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Long-term trends in NO_2 columns related to economic developments and air quality policies from 1997 to 2016 in China

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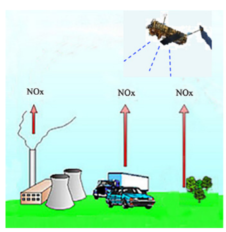
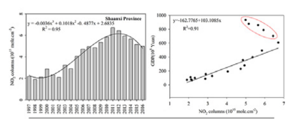
HIGHLIGHTS

- Trends in NO_2 columns from 1997 to 2016 in China are studied.
- NO_2 differences among GOME, SCIAMACHY, and GOME-2A have seasonal variations.
- Long-term NO_2 has three shapes: decrease, increase and decrease; decrease and increase; and decrease.
- The peak years of NO_2 in 17 provinces occurred in 2011 and 2012.
- Thermal power generation, traffic, agriculture, and policy determine NO_2 trends.

GRAPHICAL ABSTRACT





	Model 1 (Fix effect)			Model 2 (Random effect)		
	Coefficient	STD error	Sig.	Coefficient	STD error	Sig.
DIESLEOIL (10^3 kg/km²)	40.21	8.60	0.00	33.34	6.90	0.00
PASSER (10^3 kg/km²)	0.02	0.004	0.00	0.02	0.00	0.00
FREIGHT (1people/km²)	0.04	0.005	0.00	0.04	0.00	0.00
TPOW (10^4 w-h (km²))	1.81	0.32	0.00	1.86	0.31	0.00
P_1	11.91	21.42	0.58	14.40	22.00	0.51
P_2	23.92	24.44	0.33	31.14	24.71	0.27
P_3	-135.93	33.07	0.00	-144.56	33.26	0.00
Constant	26.54	31.81	0.40	50.26	47.88	0.00
Sig.	0.00			0.00		

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ABSTRACT

This study detected the long-term trends in NO_2 concentrations in China from 1997 to 2016 based on the NO_2 columns from GOME, SCIAMACHY, and GOME-2A. Both differences in the time-overlapped NO_2 columns from GOME vs. SCIAMACHAY and SCIAMACHAY vs. GOME-2A showed seasonal variations, and the annual NO_2 columns from GOME were 0.9% higher than those from SCIAMACHY, which exceeded that from GOME-2A by 14%. The long-term trends of the NO_2 columns on a provincial scale could be simulated by cubic models ($0.60 < R^2 < 0.96$, $p < 0.05$) and presented three shapes: first decreasing then increasing and decreasing again; first decreasing then increasing; and continuously decreasing. The peak years of NO_2 columns in 17 provinces occurred in 2011 and 2012. These trends in NO_2 columns were determined by the economic developments and enacted air quality policies in nearly all the provinces except for Xizang and Qinghai Provinces, where the trends were determined by natural NO_x emission sources. In detail, the panel data analysis showed that the simulated model had fixed effects, and the thermal power generation, consumption of diesel oil in agriculture, passenger traffic by highways, and freight traffic by highways significantly increased NO_2, while the air quality policies in the 12th five-year plan decreased NO_2 columns from 1997 to 2016. The benefits to decreasing NO_2 columns from the air quality policies issued in the 10th and 11th five-year plans were offset by the quickly increasing economies.

1. Introduction

Nitrogen dioxide (NO_2) harms human health, and influences chemical compositions in the atmosphere through changing tropospheric

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hydroxyl radical (OH) concentrations, which are a catalyst to remove various atmospheric pollutants (Chiusolo et al., 2011; Logan, 1983). China has been among those areas with the highest NO_2 concentrations due to the rapid industry developments in recent years (Krotkov et al., 2016). However, the Chinese government has enacted a series of policies and actions to prevent further NO_x emissions since the 1990s, considering the adverse effects of human exposures to NO_2. Therefore, it is important to detect the long-term trend of atmospheric NO_2 concentrations and to evaluate the effect of the enacted policies and the key economic factors on NO_2 variations.

Although no clear policies were enacted to control NO_x emissions during the 9th five-year plan (1996–2000) and the 10th five-year plan (2000–2005), the government tried to prevent further air pollution. For example, the "Decision of the State Council on Several Issues Concerning Environmental Protection" issued in 1996 stated that "15 major categories of small pollutant enterprises" related to pollutant emissions should be closed; pollution fees became collectable on all discharges (Jin et al., 2016); "Two Control Zones" was issued in 1998 and became effective in 2002; and a new national emission standard (China 2) for cars was implemented during this period.

The 11th five-year plan (2005–2010) proposed a clear goal to control the increasing NO_x emission trends and decrease the NO_x emissions per power production unit. The Energy Saving and Emission Reduction policy was put into effect to reduce energy consumption per unit of gross domestic product (GDP) by 20% (Wang and Hao, 2012). The 12th five-year plan (2010–2015) further clearly announced a goal to reduce NO_x emissions by 10% in 2015 on a national scale and by 13% in key regions, comparing with those in 2010. Detailed measures to reduce NOx emissions from power plants, cement plants, and transportation were included. From 2011, selective catalytic reduction equipment has been installed at both power plants and heavy industries, and this equipment is expected to reduce emissions by 70% (Liu et al., 2016). Additionally, strong regulations on emission standards (China 4) for cars were implemented from 2007 to 2015 (Wu et al., 2017).

Some studies have evaluated the temporal variations of NO_2 concentrations in China based on the satellite-based NO_2 columns, taking the advantage of high spatial and temporal resolutions. Several satellite sensors, GOME (Global Ozone Monitoring Experiment, 1996–2002), GOME-2 (2007–), OMPS (Ozone Mapping and Profiler Suite, 2011–), SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography, 2002–2012), and OMI (Ozone Monitoring Instrument, 2004–), could monitor tropospheric NO_2 columns. Based on the satellite monitoring, a large increase of NO_2 columns was found over eastern China from 1996 to 2004 or 2005 (Richter et al., 2005; Van der A et al., 2006), where had a further increasing trend from 2005 to 2011, then decreasing from 2011 to 2015 (de Foy et al., 2016; Krotkov et al., 2016). In western China, a rapid growth in NO_2 pollution was detected from 2005 to 2013 (Cui et al., 2016). Moreover, the surface NO_2 concentrations tripled in East Asia including China from 1996 to 2012 (Geddes et al., 2016). Most of these studies detected the NO_2 trends from the mid-1990s to the mid-2000s based on the monitoring from GOME and SCIAMACHY or from the mid-2000s to 2010s based on OMI, focusing on eastern or western China. However, the long-term variations in NO_2 greatly varied throughout China due to the varied economic development levels and policies, which have not yet been fully studied.

The previous studies used the NO_2 columns from GOME and SCIAMACHY without any correction to detect NO_2 trends from the mid-1990s to the mid-2000s since the bias between the two datasets was lower than the minimum error in the data (Richter et al., 2005; Van der A et al., 2006). For the tropospheric NO_2 columns, SCIAMACHY gained higher values than GOME-2A on a national scale over China, and both of them were higher than OMI (Chen et al., 2017). Additionally, the gaps of NO_2 columns identified by different sensors seasonally varied (Chen et al., 2017). These results indicated that the differences in the NO_2 columns measured by different sensors exhibited spatial and seasonal variations. Therefore, a correction involving the spatial and seasonal variations was required when using NO_2 datasets from different sensors.

This study aims to detect the long-term trends of NO_2 columns from GOME, SCIAMACHY, and GOME-2A from 1997 to 2016 on a provincial scale over China and to evaluate the influences of related economic developments and enacted polices. First, a long-term dataset of yearly NO_2 columns was produced taking the SCIAMACHY as a reference, second, a cubic model was proposed to detect the long-term trends of NO_2, and finally the influences of economic development and air quality policies on NO_2 variations were quantitatively evaluated based on a panel data analysis.

2. Materials and methods

2.1. Tropospheric NO_2 columns

The troposphere NO_2 columns from GOME, SCIAMACHY, and GOME-2A are selected considering the consistency of their overpass times and the period covering. GOME is a nadir-viewing spectrometer designed to monitor a range of atmospheric trace constituents globally in the troposphere and stratosphere, carried by European Remote Sensing Satellite (ERS-2). GOME-2 is one of the new-generation optical spectrometers carried on the EUMETSAT's Meteorological Operational Satellites (MetOp satellites), including GOME-2/METOP_A (A, launched in October 2006) and GOME-2/METOP-B (B, launched in September 2012). SCIAMACHY launched on board Environmental Satellite (ENVISAT), with the wavelength ranging from 240 to 2380 nm. SCIAMACHY yield total-column values as well as distribution profiles of various trace gases in atmosphere.

Three datasets of NO_2 columns from GOME, SCIAMACHY, and GOME-2/METOP-A are freely downloaded from http://www.temis.nl/airpollution/no2.html (Boersma et al., 2004). The spatial resolution of the data is $0.25° \times 0.25°$ by grid. The overpass time per location is at 9:30–10:30 of the local time, which avoid systematic differences in their time series. Here, monthly mean NO_2 columns are used. The NO_2 columns from GOME, SCIAMACHY, and GOME-2 spanned from January 1997 to June 2003, from August 2002 to March 2012, from January 2007 to December 2016, respectively.

2.2. Monthly temperature and precipitation data

To study the influencing factors on the long-term trends of NO_2 columns, the averages of monthly air temperature (°C) and total precipitation (mm) are considered in our analysis. These data are derived from the Centre for Environmental Data Analysis (CEDA), with a spatial resolution of $0.5° \times 0.5°$ (http://badc.nerc.ac.uk/). In this study, the average of temperature and the total amount of precipitations in the growing season (May to October) in Xizang and Qinghai provinces from 1997 to 2016 are used.

2.3. Linear regression model to correct NO_2 columns from different satellite sensors

Two datasets of NO_2 columns (GOME vs. SCIAMACHY and SCIAMACHY vs. GOME-2A) with overlapped temporal coverage are used to compare different datasets on a provincial scale. The time spanned from August 2002 to June 2003 for GOME vs. SCIAMACHY, and from Jan 2007 to March 2012 for SCIAMACHY vs. GOME-2A, respectively. Since NO_2 columns are greatly influenced by the emissions from the neighboring grounds, the four municipalities are combined into their neighboring provinces, respectively. Beijing, Tianjin and Hebei (BJ-TJ-HB) are taken as one unit, Shanghai is merged into Jiangsu Province (SH-JS), and Chongqing is combined with Sichuan Province (CQ-SC). Thus in total 28 units are considered.