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Exposure-plant response of ambient ozone over the tropical Indian region

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Abstract

A high resolution regional chemistry-transport model has been used to study the distribution of exposure-plant response index (AOT40, Accumulated exposure Over a Threshold of 40 ppb, expressed as ppb h) over the Indian geographical region for the year 2003 as case study. The directives on ozone pollution in ambient air provided by United Nations Economic Commission for Europe (UNECE) and World Health Organization (WHO) for vegetation protection (AOT40) have been used to assess the air quality. A substantial temporal and spatial variation in AOT40 values has been observed across the Indian region. Large areas of India show ozone values above the AOT40 threshold limit (3000 ppb h for 3 months). Simulated AOT40 values are found to be substantially higher throughout the year over the most fertile Indo-Gangetic plains than the other regions of India, which can have an adverse effect on plants and vegetation in this region. The observed monthly AOT40 values reported from an Indian station, agree reasonably well with model simulated results. We find that the simulated AOT40 target values for protection of vegetation is exceeded even in individual months, especially during November and April. Necessary and effective emission reduction strategies are therefore required to be developed in order to curb the surface level ozone pollution to protect the vegetation from further damage in India whose economy is highly dependent on agricultural sector and may influence the global balance.

1 Introduction

Near surface ozone is a pollutant of important concern due to its adverse effects on agricultural productivity (Mills et al., 2007) and human health (Avol et al., 1998), and is now a major environmental concern in many regions of the world. Surface ozone is mainly produced through photochemical reactions involving volatile organic compounds and NO_x in the presence of sunlight, and also acts as a precursor for the highly reactive hydroxyl radical (Logan et al., 1981; Thompson, 1992). Epidemiological and toxicological studies indicate that higher concentration of ozone in the boundary layer is harmful to biological health (Avol et al., 1998). The enhanced levels of ozone close to surface also decrease the yield of agricultural crops (Mills et al., 2007). A number of recent studies from selected sites across South Asia have specifically addressed the sensitivity of locally-grown crops to the ozone levels (Agrawal, 2003; Wahid, 2003). Ghude et al. (2006) have shown that the observed surface ozone levels over Delhi are high enough to exceed "critical levels" which are considered to be safe for human health. However, detailed results related to AOT40 for vegetation index based on observational data for the Indian region is sparse. Using surface level measurements from Pune, Beig et al. (2008) have recently calculated the AOT40 and shown that ozone levels have surpassed the "critical levels" in most parts of the year for vegetation and forest. This is the only work where detailed study about the AOT40 based on observed data has been reported over any Indian station. In the past few decades, India has been undergoing rapid industrial and economic growth with increasing emissions of trace gases and pollutants (Ghude et al., 2008). Due to all these reasons, the tropospheric ozone level is an issue of concern in the last few decades. Necessary and effective emission reduction strategies are required to be developed in order to curb the surface level ozone pollution to protect the vegetation from further damage in India whose economy is highly dependent on agricultural sector. Hence, more efforts are needed to understand the spatial and temporal distribution of cumulative exposure indices and threshold exceedances over the whole domain of India.

The number of measurement sites in India having valid and long-term representative measurements of surface ozone is too small to allow for a reliable assessment of regional distribution of AOT40 to assess the potential for ozone induced damage on crop grown in this region. Regional chemical transport models have the potential to fill in this gap. There are few recent modeling studies aiming at describing gridded distribution of monthly AOT40 values over the Indian region (Mittal et al., 2007; Engardt, 2008). These studies were performed using a global emission inventory. However, recently a new gridded emission inventory of ozone precursors over the Indian geographical region have been prepared based on micro-level of all activity data (Dalvi et al., 2006; Beig and Brasseur, 2006) which are claimed to be better and found to be quite different than used by earlier modelers. Recently, Roy et al. (2008) have used this new emission inventory in the regional 3-D chemistry transport model for Indian region but the impact of cumulative ozone exposure (AOT40) over the entire Indian region has not been reported so far.

In view of the fact that sufficient measurements of AOT40 are very sparse over the Indian region, and there is a need for estimating the AOT40 over the complete Indian region, we made an attempt in this paper to simulate the ozone cumulative exposure indices and threshold exceedances using the regional chemistry-transport model (REMO-CTM) with new Indian emission inventory for the year 2003 as base case. We have also assessed the simulated results by comparing it with the statistically robust observational data (Beig et al., 2008) available for the suburban site Pune.

2 Method

2.1 Model details

The model REMO-CTM is a 3-D regional, off-line, eulerian and hydrostatic model. The model has been applied with the ECHAM-4 physics (Jacob et al., 2001, 2007) in the current study. A terrain following hybrid pressure-sigma coordinate is used in the vertical direction with 20 levels of increasing thickness between 0 to 10 hpa pressure level. The horizontal resolution is 0.5 degree on a spherical rotated grid. Further detail of this model is available in Langmann (2000) with references therein. In this study the meteorological parameters generated from the atmospheric component of the on-line model REMO were used to drive the off-line chemical-transport model REMO-CTM. After initializing REMO-CTM once, the model was run in climate mode for the year 2003 using ECMWF analyses at the lateral boundaries which have been updated every 6 h.

The emissions for all the species were obtained from the Reanalysis of the Tropospheric chemical composition (RETRO) data which provides $0.5^0 \times 0.5^0$ emission data set (Olivier et al., 2003) and the recent high-resolution estimates of the new Indian national emission inventory (Roy et al., 2008 and reference therein).

2.2 AOT40

A number of methodologies have been developed to assess the damaging effects of ozone on vegetation. AOT40 is most widely used exposure plant response index set by the United Nations Economic Commission for Europe (UNECE), United States Environmental Protection Agency (USEPA) and World Meteorological Organization (WMO) (World Health Organization (WHO), 2000). All these measurements are based on the concentrations occurring during the sunlit hours of the vegetation seasons. The AOT40 values of 3000 ppb h accumulated over a 3 months growing season, and 10 000 ppb h over 6 months, correspond to the critical levels (5% yield loss) for the protection of agricultural crops and forest, respectively. It is implied that the critical level for daily AOT40 values is around 33 ppb h (~3000/90) which should not be exceeded. The Plant Exceedance Days (PED) are defined as those days when the daily AOT40 value exceeds the critical limit (Beig et al., 2008). In the current study, a cumulative ozone exposure index (AOT40) is calculated for every day by summing the differences between the simulated hourly ozone concentrations at surface (in ppb) and 40 ppb, for every hour when the concentration is greater than 40 ppb during the daylight hours between 7 a.m.–7 p.m. These daily AOT40 values are added when AOT40 over a month period is calculated. In addition to daily AOT40 values, we have also calculated daily 8 h mean and daily maximum ozone concentration from the simulated results. It is important to note that the critical levels for AOT40 as mentioned in the EU directive are defined as multi-year means so as to compensate for annual variations (Klumpp et al., 2006) but the results presented here are based on the values for a particular year 2003.

In the following section, we present the model calculated monthly and daily AOT40 values, daily 8 h average and the daily maximum ozone levels over the Indian region for

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the year 2003. We also calculated the model simulated monthly distribution of AOT40 values over the Indian region for the months of May 2003, July 2003 and October 2003. These three months have been chosen as the representative months for the pre-monsoon, monsoon and post-monsoon seasons over India.

3 Results and discussion

Figure 1 shows the comparison between monthly AOT40 values calculated from the model and from the point observation at Pune for the year 2003. It is found that observed monthly AOT40 values lie reasonably in the same range as the modeled values at Pune indicating that our model is capable of reproducing the monthly AOT40 values. It is interesting to note that the UNECE and WHO guideline for the critical limit of AOT40 (3000 ppb h for 3 months) is exceeded even in the individual months. At Pune, elevated monthly AOT40 values were found mostly between November 2003 and May 2003 both in observed and simulated results, which corresponds to the "Rabi" crop growing season in India. The highest level of monthly AOT40 is seen for the month of March 2003 both in observed and model results. Model underestimates AOT40 values during late winter and pre-monsoon season at Pune, although the pattern of seasonal variation is similar between the observed and modeled AOT40 values. Over a 6-month period (November–April) the observed AOT40 cumulative ozone exposure exceeded up to 36 000 ppb h which is almost 3.6 times the critical level set by for the protection of forest. While, modeled AOT40 cumulative ozone exposure exceeded up to 27 100 ppb h during this period, which is around 2.7 times higher that the critical level for the forest. Beig et al. (2008) reported that the elevated levels of surface ozone and excess of AOT40 values during this period is due to the long range transport of background ozone and its precursors at Pune from the northern plains of Indian subcontinent, which is affluent in ozone and precursor gases (Beig and Ali, 2006). The lowest monthly AOT40 values are generally found during monsoon months. This is due to the inflow of clean marine air mass towards the Indian region brought by the

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southwesterly winds prevailing during this period and lesser solar insolation (due to cloudy conditions) which leads to lower photochemical production of ozone during this time (Beig et al., 2008).

Figure 2a–c compares the modeled and observed daily AOT40 values (PED), daily 8 h average and daily maximum ozone levels, respectively at Pune for the year 2003. The modeled daily AOT40 values, daily 8 h average and daily maximum ozone concentration varies from 0 to 454 ppb h, 25 to 76 ppb and, 31 to 100 ppb, respectively. Whereas, the corresponding observed values were found to vary approximately from 0 to 600 ppb h, 13 to 107 ppb and 15 to 122 ppb, respectively. Daily AOT40 values were found to be almost zero during most of the time in the monsoon (June–September). The daily maximum ozone levels and the daily 8 h average ozone concentration were found to be comparatively lower during the same period. Reduced solar insolation due to frequent cloudy conditions along with the influx of fresh marine air from the oceanic regions towards the Indian land masses leads to lesser photochemical production of ozone during this period. Although the model qualitatively reproduces a similar phenomena, a reasonable quantitative agreement was not obtained in this regard possibly due to the inability of the regional model with 0.5×0.5 degree resolution, to capture any sudden, localized excess rainfall event which has happened during the monsoon months of the year 2003 as per the rainfall records (IMD-report, 2003) which is discussed in detail by us elsewhere (Roy et al., 2008).

Figure 3 shows the modeled AOT40 distribution at surface level over the Indian subcontinent for the months of May, July and October 2003. It is worth mentioning that even in a single month period (particularly during the month of May) large area of India shows AOT40 values above the 3000 ppb h (for 3 months), which is related to 5% decrease of the yield of many important crops in India. It is also observed that maximum AOT40 values are reached at different times at different regions across the India. In all the three months discussed in this study, simulated AOT40 values are found to be substantially higher over the Indo-Gangetic (IG) plains than the other regions of India, which can have an adverse effect on vegetation in this region. However, during the monsoon season comparatively reduced AOT40 values are observed over the IG region. The maximum level of AOT40 over the Indo-Gangetic plains of India is found to be ~14 000 ppb h during October and ~12 000 ppb h during May. While, during July the maximum level of AOT40 is found to be around 6000 ppb h over the IG-region. As can be seen from Fig. 3, the AOT40 values are higher than the critical level in some parts of western India during the month October, which is a "Kharif" crop growing season in India. Whereas, over some parts of southern Indian AOT40 values are higher than the critical level during the month of May. Comparatively low values of AOT40 are seen in the month of July 2003 over most of the geographical region of India except over the IG-region where maximum level of AOT40 is found to be 6500 ppb h. The reduced AOT40 values over much of the Indian region during July is mainly due to the south west monsoon circulation which helps in transporting pristine marine air towards the Indian land masses. Also lower solar radiation due to prevailing cloudy situations leads to lesser photochemical production of ozone. While, the higher AOT40 values over the IG-region as compared to the remaining parts of India in all the three months, can be attributed to the fact that this region is affluent in the ozone precursors due to high anthropogenic activity (Ghude et al., 2007, 2008). Included among the emission sources scattered over the entire IG region are coal-based thermal power plants, steel, sugar, and other small and medium industries (several of which use coal as fuel), fossil fuel extraction (coal mining, crude oil production, natural gas production, etc.) and open burning of litter and biofuels used for domestic cooking (Ghude et al., 2008; Beig et al., 2008; Sahu et al., 2008). All these sources lead to observed high ozone values over IG region. Also, this highly populated area (Ghude et al., 2008) is prone to confinement of tracers due to its favorable synoptic conditions and orographic features which favours the photochemical buildup of ozone (Beig et al.,2006; Kulkarni et.al., 2008).

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4 Conclusions

In absence of sufficient observational information available about AOT40 over the Indian region, we use the regional chemistry-transport model to estimate cumulative exposure indices in Indian region for the year 2003. We have also presented a comparison between modeled and measured monthly AOT40 values, daily 8 h average, daily maximum near surface ozone concentration and daily AOT40 vales at suburban station (Pune). Model is able to reproduce the observed monthly AOT40 values reasonably well. The exposure-plant response index, is exceeded even in the individual months mostly between November and April at Pune. A substantial temporal and spatial variation in AOT40 values has been observed across the Indian region. Large areas of India show that the directive set by the UNECE and WHO for the critical limit of AOT40 is exceeded even in the individual months. It is noticed that maximum AOT40 values are reached at different times at different regions across the Indian region. Comparatively low values of AOT40 are seen in monsoon months over most of the geographical region of India. These values are found to be substantially higher over the Indo-Gangetic plains than the other regions of India. Considering the fact that triple cropping is practiced in the IG-regions, the elevated AOT40 values can have an adverse effect on vegetation in this region.

The results clearly indicate that presently the enhanced concentrations of ozone can have a potential impact on crop yield and forest over the large areas of India. Effective and appropriate regional/local emission control strategies needs to be developed to reduce the incessantly increasing ground level ozone pollution. Regional 3-D photochemical air quality models capable of predicting the evolution of the chemical state of the atmosphere in response to natural or anthropogenic perturbations can play a significant role in defining such mitigation strategies.

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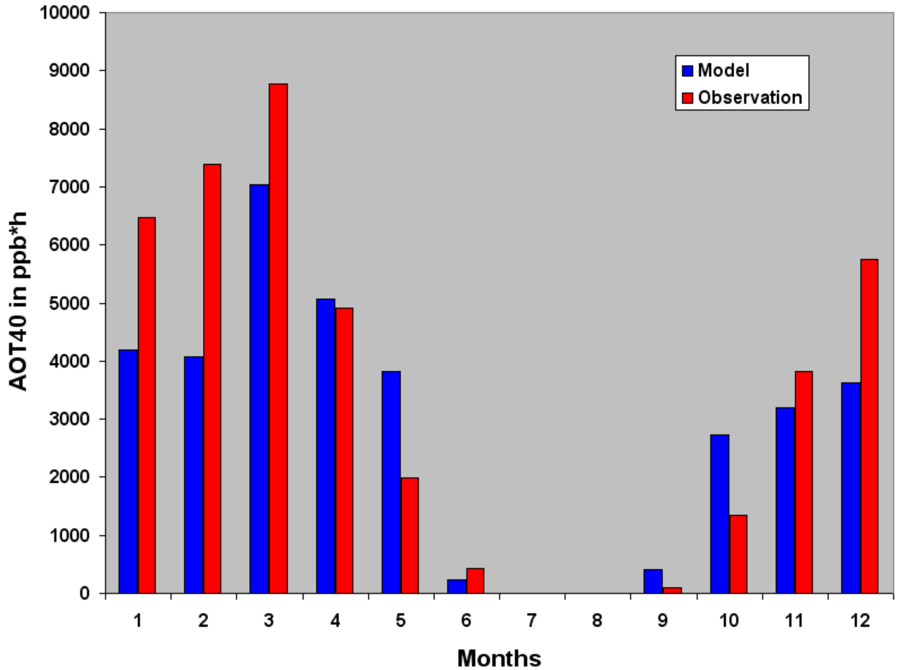

Fig. 1. Comparison of model simulated monthly values of AOT40 (7–19 h) with observational data for the year 2003 at Pune.

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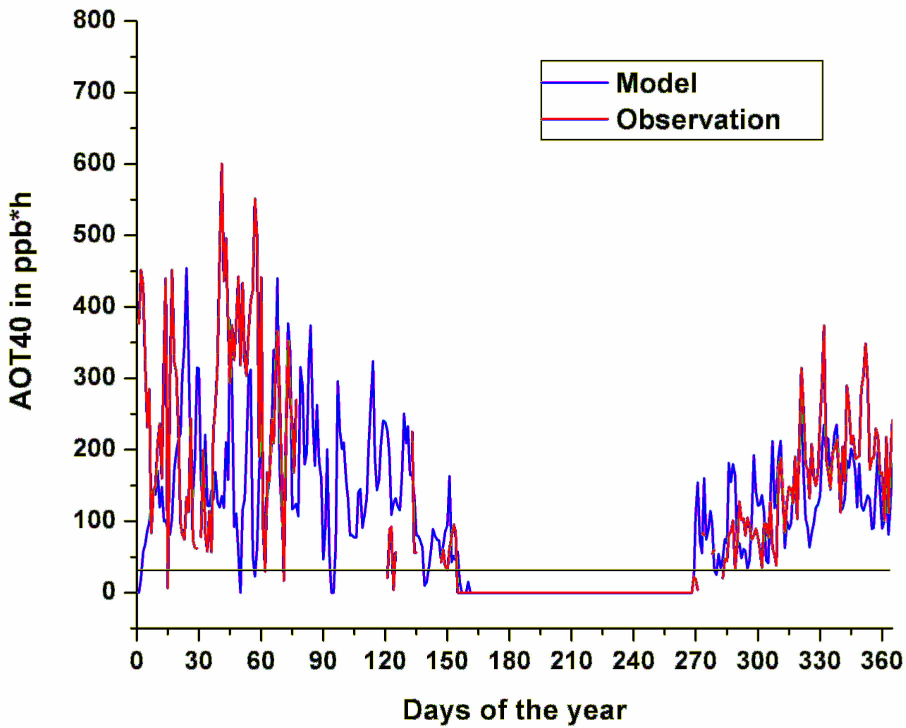

Fig. 2a. Comparison of model calculated daily values of AOT40 with observed data for the year 2003 at Pune. Black horizontal grid line through 33 ppb h corresponds to the Plant Exceedance Days (PED).

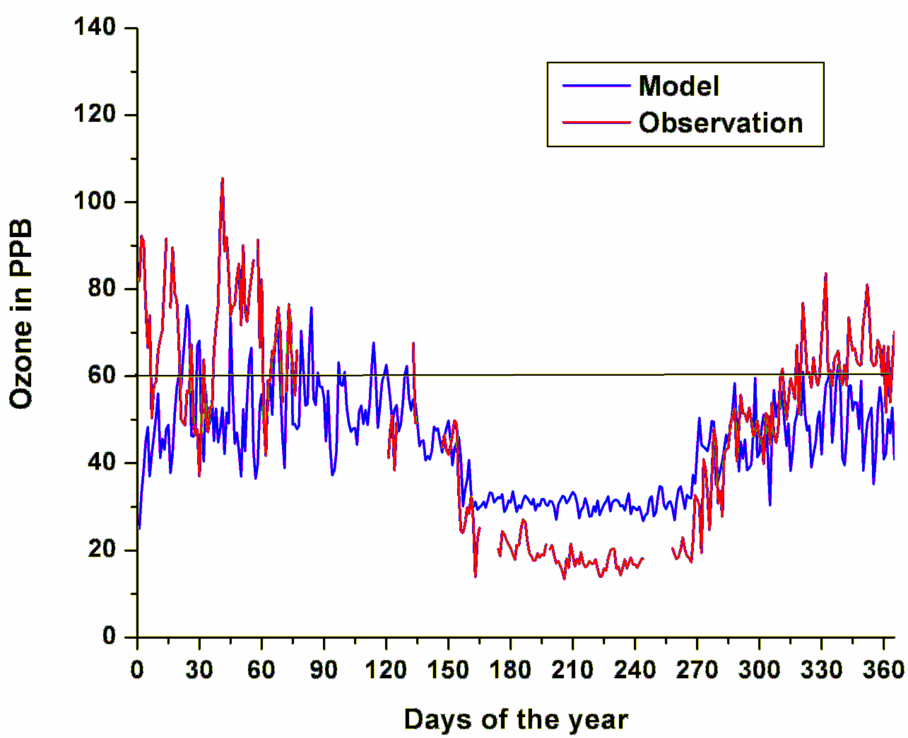

Fig. 2b. Comparison between modeled and observed daily 8 h average of ozone concentration at Pune for the year 2003. Black horizontal grid line through 60 ppb corresponds to the health protection threshold (8 h>60 ppb).

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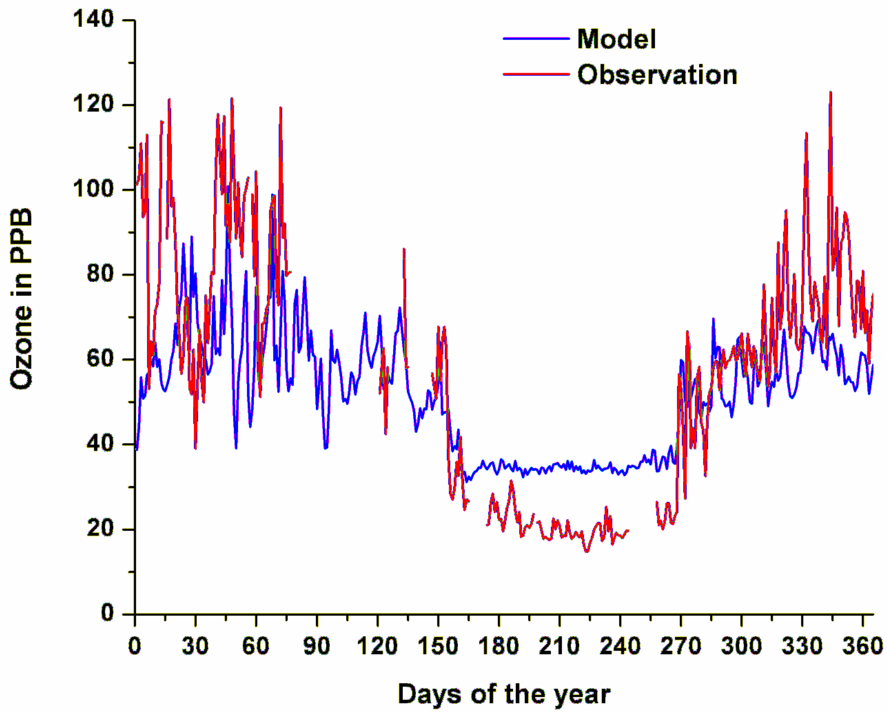

Fig. 2c. Comparison between modeled and observed daily maximum ozone concentrations for the year 2003 at Pune.

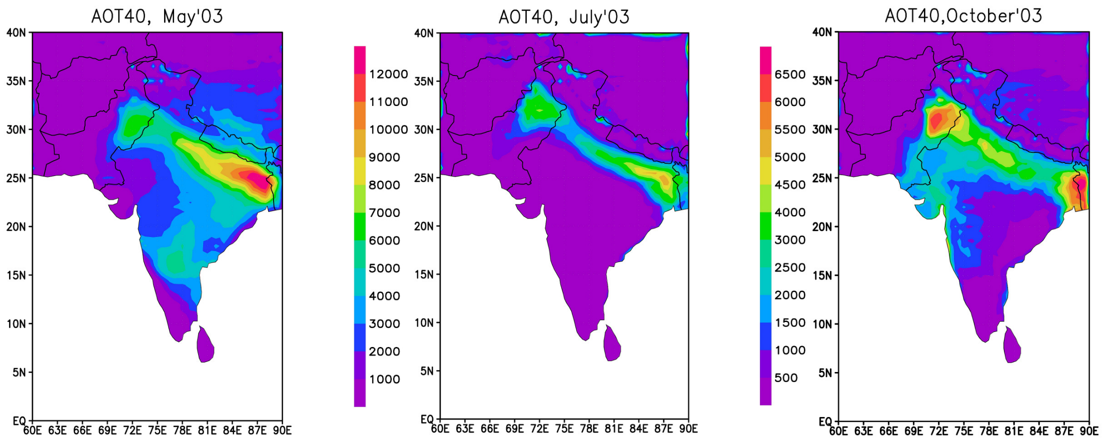

Fig. 3. AOT40 values for the months of May 2003, July 2003 and October 2003 over the Indian region as simulated by REMO-CTM.

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