Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2017-101, 2017
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 9 March 2017

NO_2 pollution over India observed from space — the impact of rapid economic growth, and a recent decline

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Abstract. The Indian economy has grown significantly during the past decades. Satellite-based remote sensing enables atmospheric pollution to be observed globally, in remote regions, and in regions where the infrastructure for air quality monitoring is limited. Here, we investigate the temporal evolution of tropospheric nitrogen dioxide (NO_2) since the early 2000s, and correlate NO_2 abundances with indicators of economic development, notably gross state domestic product and electricity generation capacity, for all 35 Indian states and union territories.

From 2003–2012, NO_2 pollution and economic growth are strongly correlated, leading to annual increases of up to 4.4%. This increase is strongest in states in East India having heavy industry. In 2012, the amount of tropospheric NO_2 reached a maximum; since then, tropospheric NO_2 pollution has stabilized or is even declining. While the Indian economy continues to grow, this decline in observed NO_2 values may be a result of a slow-down in Indian economic growth, combined with the implementation of cleaner technology.

Additionally, we identify regional pollution sources such as individual steel smelters and the cement industry, which are severely degrading air quality. In Tamil Nadu, economic growth has not led to increasing NO_2 columns, which we attribute to the investment in the development of renewable energy sources during the 2000s.

1 Introduction

Beginning in the 1950s, the Republic of India has seen tremendous growth of its population and economy. In the past 2–3 decades, this growth has been particularly dramatic. Between 2001 and 2011, the Indian population increased by 17.7%; the growth has been considerably more pronounced in urban (+31.8%) as compared to rural areas (+12.3%) (Office of the Registrar General & Census Commissioner, India, 2013). At the same time, the average population density in India increased from 325 to 382 km^{-2}. Among the more populous states (population larger than 10,000,000), the growth rate varied between +4.9% (Kerala) and +25.4% (Bihar); in virtually all states the urban population grew more rapidly than the rural population.

This strong increase in population has been accompanied by an enormous growth of the Indian economy; between the fiscal years (April–March) 2000/01 and 2013/14, the Indian gross domestic product (GDP) at factor cost and at constant prices has increased by ~144% (Reserve Bank of India, 2015).

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Due to the high population density throughout India, and especially in the Indo-Gangetic Plain, the issue of poor air quality, resulting from anthropogenic emissions associated with this rapid economic growth, and its impact on human health has been recognized as an increasingly important societal issue. In this context, the nitrogen oxides (NO_x = NO + NO_2) are important pollutants, because they are both toxic and participate in catalytic cycles producing the secondary pollutant and climate gas ozone (O_3). Their oxidation in the gas phase by OH and reaction on wet surfaces or aerosols leads to nitric acid (HNO_3) formation and acid deposition. More than half the NO_x emissions originate from anthropogenic sources, while those from the biosphere, lightning, and biomass burning play minor roles (Solomon et al., 2007). Consequently, maps of the tropospheric vertical column density (VCD_{trop}) of NO_2 are dominated by the regions of anthropogenic activity, involving fossil fuel combustion (see Fig. 1).

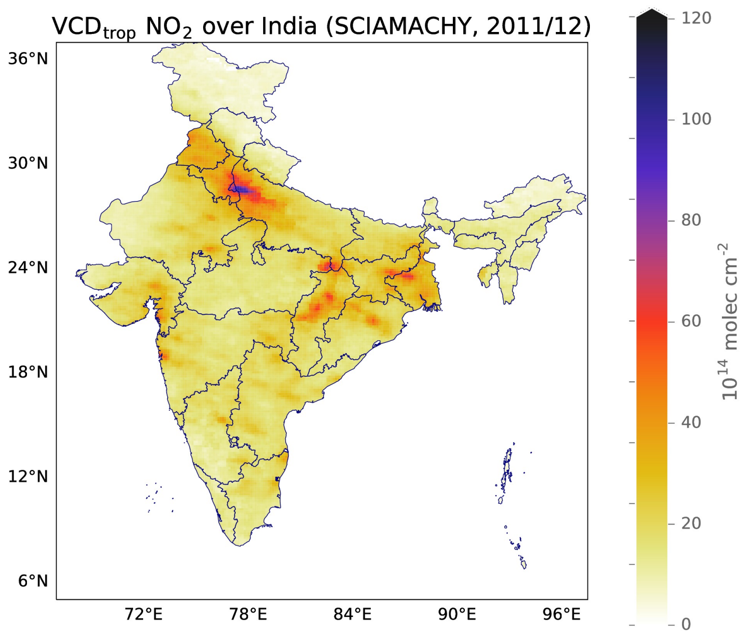

Figure 1. Vertical NO_2 columns in the troposphere over India, as measured by the SCIAMACHY instrument, averaged over the 2011/12 fiscal year. Figure created with Cartopy (http://scitools.org.uk/cartopy) v0.14.2 using Natural Earth data.

Nitrogen dioxide (NO_2) has a strong and characteristically structured electronic vibrational rotational ultraviolet and visible spectrum, and its concentrations are such that its absorption is well observed in polluted region by remote sensing methods (Burrows et al., 2011). Since the mid-1990s, global data products of tropospheric NO_2 abundances retrieved from measurements by remote sensing instrumentation on satellite platforms are available. They are usually given as so-called vertical tropospheric columns (VCDs) which are defined as the vertical integral of the tropospheric NO_2 concentrations. These data sets are retrieved from satellite-based nadir observations of the upwelling radiance in the blue part of the spectrum, using differential optical absorption spectroscopy (DOAS) (Platt and Stutz, 2008). The measurements are taken by the Global Ozone

Monitoring Experiment (GOME, on-board ERS-2) (Burrows et al., 1999), the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY, on the ENVISAT platform) (Burrows et al., 1995; Bovensmann et al., 1999), the Ozone Monitoring Instrument (OMI, on-board NASA's Aura satellite) (Levelt et al., 2006), and the GOME-2 instruments (on-board Metop-A and Metop-B) (Callies et al., 2000). In this study, we use two data sets of VCD_{trop} NO_2, derived respectively from measurements of the SCIAMACHY instrument using the limb-nadir matching technique (Hilboll et al., 2013b), and a data set combining five available satellite products (Hilboll et al., 2013a).

Tropospheric abundances of NO_2 over India have been the subject of numerous studies. For example, when GOME and SCIAMACHY measurements for the period 1996–2006 were analysed, trends over five larger regions of economic interest were derived. That study found (statistically insignificant) growth rates of between +1.0% and +2.5% annually (Ghude et al., 2008). In addition, that study, by using a selection of 9 individual thermal power plants, obtained a linear dependence of the NO_2 column observed at the power plant locations on the installed power generation capacity. This trend analysis over regions of strong economic activity was later extended to the 1996–2012 period, when in the region of Delhi, the tropospheric NO_2 loading increased by $4.05 \pm 0.84\%$ per year (Hilboll et al., 2013a). Surface NO_x emissions were estimated from SCIAMACHY and OMI measurements of VCD_{trop} NO_2, yielding an average annual growth rate of 3.8% for the whole of India, in good agreement with emission inventories (Ghude et al., 2013a).

In the past three decades urbanization of the population has increased considerably and an ever-increasing part of the Indian population lives in large urban agglomerations. The three largest Indian megacities Delhi, Kolkata, and Mumbai have a combined population of almost 50 million inhabitants. The ambient concentrations of air pollutants have risen strongly in these major pollution centers. For example, tropospheric NO_2 columns over Kolkata and Mumbai increased by 3.2 and 3.6 % yr^{-1}, respectively, during 1996–2012, relative to the 1996 values (Hilboll et al., 2013a). A recent study focused on megacity emissions from traffic sources, because they account for 72% and 60% of total NO_x emissions in Delhi and Mumbai, respectively. However, the authors found surprisingly low increases of ambient NO_x pollution in the cities investigated, most notably in Kolkata (Gurjar et al., 2016).

The strong economic growth of the Indian economy is reflected by an increasing demand for electricity, with the national *five year plans* pushing for a continuous increase in the power generation capacity in order to facilitate the prescribed industrial growth rate of 9% yr^{-1}. More than half of the total Indian generation capacity comprises of coal fired power plants, resulting in coal-based power generation being a major source of pollutant emissions with 80000–115000 annual premature deaths attributed to this source of pollution (Guttikunda and Jawahar, 2014). Consequently, NO_2 columns over the states Chhattisgarh and Odisha have increased by $50 \pm 20\%$ from 2005 to 2015 (Krotkov et al., 2016).

The seasonal cycle of tropospheric NO_2 columns over India is strongly influenced by the monsoon, with minimums occurring during pre-monsoon (Apr–May) and summer monsoon (Jun–Sep) seasons and a strong maximum during the dry season (Dec–Mar) (Ghude et al., 2008). It also strongly depends on the dominant NO_x source in a given region; regions dominated by anthropogenic NO_x emissions show a clear minimum in VCD_{trop} NO_2 during August, followed by a steep increase up until December, and then a slight decrease, possibly leading to a local maximum in May or June, to the August minimum. Those regions dominated by biomass burning or soil emissions also have their NO_2 minimum in summer (July/August), but the month of maximum NO_2 columns varies (Ghude et al., 2013a). This strong winter maximum, however, has not been identified in a recent study using OMI measurements for the year 2007/08 (David and Nair, 2013). Finally, seasonal trend patterns similar to that for NO_2 have been observed for aerosol optical depth (AOD), with increases in AOD in the dry season, and inconsistent or weak trends during the monsoon (Babu et al., 2013).

This study is the first investigation of the long-term changes of the columnar tropospheric NO_2 abundance over all 35 states and union territories of the Republic of India. We present the rates of change of VCD_{trop} NO_2, and compare and correlate these with and to socio-economic factors representative of the major anthropogenic emission sources: the gross state domestic product as an indicator of overall economic growth, the installed power generation capacity, directly linked to NO_x emissions caused by electricity generation, and the number of registered motor vehicles, indicative of traffic-related NO_x emissions.

2 Methods

2.1 Satellite measurements

Vertical tropospheric columns NO_2 were retrieved from measurements by the SCIAMACHY (ESA Envisat, 2002–2012), GOME-2 (MetOp-A 2006–present, MetOp-B 2012–present), and OMI (NASA Aura 2004–present) instruments. ENVISAT flew and MetOp-A and -B fly in sun-synchronous orbits in descending node, having a constant local equator crossing time of 10:00 LT and 09:30 LT, respectively (Burrows et al., 1995; Bovensmann et al., 1999; Callies et al., 2000). Aura is also in a sun-synchronous orbit but flies in ascending node with an equator crossing time of 13:30 LT.

The SCIAMACHY dataset used in this study is constructed using the limb-nadir matching technique (Hilboll et al., 2013b). Specifically, the analysis involves a) a spectral fitting with the DOAS procedure (Platt and Stutz, 2008; Richter and Burrows, 2002), b) subtraction of the stratospheric background NO_2 concentrations using limb-mode measurements by SCIAMACHY itself (Rozanov et al., 2005), and c) radiative transfer simulations, using the model SCIATRAN (Rozanov et al., 2014), to account for the effective light path through the atmosphere.

Additionally, we use VCD_{trop} NO_2 retrieved measurements from the GOME-2 instruments (Callies et al., 2000) on-board the European MetOp-A and MetOp-B satellites, and from the OMI instrument on-board NASA Aura (Levelt et al., 2006). The analysis for these two instruments is similar to the SCIAMACHY data analysis, the main differences being a different wavelength window for the spectral fitting and the use of a chemistry-transport-model to account for stratospheric NO_2 background values (Richter et al., 2011; Hilboll et al., 2013a).

2.2 State and union territory borders

This study works with the borders of Indian states and union territories as in place in 2014, using the Natural Earth dataset (Natural Earth, 2013). Therefore, the state *Telangana*, formed on 2 June 2014, is not separately included in the analysis but rather included in the *Andhra Pradesh* data.

2.3 Gross state domestic product

The *Reserve Bank of India* publishes the states' domestic products on an annual basis (Reserve Bank of India, 2016). For this study, we use Gross State Domestic Product at constant (2004/05) prices at factor cost, provided per fiscal year, i.e., for periods 1 April–31 March.

2.4 Population

For this study, we use gridded population density data for the year 2000 from version 1 of the Global Rural-Urban Mapping Project (GRUMP) (Center for International Earth Science Information Network, Columbia University et al., 2011).

2.5 Electricity production

The Indian *Ministry of Power* publishes monthly reports which contain information on the total installed electricity generation capacity on a state-wise level, split up into sectors (state, private, central) and mode (coal, gas, diesel, nuclear, hydro, renewable). The reports are available at the ministry's website (Central Electricity Authority, Ministry of Power, 2016) for most years between 2003 and 2016.

When investigating the state-wise relative changes, some states / UTs (Daman & Diu, Dadra & Nagar Haveli, Sikkim) show implausible irregularities. While it seems obvious that the official datasets are incorrect in these cases, the affected states / UTs only weakly contribute to Indian electricity production, and the results of this study are thus not affected by these irregularities.

2.6 Vehicle registrations

The Indian *Ministry of Road Transport and Highways* annually publishes state-wise numbers of registered motor vehicles in their so-called Road-Transport Yearbook, available at (Ministry of Road Transport and Highways, 2016). These yearbooks are available since the year 2006, and they also contain data for some selected large urban agglomerations.

Apparently, the data for Arunachal Pradesh show an implausible increase of the number of registered motor vehicles from 2011 to 2012.

2.7 Trend analysis

Monthly SCIAMACHY VCD_{trop} NO_2 values have been analysed for their annual growth rates by fitting a linear function, plus a constant offset, plus a fourth-order harmonic seasonal cycle of constant amplitude and frequency (Hilboll et al., 2013a). All absolute growth rates have been divided by the underlying value for the 2007/08 fiscal year to yield relative annual trends. A trend is not statistically significant if the 95% confidence interval of the slope parameter includes the 0.

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3 Results and Discussion

3.1 Increase of tropospheric NO_2 pollution as observed from space

The tropospheric NO_2 load over the Indian subcontinent has strongly increased since the beginning of space-borne measurements in 1995 (Hilboll et al., 2013a). The VCD_{trop} NO_2 retrieved from the hyper-spectral satellite sensors SCIAMACHY, GOME-2, and OMI consistently show a strong increase from 2003 onward, until they reach a maximum in 2012, with the amount stabilizing or declining thereafter (see Fig. 2, top left). When looking at the key polluted regions individually, this progression becomes even more distinct. For example, in the North Indian Plain, where the bulk of the Indian population resides (Fig. 2, top right), all sensors agree that the VCD_{trop} NO_2 increased steadily from 2003 to 2011 and then appears to peak in 2012 before declining by ~15% between 2012 and 2015. In the coal mining and heavy industry laden states Chhattisgarh, Jharkand, and Odisha (Fig. 2, bottom left), tropospheric NO_2 VCDs increased by ~30% between 2003 and 2012, with the amount stabilizing thereafter. In South India (Fig. 2, bottom right), the picture is not as clear. Here, the data from OMI show increasing tropospheric NO_2 VCDs from 2005 to 2012, with decreasing values thereafter; all other instruments show no clear trends.

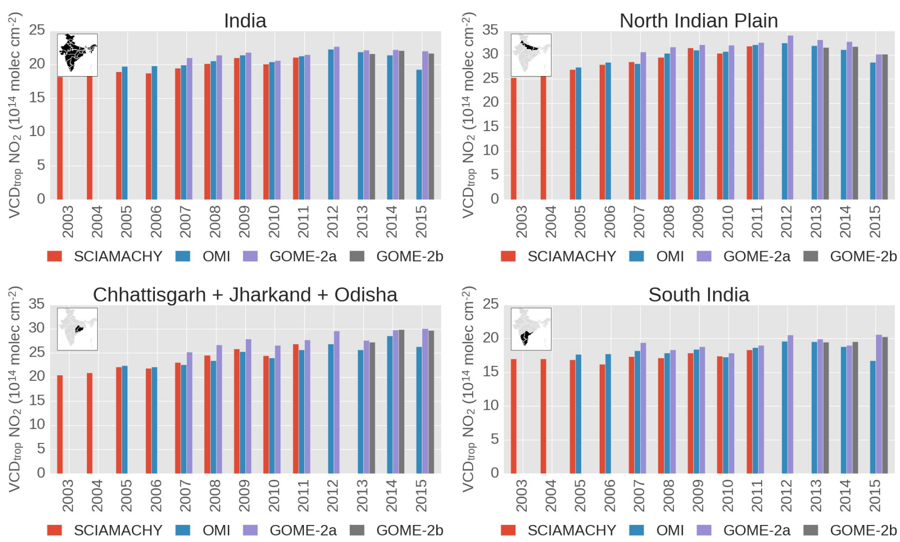

Figure 2. Annual mean tropospheric NO_2 columns, as observed by the satellite instruments SCIAMACHY/ENVISAT, OMI/Aura, GOME-2/MetOp-A, and GOME-2/MetOp-B: All of continental India (top left), North Indian Plain (Haryana, Punjab, Bihar, Uttar Pradesh, Delhi, top right), Chhattisgarh, Jharkhand, and Odisha (bottom left), and South India (Kerala, Tamil Nadu, Karnataka, and Andhra Pradesh, bottom right). Maps created with Cartopy (http://scitools.org.uk/cartopy) v0.14.2 using Natural Earth data.

The slow-down of tropospheric NO_2 increases over India seems surprising, as the Indian economy has continued to grow after the observed NO_2 peak in 2012. However, as the same pattern is visible in measurements by all four instruments, and since data from the Tropospheric Emission Monitoring Internet Service (TEMIS) (Boersma et al., 2011, 2004) show similar

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behavior (see Supplementary Fig. S1), instrumental problems or retrieval artifacts seem unlikely to be the explanation of this phenomenon. The observed stabilization of VCD_{trop} NO_2 values has similarities with recent findings for China, where VCD_{trop} NO_2 were shown to decline by ~6% yr^{-1} after 2011 (Richter et al., 2015; Irie et al., 2016).

Possible explanations for the slow-down of VCD_{trop} NO_2 increases include changing meteorological regimes (influencing, e.g., chemical reaction rates and visibility of tropospheric air masses to satellite observations) (Voulgarakis et al., 2010), potential changes in the tropospheric chemistry (leading to decreased NO_x concentrations or to a shift in the NO/NO_2 partitioning), and reduced NO_x emissions (either due to a slowing down of the Indian economy or due to technological improvements, i.e., cleaner technology).

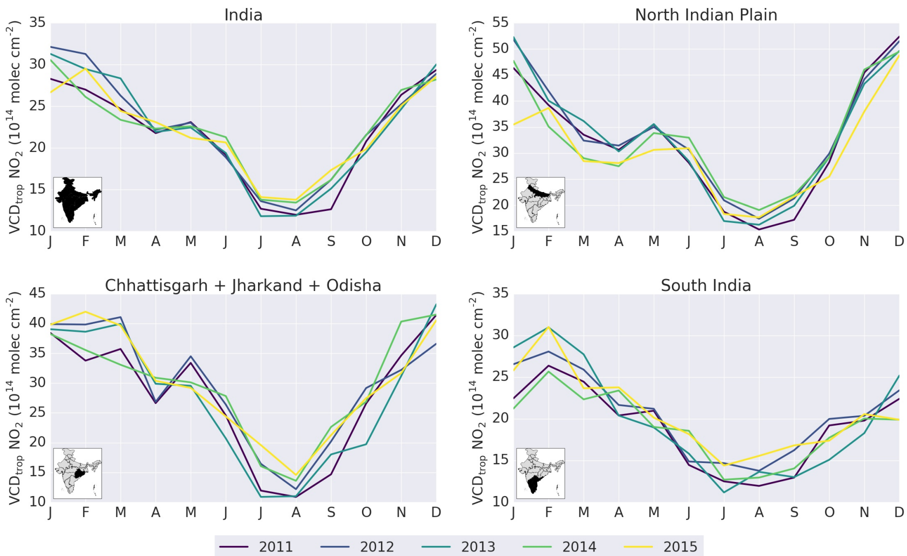

Figure 3. Inter-annual changes of the seasonal cycle of monthly mean tropospheric NO_2 columns, as observed by the satellite instrument GOME-2/MetOp-A: All of continental India (top left), North Indian Plain (Haryana, Punjab, Bihar, Uttar Pradesh, Delhi, top right), Chhattisgarh, Jharkhand, and Odisha (bottom left), and South India (Kerala, Tamil Nadu, Karnataka, and Andhra Pradesh, bottom right). Maps created with Cartopy (http://scitools.org.uk/cartopy) v0.14.2 using Natural Earth data.

The slow-down of VCD_{trop} NO_2 increases is not distributed uniformly throughout the year. Throughout India, VCD_{trop} NO_2 have been continuously increasing during summer term (April–September), but decreased during winter term (October–March), as displayed in Fig. 3 (top left).

Throughout winter, when NO_x lifetime is longer due to less pronounced photodissociation, leading to the maximum in the VCD_{trop} NO_2 seasonal cycle, values are dominated by anthropogenic emissions (Ghude et al., 2013a). While the growth rates of the Indian economy are not as high as in the previous decade, the Gross State Domestic Product (GSDP) of most states continues to grow, at least linearly, until the fiscal year 2014/15, the most recent data currently available (see Supplementary Fig. S2). Anthropogenic NO_x emissions in India mostly originate from traffic and electricity generation / coal burning.

With the introduction of the Bharat IV standard fuel quality and emissions from motor vehicles quality in 2010–2014, the Indian government has succeeded in limiting the growth of traffic-related NO_x emissions (Bansal and Bandivadekar, 2013). This reduced growth rate of traffic-related NO_x emissions contributes to the observed VCD_{trop} NO_2 decreases in the winter term, especially in regions like the North Indian Plain, where population density is among the highest on the planet, and anthropogenic NO_x emissions from traffic play a major role (see Fig. 3, top right). As older vehicles slowly begin to be phased out, these emission regulations will further contribute to air quality improvements in India.

In contrast, emissions from coal-fired power plants are currently not effectively regulated (Guttikunda and Jawahar, 2014); serious regulations will only become effective in 2017 (Ministry of Environment, Forests and Climate Change, 2015). This is reflected by VCD_{trop} NO_2 over Chhattisgarh, Jharkand, and Odisha, where VCD_{trop} NO_2 continue to increase during most of the year. (see Fig. 3, bottom left).

Compared to earlier years, 2014 and 2015 have seen a considerably slower progression of the summer monsoon onset from South India towards the northwest (pai, 2015, 2016). While the onset of the monsoon induces emission spikes in regions with mostly biogenic NO_x emission sources (Ghude et al., 2010), the monsoon generally leads to decreasing NO_x concentrations, both due to increased wash-out caused by the intense rainfall and cleaner, marine air masses being transported inland (Ghude et al., 2013a). In 2014 and 2015, when the onset and progression of the monsoon was delayed compared to earlier years by 1–2 weeks, this lead to higher VCD_{trop} NO_2 than in previous years, especially in South India (see Fig. 3, bottom right), possibly caused by lower wet deposition and later import of clean air masses. Consequently, the delayed monsoon onset could have masked an underlying, decreasing trend in NO_x concentrations.

3.2 Economic factors driving changes in local NO_2 pollution

The Indian economy has grown strongly over the past decade, and almost all states and Union Territories (UTs) have seen a more than twofold increase in their Gross State Domestic Product (GSDP). As shown in Fig. 4, the VCD_{trop} NO_2 growth rates vary greatly over India. This is at first glance surprising, as large parts of India have high population densities of more than 500 people km^{-2} (Center for International Earth Science Information Network, Columbia University et al., 2011).

As is shown by Fig. 4, there are large areas, especially in central and southern India, where no significant change in VCD_{trop} NO_2 is observed. In the Indo-Gangetic Plain, population densities and thus anthropogenic NO_x emissions from traffic and heating and their rates of increase are high. However, several areas in India show exceptionally strong rates of change of VCD_{trop} NO_2. These include the area around the city of Ballari (formerly Bellary) in the state of Karnataka, large areas of the state Chhattisgarh and parts of neighbouring Odisha (formerly Orissa), and the area between the cities of Beawar and Jodhpur in central Rajasthan.

In the region around Ballari, the strong NO_2 increase can be explained by the rapid growth of its steel industry. The Ballari region lies within one of the major Indian iron ore deposits, and the state government in 2009 announced that *the state wanted to move from just exporting ore to value-added production of steel* (Narasimhan, 2009). We consider the rapid increase in VCD_{trop} NO_2 in the Ballari region over recent years to be related to this industrialization (see Fig. 5). In particular, the Vijayanagar steel plant west of Ballari, at a capacity of 10 Mt yr^{-1} is among the largest steel plants worldwide (JSW Steel, 2016). In the year

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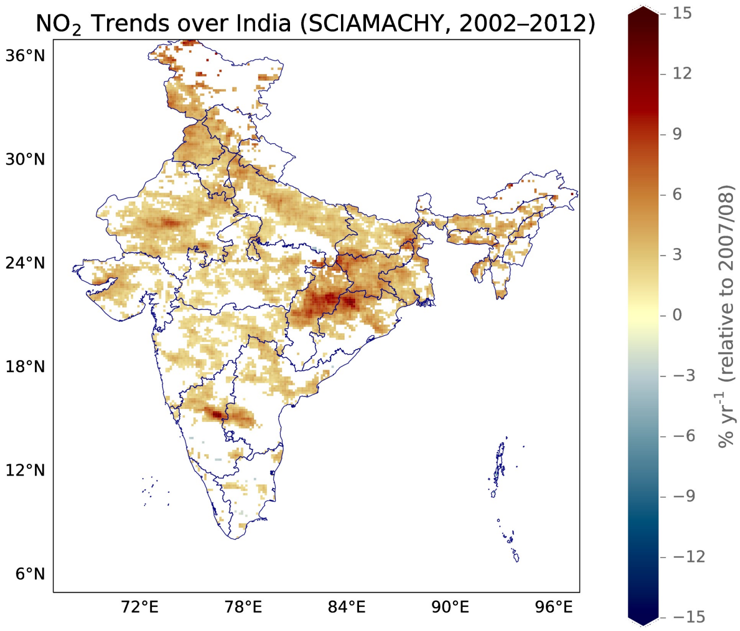

Figure 4. Relative annual change rate of VCD_{trop} NO_2 over India, for the whole SCIAMACHY measurement time series (August 2002–April 2012). All change rates are relative to the 2007/08 fiscal year. Areas where change rates are statistically insignificant are shown in white. Figure created with Cartopy (http://scitools.org.uk/cartopy) v0.14.2 using Natural Earth data.

2009, India's largest blast furnace was commissioned at this location (The Economic Times, 2014), and the NO_2 pollution in the area shows extremely strong increases in the years 2010 and 2011 (see Fig. 5). Especially in 2011, the plant's location is at the south-east corner of a large plume of strongly enhanced VCD_{trop} NO_2, consistent with the predominant wind direction (south-east) during non-monsoon months, which clearly form the peak of the seasonal variation in NO_2 abundance in India (Ghude et al., 2013a; David and Nair, 2013).

The state Chhattisgarh has enormous coal reserves, which are used to fuel a rapidly growing electricity production. According to the national *Ministry of Power*, the installed capacity of thermal power plants has almost tripled from 2003 to 2013, to meet the increasing power demand by neighboring states. Thermal power plants which are fueled by oil, gas, and coal make up more than 90% of the state's total installed capacity, and power production is so high that electricity is exported to other states.

Rajasthan, India's largest state, is dominated by the agricultural industry. The Beawar-Jodhpur corridor in central Rajasthan shows comparatively low population densities of <100 km^{-2}. Therefore it seems unlikely that the observed NO_2 increases are driven by traffic and residential sources. Rajasthan is however the second-largest cement producing state in India. During the years 2007–2011 alone, the cement production is estimated to have increased by more than 30% (Cement Manufacturers' Association, 2014). *Shree Cement Ltd.*, one of the largest Indian cement manufacturers, whose kilns are located in Beawar and Ras in central Rajastahan, increased its annual cement production more than six-fold, from 23.83 to 142.22 Mt, between 2000/01 and 2013/14 (Shree Cement Limited, 2014). As cement production is energy intensive and leads to NO_x emissions both

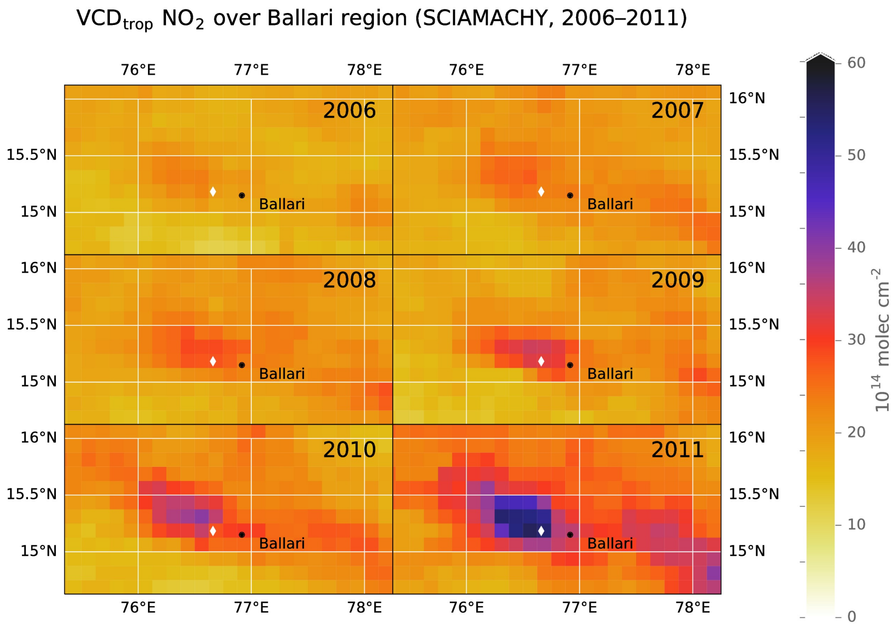

Figure 5. Annual mean VCD$_{trop}$ NO$_2$ from SCIAMACHY measurements for the region around Ballari in Karnataka, for the years 2006–2011 (non-monsoon months only, i.e., May–September are excluded). The location of the Vijayanagar steel plant is marked in white.

through the high temperature oxidation of ambient N_2 and the conversion of fuel bound nitrogen to NO_x during combustion, and in the absence of other strong industrial sources in the area, it seems likely that the observed strong increases in NO_2 pollution in central Rajasthan are attributable to the rapid increase in cement production.

3.3 State-wise aggregated economic growth indicators related to NO_2 pollution

The growth, which the Indian economy has experienced over the past decades, is a result of a country-wide development; almost all states have seen more than 8% annual increase in their GSDP in the 2004/05–2014/15 period, resulting in an increase of 65%–211% (see Supplementary Fig. S2 and Table 1). In many states, the strong economic growth coincides with large increases in the NO_2 pollution levels. The Pearson correlation coefficient between the two is > 0.7 in the vast majority of states (see Supplementary Fig. S3). Most of the states showing lower correlation coefficients are where the VCD$_{trop}$ NO_2 is small. The noteworthy exceptions are Delhi, Gujarat, and Tamil Nadu, where the correlation coefficient is only ~0.5.

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Table 1: State-wise trends in VCD_{trop} NO_2 and economic parameters (GSDP and Electricity generation). All trends are relative to the fiscal year 2007/08. Values which are not statistically significant are marked *in italics*. See Sect. 2.7 for details on the trend analysis.

State / Union Territory	VCD_{trop} NO_2 SCIA 2003/04–2011/12 (% yr^{-1})	GSDP 2004/05–2014/15 (% yr^{-1})	Electricity (total) 2002/03–2015/16 (% yr^{-1})	Electricity (fossil) 2002/03–2015/16 (% yr^{-1})	Registered vehicles 1999/2000–2011/12 (% yr^{-1})
Andhra Pradesh	1.6 ±0.38	7.1 ±2.3	9.2 ±16.0	11.0 ±19.0	8.7 ±9.5
Arunachal Pradesh	*-0.033 ±0.86*	6.8 ±4.1	4.3 ±5.5	3.8 ±14.0	35.0 ±160.0
Assam	1.5 ±0.7	6.5 ±3.3	*0.5 ±9.0*	*-0.76 ±16.0*	9.4 ±7.1
Bihar	3.1 ±0.48	12.0 ±8.5	*2.1 ±25.0*	*1.2 ±26.0*	10.0 ±14.0
Chhattisgarh	4.4 ±0.43	8.5 ±2.5	39.0 ±76.0	41.0 ±84.0	10.0 ±7.2
Goa	1.8 ±0.66	13.0 ±12.0	*1.4 ±11.0*	*0.64 ±11.0*	7.3 ±3.5
Gujarat	*0.52 ±0.55*	9.7 ±2.4	17.0 ±23.0	16.0 ±25.0	7.3 ±3.9
Himachal Pradesh	1.7 ±0.6	8.5 ±1.9	16.0 ±19.0	4.9 ±3.5	11.0 ±14.0
Haryana	2.9 ±0.63	9.5 ±2.0	11.0 ±14.0	16.0 ±21.0	8.7 ±6.0
Jharkhand	3.8 ±0.48	8.8 ±7.4	3.1 ±6.3	3.1 ±7.0	12.0 ±13.0
Jammu & Kashmir	*0.49 ±0.99*	6.0 ±2.7	7.8 ±6.8	3.4 ±2.7	8.4 ±7.0
Karnataka	1.4 ±0.44	7.4 ±2.7	9.5 ±7.0	10.0 ±12.0	10.0 ±12.0
Kerala	*0.47 ±0.53*	7.7 ±1.1	2.0 ±2.4	2.2 ±4.5	9.2 ±6.3
Maharashtra	1.2 ±0.42	8.8 ±2.3	10.0 ±14.0	11.0 ±18.0	8.1 ±4.5
Meghalaya	*1.6 ±0.88*	10.0 ±5.5	6.1 ±15.0	21.0 ±75.0	9.1 ±7.0
Manipur	*1.3 ±1.0*	5.9 ±4.2	2.0 ±6.8	4.2 ±15.0	8.0 ±7.3
Madhya Pradesh	1.1 ±0.46	10.0 ±6.2	12.0 ±22.0	15.0 ±34.0	7.5 ±7.3
Mizoram	*1.2 ±0.91*	10.0 ±7.6	3.0 ±8.9	*1.5 ±14.0*	9.2 ±6.6
Nagaland	3.1 ±1.1	8.4 ±2.8	1.8 ±9.3	10.0 ±37.0	5.2 ±5.4
Odisha	3.3 ±0.47	6.8 ±3.4	13.0 ±22.0	25.0 ±48.0	9.9 ±6.8
Punjab	3.2 ±0.58	7.1 ±0.9	6.2 ±16.0	11.0 ±30.0	6.2 ±3.7
Rajasthan	*1.0 ±0.61*	9.5 ±3.9	16.0 ±24.0	15.0 ±23.0	8.7 ±6.1
Sikkim	*0.45 ±1.0*	26.0 ±30.0	19.0 ±29.0	5.7 ±12.0	9.9 ±7.9
Tamil Nadu	*0.38 ±0.38*	9.6 ±3.0	8.5 ±9.6	6.2 ±15.0	8.6 ±3.8
Tripura	3.1 ±0.73	9.9 ±6.0	12.0 ±38.0	18.0 ±54.0	10.0 ±7.4
Uttar Pradesh	2.5 ±0.46	7.3 ±1.1	8.2 ±12.0	7.7 ±16.0	8.8 ±6.7
Uttarakhand	*0.56 ±0.69*	14.0 ±3.4	6.0 ±6.8	4.9 ±8.6	9.3 ±11.0
West Bengal	3.0 ±0.49	7.2 ±2.6	8.5 ±5.7	8.4 ±7.2	5.6 ±9.2
Andaman & Nicobar	*0.71 ±0.63*	12.0 ±3.7	*0.23 ±9.5*	*-0.092 ±10.0*	8.7 ±6.5
Chandigarh	—	6.3 ±5.2	4.1 ±4.0	2.2 ±4.5	7.9 ±7.1
Daman & Diu	*0.34 ±0.93*	—	18.0 ±59.0	16.0 ±69.0	6.2 ±2.2
Delhi	2.5 ±0.95	9.9 ±2.1	13.0 ±18.0	14.0 ±21.0	6.1 ±5.0
Dadra & Nagar Haveli	*-0.38 ±1.1*	—	12.0 ±18.0	10.0 ±21.0	11.0 ±4.9
Lakshadweep	-1.7 ±0.85	—	*-2.2 ±21.0*	*-3.1 ±22.0*	6.7 ±6.7
Puducherry	*1.1 ±0.67*	11.0 ±7.1	3.3 ±6.9	2.5 ±6.3	8.8 ±7.5

The strongly growing Indian economy has an ever increasing demand for electricity, which is mostly generated by the combustion of coal (see Supplementary Fig. S4). Most of the country's power generation capacity is located in the eight states Andhra Pradesh, Chhattisgarh, Gujarat, Karnataka, Maharashtra, Tamil Nadu, Uttar Pradesh, and West Bengal. In almost all states, the increasing demand for electricity has been met exclusively by increasing the number and capacity of coal fired power plants, which is reflected in a stronger-than-average increase of the NO_2 pollution levels. The notable exception is the

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2017-101, 2017
Manuscript under review for journal Atmos. Chem. Phys.
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state Tamil Nadu, where at least until ~2011/12 the demand for additional power generation capacity has almost exclusively been provided by renewable sources (see Fig. 6). Consequently, Tamil Nadu had not seen a serious increase of NO_2 pollution, while its GSDP increased to rank 7th among all states. In recent years, however, several new coal-based power plants have been constructed in Tamil Nadu, leading to an increase in the installed coal-based power generation capacity by ~80% from 2011/12 to 2015/16. In 2012/13, the observed VCD_{trop} NO_2 mirror this increased coal burning with an increase of ~15% compared to the year before. In the following years 2013/14 and 2014/15 however, the NO_2 columns do not increase further, in spite of the enhanced fossil fuel consumption, which is in line with the general halt of NO_2 increases observed throughout India, as discussed above.

As in recent years the demand for electricity by far surpassed the coal mining capacities of Tamil Nadu (Srikanth, 2011), the newly constructed and planned power plants are exclusively located close to the coast, to minimize transport pathways from the import harbors. In particular, the Ennore, North Chennai, and Vallur power stations, which combined account for about half of the recent increase in generation capacity, are located in the Chennai area, in the very North of the state, close to both the Bay of Bengal and the state border. This is one of the only areas where we observe statistically significant increases in VCD_{trop} NO_2 for the 2012–2015 period. Up to now, it appears that these changes are not enough to significantly influence the state-wide averages. Interestingly, the GOME-2/MetOp-A measurements show statistically significant decrases in VCD_{trop} NO_2 over the Bay of Bengal, off the coast of Tamil Nadu, the reasons of which remain unclear as of now.

So even while the factors causing the stagnating NO_2 pollution levels in Tamil Nadu remain unclear, the decoupling of VCD_{trop} NO_2 and electricity production is still strong evidence that if increasing energy demands are met from renewable sources, rapid economic growth does not necessarily lead to degrading air quality.

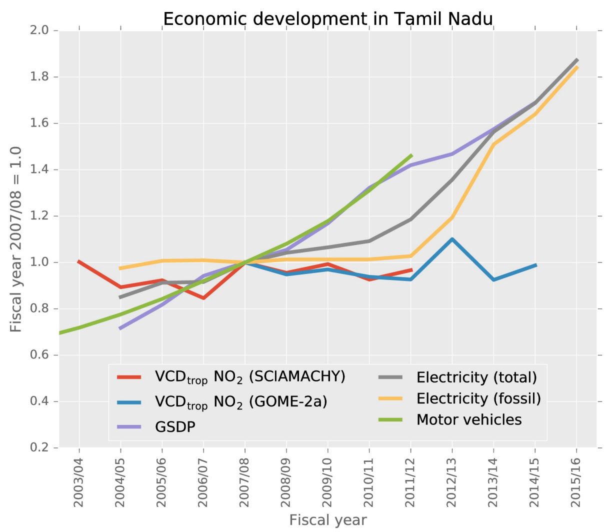

Figure 6. Time series of VCD_{trop} NO_2 from SCIAMACHY and GOME-2/MetOp-A, as well of gross state domestic product (GSDP), installed electricity generation capacity (total and fossil fuel), and the number of registered motor vehicles. All values are given per fiscal year and have been normalised to 2007/08.

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It is difficult to directly compare the NO_2 trends derived in this study to earlier studies, as some authors fail to give the reference year for cited relative change rates. For example, one study simply reported a trend of 3.8% yr^{-1} for all anthropogenic source regions in India (Ghude et al., 2013b). Nonetheless, the SCIAMACHY trend results seem to agree well, at least for those states with large population.

Using the same methodology as has been already applied to China (Reuter et al., 2014), we investigated the correlation between NO_2 and CO_2 emission increases. However, due to the comparatively small study area, we could not obtain any statistically significant results.

3.4 Implications for NO_x emission inventories

The accurate description of year-to-year changes in tropospheric NO_2 abundances is essential for an up-to-date knowledge of NO_x emission sources. Inventories of pollutant emissions often assume a certain change rate, based on a-priori assumptions, because in many parts of the world, accurate data are not available on an annual basis. In growing economies such as that of India, this can lead to biases in the emission datasets (Jena et al., 2015). There, it could be shown that all of 6 inventories of anthropogenic NO_x emission inventories lead to a substantial low-bias in simulated tropospheric NO_2 columns when compared to OMI measurements; biases ranged from ~ 3×10^{14} to 24×10^{14} molec cm^{-2}. The most probable reason for the low-bias of most NO_x emission inventories is the strong increases of the Indian economy, leading to largely increased NO_x emissions, as shown above; this increase is not adequately reflected by the bottom-up inventories which are by nature hindcast estimates of the true emissions.

4 Summary and conclusions

We have shown that the level of NO_2 pollution over the Republic of India is strongly influenced by the type of economic development. Correlation coefficients between tropospheric NO_2 load and gross state domestic product are > 0.7 for all but a few states with noteworthy industrial activity.

A recent decline in the observed NO_2 growth rates is in line with similar observations over China, albeit the reasons for this change have not been unambiguously identified. Cleaner technologies have started to slow the increase of NO_x emissions caused by traffic, but while the Indian economy has started growing at a slower pace in recent years, the combined effect of cleaner technology and economic slowdown does not fully explain the observed stagnation in NO_2 pollution. This may imply that changes in meteorology or up to now not understood changes in tropospheric chemistry are also of significance.

Strong regional differences in both the level of NO_2 pollution and its rate of increase are observed. We identified three regions, where the increase of NO_2 is considerably stronger than one would expect from population increase alone. Specifically, we could show that the extremely high annual NO_2 growth rates of around 10% observed in western Karnatakta, central Rajasthan, and throughout Chhattisgarh can be attributed to increasing industrial activity, in particular steel smelting, cement production, and thermal power generation. Finally, we could show that the state of Tamil Nadu has not experienced substantial increases in NO_2 pollution in a period when most of the additional power generation capacity was met by renewable sources, clearly indicating that economic growth does not necessarily lead to deteriorating environmental conditions,provided that the energy driving this growth is generated from clean sources.

As space-based observations of tropospheric composition remain an invaluable resource for the determination of air pollutant emissions, it is essential to continue to improve the observing system in its spatial and temporal sampling to provide improved evidence base and to improve timely knowledge of tropospheric emission trends.

5 Data availability

The data used in this study are available from the cited references (economic data, TEMIS NO_2 data) and directly from the authors upon request.

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Author contributions. All authors conceived the study, A.H. and A.R. retrieved the satellite data, A.H. analysed the results, and all authors reviewed the manuscript.

Competing interests. The authors declare no competing interests.

Acknowledgements. This study has been funded by DLR in the scope of the Sentinel-5 Precursor verification project (grant no. 50EE1247), by the DFG-Research Center/Cluster of Excellence "The Ocean in the Earth System", by the University of Bremen, the state of Bremen, and by the EU FP7 project "Partnership with ChiNa on space DAta" (PANDA, grant no. 606719).

GOME and SCIAMACHY radiances have been provided by ESA. OMI Level-2 data used in this study were acquired as part of the activities of NASA's Science Mission Directorate, and are archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). GOME-2 Level-1 data have been provided by EUMETSAT. The authors wish to thank Richard Herd for his help in acquiring the economic datasets. The borders of the Indian states and union territories have been provided by Natural Earth (Natural Earth, 2013). We acknowledge the free use of tropospheric NO_2 column data from the SCIAMACHY, OMI, and GOME-2 sensors from www.temis.nl. This document has been prepared using org-mode (Schulte et al., 2012). All data analysis has been carried out in IPython (Perez and Granger, 2007), using the *statsmodels* (Seabold and Perktold, 2010), *pandas* (McKinney, 2010), and *Iris* (Met Office, 2010b) libraries. All figures have been created with Cartopy (Met Office, 2010a) and matplotlib (Hunter, 2007).