several months. Due to this delayed response of STE, high ozone levels are observed to persist in the extra-tropical lower troposphere after the end of the El Niño event, during the La Niña period. The observed delayed atmospheric ozone response to El Niño can be attributed to the lagged response of the tropical oceans to El Niño, as suggested by Kumar and Hoerling[23]. The difficulty in establishing the relationship between El Niño and the extra-tropical stratospheric circulation may also be attributed to the entangled signals of ENSO and Quasi Biennial Oscillation in the extra-tropical stratosphere, as suggested by several researchers[24–26]. The present results confirm the findings of earlier studies[27–30], which suggest a lagged relationship between ENSO and the maximum extra-tropical stratospheric response or a possible delayed impact of ENSO on the stratosphere.

In summary, STE of ozone possibly induced by ENSO has been studied for the Indian region for two El Niño events spanning the periods April 1997–May 1998 and August 2006–February 2007 using ozonesonde and satellite measurements. The response of STE to El Niño is opposite in the tropics and extra tropics. In the tropics lifting of polluted, ozone-rich air led to reduced lower tropospheric and enhanced upper tropospheric and lower stratospheric ozone during the El Niño period, indicating transport from the troposphere into the stratosphere. Conversely, in the extra tropics, sinking motion from the stratosphere into the troposphere resulted in higher upper tropospheric ozone concentration during the El Niño period. An increase in middle and lower tropospheric ozone during the La Niña period immediately following the El Niño period suggests that the response of STE to El Niño did not manifest concurrently with the period of El Niño, but lagged by several months. ENSO-induced changes in total ozone are more prominent in the extra tropics of northeast India compared to northwest India. However, since vertical ozone profiles are available for only two El Niño events and the ozone variability between El Niño and La Niña events is relatively small, more detailed studies are needed to understand the dynamic influence of ENSO in producing ozone variability in India.

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