Impact of tropical cyclone on total ozone measured by TOMS–EP over the Indian region

Devendra Singh and Virendra Singh*

The impact of tropical cyclones formed over the Arabian Sea and Bay of Bengal on the total ozone derived from the Total Ozone Mapping Spectrometer aboard the Earth Probe satellite has been studied. We have analysed the perturbations caused in the total amount of ozone due to four severe tropical cyclones. The daily total ozone anomalies have been calculated for the lifespan of each tropical cyclone. Theses anomalies were observed to be local in character and moved with the tropical cyclone. Further, these anomalies are related to the intensification of the cyclonic systems. In general, negative anomalies were observed to be more than 20 Dobson Units at the time of maximum intensity of cyclones. Variations in daily total ozone anomalies, from development to intensification stage and then to decaying stage of each cyclone have brought out clearly the impact of tropical cyclone on the total ozone, which got depleted considerably over the affected region.

Keywords: Earth Probe satellite, ozone, Total Ozone Mapping Spectrometer, tropical cyclone.

SATELLITE observations have given scientists a global perspective on the photochemical and dynamical processes that control the atmospheric evolution of constituents like ozone. The satellites and their instruments are often designed to address specific questions and sometimes vastly exceed the developer's expectations. The Total Ozone Mapping Spectrometer (TOMS) was designed to simply map the variability of the ozone column due to atmospheric waves. Instruments on the Upper Atmosphere Research Satellite (UARS) were designed to measure upper stratospheric ozone and quantities important to ozone, including solar flux, winds and constituents that contribute to ozone destruction. The scientific payoff from UARS and TOMS vastly exceeded these modest goals. Total ozone measurements from TOMS revealed the extent and variability of the Antarctic ozone hole.

Tropical cyclones (TCs) are amongst the most destructive meteorological phenomena. They are associated with the large-scale, rapid vertical transport of water vapour, heat energy and momentum in the upper atmosphere. The normal pattern of general circulation gets affected due to thermodynamical changes in the cyclonic area. Heavy mass transportation of air takes place between different layers of the troposphere and the crucial natural balance between the different meteorological parameters is subject to change. Perturbations caused in the meteorological parameters in the troposphere and lower stratosphere by deep convection associated with the severe cyclonic storm may cause depletion in total ozone. The long-term average of TCs in the north Indian Ocean is about 5.6/yr. The frequency of cyclones in the Bay of Bengal is more than that in the Arabian Sea. The severe cyclonic storms over this region are very intense and most of the time they break the tropospause and intrude into the lower stratosphere and intense air exchange and mixing take place near the tropospause.

Chien *et al.*[1] studied the redistribution of atmospheric chemical species due to deep convective storm over the tropical Pacific Ocean. According to their study, intensive mixing of boundary layer air into the deep convective cloud can result in low ozone area inside the cloud turret and inside the anvil. The high ozone stratospheric air may also be brought simultaneously into the cloud region in the upper troposphere, particularly in the anvil area, thus affecting the total ozone budget. Further, their simulated study has found clear-cut evidence of vertical transport of water vapour through convective transport to the upper troposphere. Their model also predicted the presence of higher water vapour mixing ratio in the lower stratosphere. Chatfield and Crutzen[2] have studied the effect of rapid vertical transport by deep convective clouds on the atmospheric chemistry, especially if it affects the formation of sulphate aerosols or ozone. There is also evidence of direct intrusion of tropospheric air into the lower stratosphere during TC or deep convection, affecting the chemistry of chemical species, more so in the case of ozone[3–7].

Devendra Singh is in the Department of Science and Technology, Technology Bhawan, New Mehrauli Road, New Delhi 110 016, India; Virendra Singh is in the India Meteorological Department, Mausam Bhawan, Lodhi Road, New Delhi 110 003, India.
*For correspondence. (e-mail: dschahar_ds@yahoo.com)

During the INDOEX-1998, Mandal *et al.*[8] reported evidence of mesoscale feature of stratospheric intrusion of ozone into equatorial Indian Ocean troposphere and stratospheric intrusion of ozone through distorted tropopause into the upper and middle troposphere due to updraft and downdraft in the deep convective system in the ITCZ. It is a common knowledge that during intensive TCs, deep convective clouds pierce through the tropopause in the tropical region causing multiple breaks in the tropopause. The water vapours are carried into the lower stratosphere, which affect the concentration of ozone.

The objective of the present article is to study the impact of TCs formation in the Bay of Bengal and Arabian Sea on total ozone. Since both the Bay of Bengal and Arabian Sea in the Indian subcontinent are prone to cyclonic activity during pre-monsoon and post-monsoon seasons of the year, the results indicate direct impact of TCs on the Total Ozone (TO) budget over the Indian tropical region. Moreover, several studies on this topic have been carried out over the Pacific and Atlantic oceans. This is an attempt to fill the gap over the Indian Oceanic region.

Data and methodology

TOMS aboard the Earth Probe (EP) satellite launched in July 1996, provides measurements of the earth's total column ozone; about 90% daily global coverage by measuring the backscattered earth radiances. The analysis was restricted to those days when the TC centre lay in the middle of the orbit swath. Sometimes the TC centre fell at or near the edge of the swath, and hence a large portion of the analysis domain had no data. Therefore, these cases were not considered for analysis. Daily averages of the retrieved ozone in a 1° lat. by 1.25° long. grid can be downloaded through the internet from the NASA GSFC website. Details about TOMS–EP and data are available at the website: http:\\jwocks.gsfc.nasa.gov/eptoms/ep.html.

For the purpose of the present study, we have downloaded since the beginning of TOMS–EP data, daily values of TO over the Indian region for the month of each cyclone formation. For example, for a Bay of Bengal cyclone of May 1997, daily values of TO for the month of May 1996 to December 2005 (10 yrs) were downloaded and average value was determined, representing the long-term monthly mean value of TO for May. During the period of a TC, i.e. from formation stage to mature and then decaying stage (15–20 May 1997), monthly mean value for May as obtained above was subtracted from the daily TO value. Similar approach was used for other tropical cyclones to obtain the anomalies in TO. Data about track and cyclone intensity *T*-number along with case history of each TC, formed in the Bay of Bengal and Arabian Sea, were obtained from the archives of the India Meteorological Department (IMD), New Delhi.

Results

Ozone in the stratosphere (upper atmosphere) protects us from harmful ultraviolet radiation from the sun. However, ozone plays a different role in the troposphere where we live, because it is toxic to living things. Ozone in the upper troposphere is also a greenhouse gas, indicating that its presence contributes to global warming. On the other hand, tropospheric ozone plays a role that is key to enhancing human health and well-being, since it is involved in chemical reactions that cleanse the troposphere of certain pollutants. Before scientists began to track the presence of ozone in the troposphere with satellite data and measurements made from aircraft, they assumed that much of that part of the atmosphere was relatively free of ozone. Satellite observations with data-rich models that simulate the chemistry and dynamics of the atmosphere help us to observe the variations and depletion of ozone due to various factors. One of them is the TC causing ozone depletion but at a local level. Case studies for impact of cyclones on ozone depletion are presented in the next section.

Bay of Bengal TC, 15–20 May 1997

The cyclonic system started as a well-marked low pressure area on 15 May with intensity *T* 1.5 over the Bay of Bengal and concentrated into a deep depression on 16 May 1997; it was centred near 9.2°N and 91.0°E. It further moved in a north-northeasterly direction and became a cyclonic storm of intensity *T* 3.0 at 0600 UTC on 17 May 1997. It acquired a core of hurricane winds on the morning of 18 May 1997, and lay centred near 16.5°N and 90.5°E. It further intensified to *T* 4.5 with indication of asymmetrical eye. The system was upgraded to *T* 5.0 and it continued to move in a north-northeasterly direction and finally crossed Bangladesh coast near Chittagong at about 1200 UTC on 19 May 1997. Then the cloud field spread and the system weakened by the morning of 20 May 1997. The track of the cyclone and variation of TO anomaly with *T* number of the cyclone are shown in Figure 1 *a* and *b* respectively. It shows that TO is depleted with the intensification of the cyclone.

Figure 2 *a–d* depicts the variation of TO anomalies from 8 to 22 May 1997. Positive anomalies of smaller values were observed well before the formation of the cyclone over the Bay of Bengal on 8 May 1997 (Figure 2 *a*). These positive anomalies started converting into negative anomalies of the order of 25 Dobson Units (DU) with intensification of the cyclone on 17 May 1997 (Figure 2 *b*). Further, these negative anomalies started decreasing with the weakening of the cyclone on 18 and 22 May 1997 (Figure 2 *c* and *d* respectively). The analysis clearly brings out the pattern of negative anomaly on 17 May and decrease in negative anomaly on 22 May 1997 with respect to the Bay of Bengal cyclone.

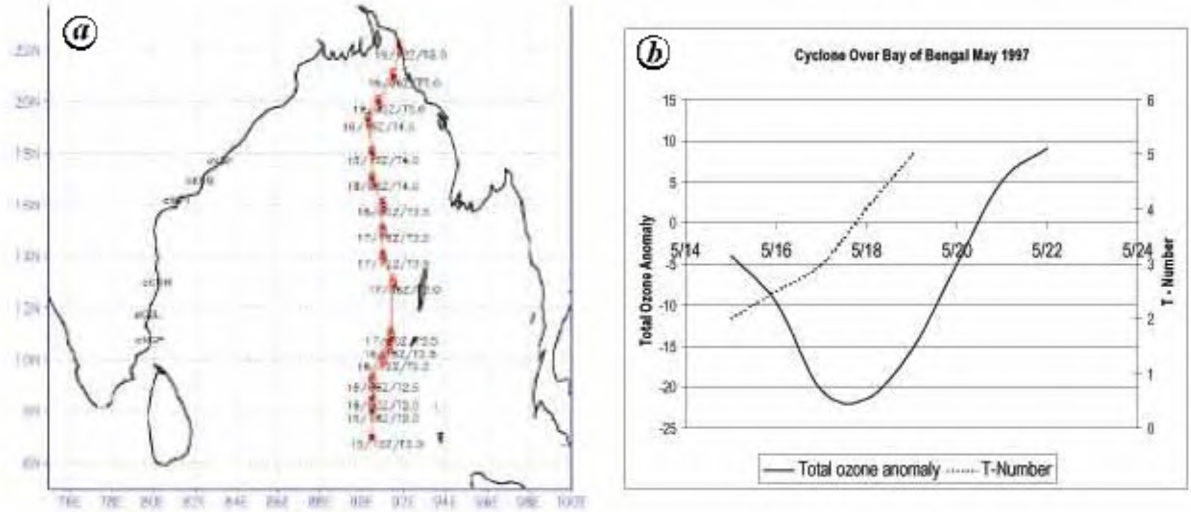

Figure 1. Track of the cyclone (***a***) and variation of TO anomaly with *T* number of the cyclone (***b***).

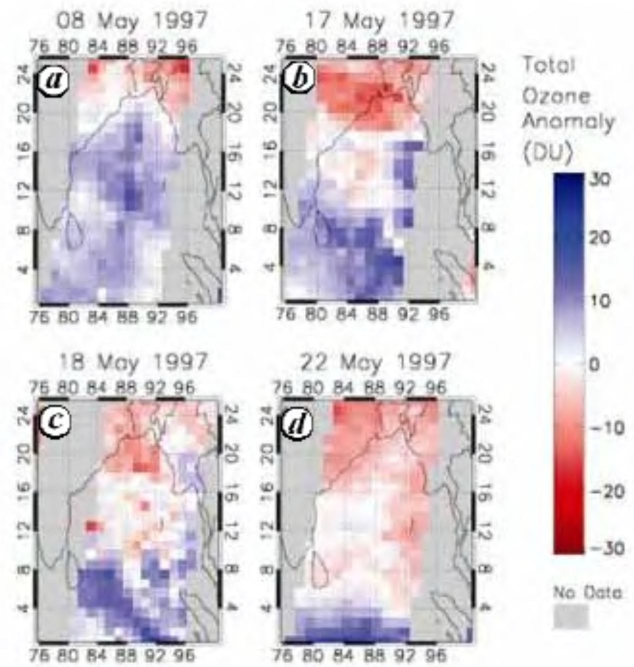

Figure 2 ***a–d***. Variation and location of total ozone anomalies with intensification and movement of cyclone from 8 to 22 May 1997.

Arabian Sea TC, 2–9 June 1998

The cyclone started as a vortex on 2 June 1998 at the leading edge of the monsoon current in the southeast Arabian Sea. It moved in a northwesterly direction and lay centred at 11.0°N north and 71.0°E, with intensity *T* 1.5 on 4 June 1998 at 0300 UTC. The cyclone organized with signs of feeder bands becoming tighter and curving on 5 June 1998 at 0900 UTC. Further, it assumed a minimal tropical storm stage of *T* 2.5 with centre near 11.0°N and 70.0°E. The cyclone intensified further on 6 June 1998 at 0600 UTC and acquired an intensity of *T* 3.5 with centre near 12.5°N and 68.8°E. It continued to intensify further with an eye pattern and was upgraded to intensity *T* 5.0 at 0600 UTC on 8 June 1998, with centre at 18.5°N and 67.5°E. Then the system recurved, and took a northeasterly course and became slightly disorganized. It was classified *T* 4.5 moving in a north-northeasterly direction. The cyclone crossed Gujarat coast by 0300 UTC on 9 June 1998 near Porbandar. Further, it weakened gradually and moved over to northwest India. The track of the cyclone and variation of TO anomaly with *T* number of the cyclone are shown in Figure 3 *a* and *b* respectively.

Figure 4 *a–d* depicts the variation of TO anomalies from 1 to 12 June 1998. There were no perturbations of TO observed before the formation of the cyclone over south Arabian Sea on 1 June 1998 (Figure 4 *a*). Negative anomalies started with intensification of the cyclone on 5 June 1998 (Figure 4 *b*). The magnitude of these negative anomalies further increased to about 25 DU with the intensified cyclone and moved with the centre of the cyclone on 8 June 1998 (Figure 4 *c*). The magnitude of negative anomalies started decreasing with the weakening of the cyclone on subsequent days. There were no negative anomalies observed after the disappearance of cyclone on 12 June 1998 (Figure 4 *d*). Once again, this analysis clearly brings out the pattern of negative anomalies on 8 June 1998 and the decrease in negative anomalies on 12 June 1998 over the Arabian Sea.

Bay of Bengal TC, 25–31 October 1999

The super cyclonic storm formed over the Bay of Bengal during 25–31 October 1999, and crossed the Orissa coast, India, causing massive destruction. The cyclone forma-

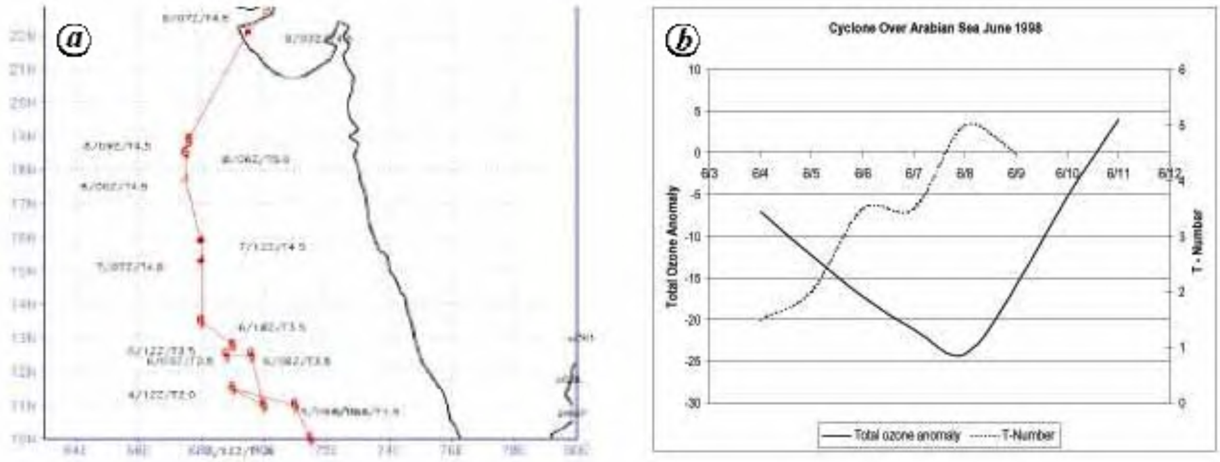

Figure 3 ***a*****,** ***b*****.** Same as Figure 1 *a* and *b*, but for the June 1998 cyclone.

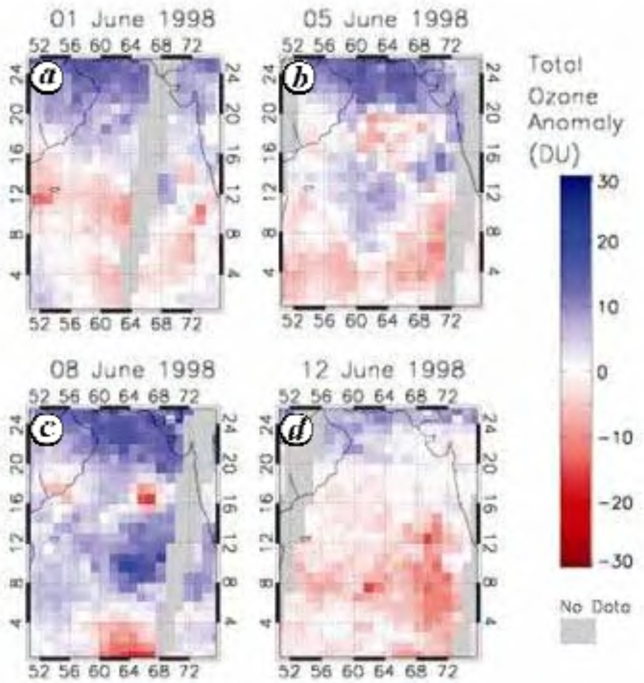

Figure 4 ***a–d*****.** Same as Figure 2 *a–d*, but for 1–12 June 1998 cyclone.

tion started as a well-marked low pressure area in the north Andaman Sea in the morning of 25 October 1999. It started moving in a west-northwesterly direction and intensified further and developed into a cyclone of intensity *T* 3.0 on 26 October 1999. The intensity of the cyclone increased to *T* 3.5 by the evening of the same day and lay centred 16.1°N and 92.0°E. It further intensified into a very severe cyclonic storm at 1500 UTC on 27 October 1999, with intensity *T* 4.0 and moved in a west-northwesterly direction. The cyclone showed a clear eye with intensity *T* 4.5 at 0300 UTC on 28 October 1999. The system rapidly intensified further on 28 October 1999 itself with intensity *T* 6.0 at 1500 UTC on 28 October 1999. It continued to move in a northwesterly direction with a wide eye. On the morning of 29 October 1999, the visible imagery at 0300 UTC showed that the embedded distance of the clear eye had increased further to one degree and the intensity of the cyclone was raised to *T* 7.0. The cyclone was classified as a super cyclone. Subsequently, it weakened. The track of the cyclone and variation of TO anomaly with *T* number of the cyclone are shown in Figure 5 *a* and *b* respectively.

Figure 6 *a–d* depicts variation in TO anomalies from 23 to 30 October 1999. Positive anomalies of smaller values were observed well before the formation of the cyclone over the entire Bay of Bengal on 23 October 1999 (Figure 6 *a*). These positive anomalies started converting into negative anomalies with intensification of the cyclone over the Bay of Bengal as on 26 October 1999 (Figure 6 *b*). The magnitude of these negative anomalies further increased to about 25 DU at the time of the intensified cyclone and moved with the centre of the cyclone on 28 October 1999 (Figure 6 *c*). These negative anomalies started decreasing with the weakening of the cyclone on 30 October 1999 (Figure 6 *d*). Depletion of ozone due to the cyclone is further corroborated by this analysis.

Arabian Sea TC, 21–29 May 2001

The genesis of the cyclonic storm started from a vortex in the southeast Arabian Sea on 21 May 2001. The intensity of the cyclone was *T* 2.5, with centre at 13.8°N and 71.2°E on 22 May 2001 at 0300 UTC, and system was heading towards the east-northeast direction. This system rapidly intensified further and intensity increased to *T* 3.5 and then to *T* 4.0 by 2100 UTC on 22 May 2001 itself. It showed signs of recurvature and start moving in north-

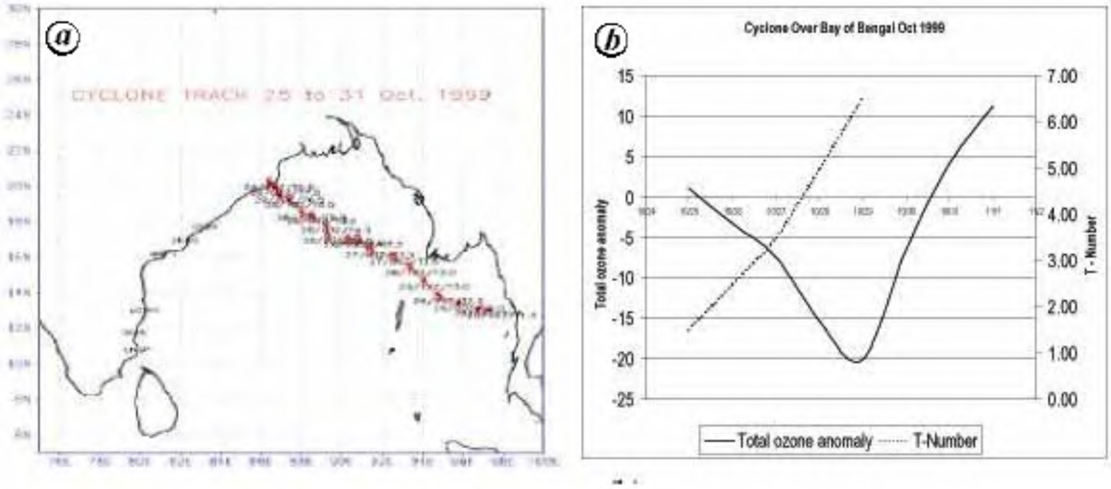

Figure 5 ***a*, *b*.** Same as Figure 1 *a* and *b*, but for the October 1999 cyclone.

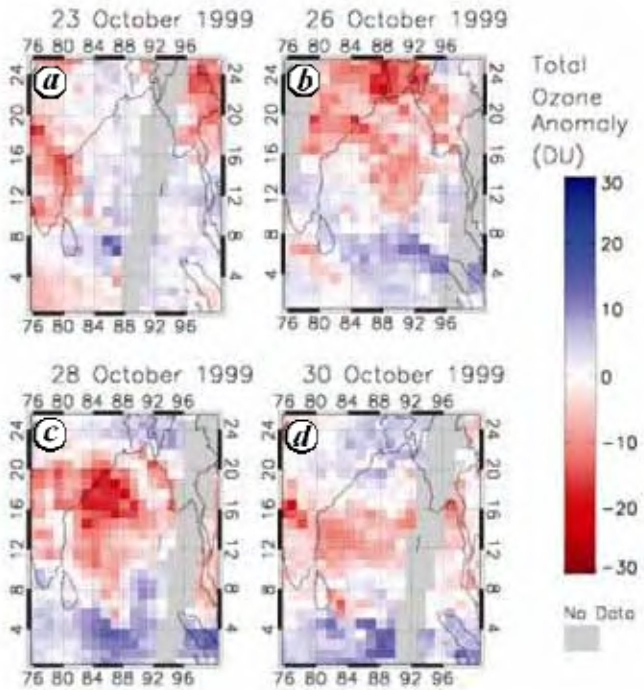

Figure 6 ***a–d*.** Same as Figure 2 *a–d*, but for the 23–30 October 1999 cyclone.

westerly direction at 0300 UTC on 23 May 2001, with a eye visible. The intensity was further increased to *T* 5.0, when the eye became clear with centre at 15.6°N and 71.1°E. The cyclone acquired the intensity of *T* 6.0 by 0900 UTC on 24 May 2001 and lay centred at 16.8°N and 68.6°E. The cyclone started showing signs of weakness and its intensity decreased to *T* 5.0 and then to *T* 4.0 by 2100 UTC on 25 May 2001. The intensity was further reduced to *T* 3.0 and then to *T* 2.5 due to disorganization of cloud pattern on 26 May 2001. The movement of this cyclone was typical, except in the later stages when it crossed the Gujarat coast as a weak system. The track of the cyclone and variation of TO anomaly with the *T* number of the cyclone are shown in Figure 7 *a* and *b* respectively.

Figure 8 *a–d* depicts the variation of TO anomalies from 20 to 30 May 2001. Negative anomalies of small values of the order of 3 to 4 DU were observed few days before the formation of the cyclone over south Arabian Sea on 20 May 2001 (Figure 8 *a*). The negative anomalies increased to about 20 DU at the time of intensification and moved with the centre of the cyclone on 24 May 2001 (Figure 8 *b*). The magnitude of negative anomalies started decreasing with the weakening of the cyclone on subsequent days. These negative anomalies moved with the centre of the cyclone on 28 and 30 May 2001 (Figure 8 *c* and *d* respectively). The magnitude of negative anomalies was found to be correlated with the intensification of the cyclones and moving with the centre of the cyclones in all the four case studies.

Discussion

There has been a certain decline of stratospheric ozone in the northern hemisphere during the past 20 years. Ozone thinning can occur when increased emissions of methane get transformed into water in the stratosphere. At high altitudes, water vapour can be broken down into molecules that destroy ozone. Though complex and not well understood, there is evidence that water vapour can get wafted from the troposphere into the stratosphere by shifting air currents caused by climate change. Climate change from greenhouse gases can also affect ozone by heating the lower stratosphere where most of the ozone exists. When the lower stratosphere heats up, chemical reactions speed up, and ozone gets depleted. The chemical and atmospheric processes in the lower stratosphere are complex, quite variable, and not well understood. However, in the upper stratosphere the processes are simpler and better understood. Hence these findings are to make inferences about ozone in the lower stratosphere.

Increased UV-B radiation resulting from stratospheric ozone depletion, and global warming affect air pollution,

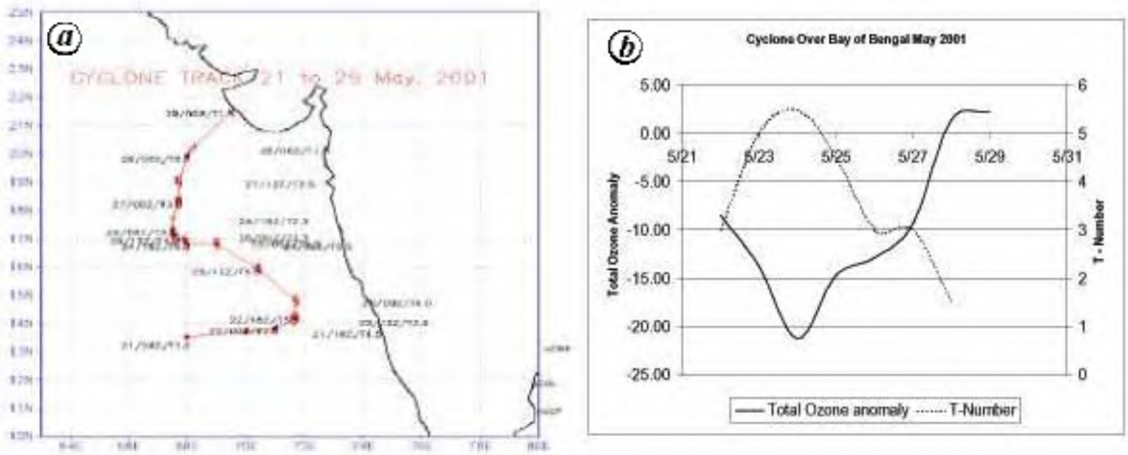

Figure 7 ***a*, *b*.** Same as Figure 1 *a* and *b*, but for the May 2001 cyclone.

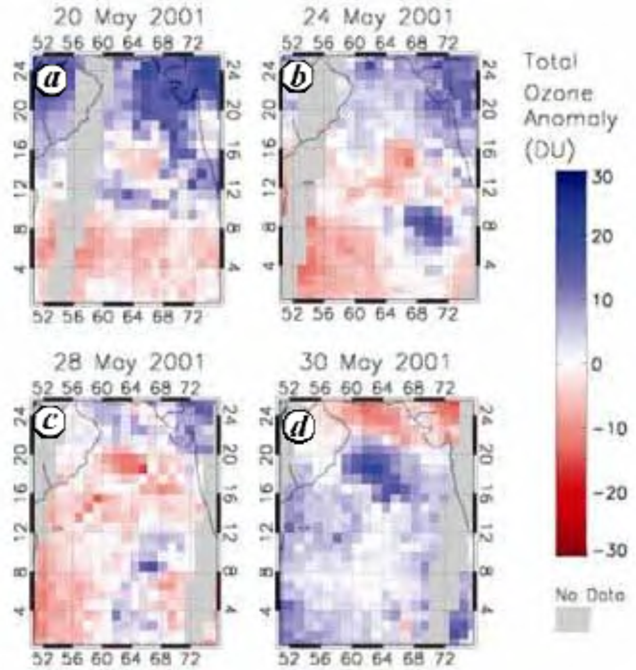

Figure 8*a–d*. Same as Figure 2 *a–d*, but for the 20–30 May 2001 cyclone.

human health, vegetation, fisheries and natural systems. In addition, it is likely that further reduction of stratospheric ozone could have a direct impact on the warming itself, by altering the atmospheric chemistry within the troposphere. Although it would hardly be surprising that a significant drop in stratospheric ozone could affect surface temperatures, it is not possible to indicate whether this would magnify or reduce the projected rate of global warming. Increased UV-B radiation striking the surface of the ocean could, however, act to enhance the warming by reducing the biomass of CO_2 absorbing marine phytoplankton.

Summary

In the presence of a tropical cyclonic storm over the Indian region, the TO budget is affected. The negative anomaly number reaches up to about 20 DU at the time of peak cyclonic intensity. The TO anomalies move with the cyclonic system and the magnitude is dependent on the intensity of the system, i.e. peak intensity was well correlated with the maximum fall in the TO. The TO anamolies were of typical dimensions and local in character. They became more marked and confined with intensification of TC. In the formation and decay stages of TC, the anomalies also spread in dimensions.

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