Evaluation of NO₂ column variations over the atmosphere of Kazakhstan using satellite data

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Abstract. Tropospheric NO₂ concentrations obtained from the measurements of the Ozone Monitoring Instrument on board the NASA Aura satellite from 2005 to 2016 were studied to identify major NO₂ emission hot spots, trends, and seasonal variations over Kazakhstan. Emission hot spots are observed over the locations of thermal power plants (Ekibastuz) and major urban and industrial regions (Almaty and Shymkent), as well as the capital city (Astana). Some decreasing trends have been observed for NO₂ over Ekibastuz, whereas the regions of Almaty and Shymkent showed increasing trends due to industrial growth. The seasonal pattern of the NO₂ concentration shows a difference between three industrial cities of Almaty, Shymkent, and Ekibastuz versus the rest of Kazakhstan. In these three cities, a NO₂ maximum is found during wintertime, which we attribute to seasonality of emissions associated with electricity production and the longer chemical lifetime of NO₂ in winter. In contrast, in Astana and the rest of Kazakhstan, the NO₂ concentration reaches a maximum in the summer. © 2018 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JRS.12.042610](https://doi.org/10.1117/1.JRS.12.042610)]

Keywords: NO₂; NASA Aura Satellite; Kazakhstan; Almaty; Astana; power plants.

Paper 180367SS received May 28, 2018; accepted for publication Sep. 28, 2018; published online Oct. 25, 2018.

1 Introduction

Nitrogen dioxide (NO₂) and its precursor nitric acid (NO) together are known as nitrogen oxides (NO_x), which play a vital role in the tropospheric chemistry. NO_x is a precursor of tropospheric ozone and nitrate particulate matter, both of which affect air quality and climate.¹ NO_x concentrations in the troposphere are highly variable in both space and time, reflecting its short chemical lifetime in the atmosphere and its nonuniform distribution.² The lifetime of NO₂ was reported to be ~6 h in summer, ~6 to 12 h in spring and fall, and 12 to 20 h in winter, due to the variability in the photolysis rate and water vapor content in the atmosphere.³

Emissions of NO_x come from both anthropogenic and natural sources. Elevated temperatures associated with combustion combine ambient N₂ and O₂ to form NO, which oxidizes to NO₂. Major contributors to global NO_x emissions include industrial activities, electricity generation, transportation, and prescribed burnings.⁴ Natural phenomena, such as lightning, wildfires, and soil microbial activities, contribute to NO_x emissions.⁵

This study focuses on NO_x emissions in Kazakhstan, which is the ninth largest country in the world at 2.72 million km², one of the top coal and oil producing countries in the world,⁶ while

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maintaining one of the lowest population densities of any country at 7 per km².⁷ Over 50% of the Kazakhstan's energy is supplied by coal, and the oil sector is the largest determinant of the country's economic growth (ibid). Between 2002 and 2016, the gross domestic product of Kazakhstan has increased sixfold. In 2014, the highest per capita household coal consumption occurred in Poland (165 kgoe/cap), followed by Kazakhstan (157 kgoe/cap), and Mongolia (104 kgoe/cap).^{8,9} Kazakhstan experiences unique metrological conditions where the temperature in winter time may go down to −40°C in the north. Characterizing NO_x emissions in this large, energy-intense country bears relevance to air quality and climate impacts for the region, country, and world. The World Bank found that the air quality monitoring network in Kazakhstan may experience unrepresentative sampling because the number of monitoring sites are low, and the selection of monitored pollutants does not comply with recognized priority pollutants.¹⁰ To address this data need, we apply satellite retrievals of NO₂ to assess NO_x trends and spatial variability in Kazakhstan.

Long-term observations of satellite NO₂ columns can constrain NO_x emission inventories and significantly reduce model uncertainties in simulations studies.¹¹ Prior studies using satellite data indicate that NO₂ levels decreased sharply over the last decade in many countries, such as the United States, Japan, Australia, New Zealand, and those in Western Europe.^{12–15} This decrease resulted from a combination of the implementation of emission control devices on thermal power plants, the shuttering of inefficient plants, and stricter vehicle emission standards.¹⁶ Liu et al.¹⁷ found that a high NO_x concentration does not necessarily correspond to a long lifetime, and the correlation between NO_x lifetime and NO₂ tropospheric vertical column density is rather low ($R^2 = 0.22$), probably due to the complex NO_x chemistry, which is also affected by meteorological and chemical variability, such as variations in UV flux, water vapor, and VOC levels.¹⁸

Currently, only a few studies regarding the atmosphere of Central Asia are available. In particular, no studies were found in the literature that investigates NO₂ concentrations variability in Kazakhstan. The objective of this study was to examine the temporal evolution of tropospheric NO₂ in four major cities of Kazakhstan including Astana, Shymkent, Almaty, and Ekibastuz from 2005 to 2016 using the data from ozone monitoring instrument (OMI) launched on the NASA Aura satellite in July 2004.

2 OMI Tropospheric NO₂ Columns

Our study uses data from OMI to assess air quality patterns and trends in Kazakhstan. OMI is a nadir-viewing wide-field imaging spectrometer data on the board of NASA Aura satellite. Its ground resolution is 13 km × 25 km, spectral and spatial detection is 780 × 576 pixels, respectively, and can detect UV with wavelength 350 to 500 nm. The instrument observes Earth's backscattered radiation in the ultraviolet and a visible range of 350 to 500 nm with a wide-telescope feeding two imaging grating spectrometers. Aura was launched on July 14, 2004, into a Sun-synchronous polar orbit at ~705-km altitude with a local equator crossing time of 13:45 in the ascending node.^{3,19}

The hyperspectral capabilities of the instrument can improve the accuracy and precision of the total ozone concentration. Also, it allows for accurate radiometric and wavelength selfcalibration over the long term. The Dutch OMI NO₂ (DOMINO) retrieval algorithm consists of three steps. First, the slant columns of NO₂ are obtained from the OMI reflectance spectra in the 405- to 465-nm window using the DOAS technique.²⁰ Second, the stratospheric and tropospheric contributions to the OMI NO₂ slant columns are separated by assimilating the slant columns of a global chemistry and transport model.^{21,22} We used monthly average level-3 product. Finally, tropospheric slant column is converted to a vertical column with the tropospheric air mass factor.

The tropospheric NO₂ column retrievals used are from the version-2 DOMINO data product for OMI²² obtained through the TEMIS25 website. The ground pixel size of the OMI retrievals is 13 to 24 km with a daily global coverage. This study employs the monthly average level 3 OMI NO₂ product available at 0.25 deg × 0.25 deg because these data are gridded files on a fixed grid. One grid cell (0.25 deg × 0.25 deg) falls in each city. Since cities are not perfectly square

shaped, at the edges there might be some uncertainties. In the case of Almaty, which is surrounded by mountains, the grid cell did not cover mountains.

3 Study Area

We focus on the four major cities of Kazakhstan including Astana, Shymkent, Almaty, and Ekibastuz from 2005 to 2016. These four cities are among most populated and largest urban areas where potential NO₂ emissions exist.

Almaty (43.22°N, 76.85°E) is located in the valley of big and small Almatinka rivers at the foot of Trans-Ili Alatau mountains (Fig. 1). The city is surrounded by mountains and hills, limiting horizontal movement of air. Wind generally blows southward during the day, bringing cold and polluted air from the North and northward at night.²³ The population of Almaty has increased from 2005 to 2016 by 42% (Fig. 2).²⁴ Sources of NO₂ in Almaty include thermal power plants, motor vehicles, boilers from military garrisons of regional operational units of the Ministry of Defense, boiler companies, and building material manufacturing. Emissions from transportation account for ~80% of NO_x emissions in Almaty.²³ As of 2010, over 500,000 vehicles were registered in Almaty, of which 54.6% were produced from 1996 to 2003, 20.9% from 2003 to 2008, and only 2.4% recently manufactured, suggesting that engines do not comply with modern emission standards.²³

Shymkent (42.34°N, 69.69°E) is an industrial city with the population of 902,000 by 2016. The city population has increased from 2005 to 2016 by 68% (Fig. 3).²⁵ The main sources of NO₂ come from stationary and mobile sources (Fig. 4). The stationary sources include lead, petrochemical, chemical, thermal power plants, and uranium mining enterprises. Mobile sources have been reported to be the main source of formaldehyde, nitrogen dioxide, and carbon monoxide.²⁶ The estimated total emissions of harmful substances in the atmosphere in the

Fig. 1 Almaty Google map. Almaty is located in the valley of big and small Almatinka rivers at the foot of Trans-Ili Alatau mountains.

Fig. 2 The population of Almaty has increased from 2005 to 2016 by 42%.²⁴

Fig. 3 The city population of Shymkent has increased from 2005 to 2016 by 68%.²⁵

Fig. 4 Shymkent Google map. The main sources of NO₂ over Shymkent come from stationary and mobile sources.

city of Shymkent show that the ratio of hazardous substances emitted by stationary sources to harmful substances released by mobile sources average 1 to 4.5 annually.²⁷

Ekibastuz (51.73°N, 75.32°E) is located in the Pavlodar region of the Republic of Kazakhstan (Fig. 5). An increase in population was observed for Ekibastuz from 2006 to 2016 by 8.6% (Fig. 6). One of the largest coal deposits in Kazakhstan is in Ekibastuz, where high-ash coal is extracted by an open-pit method, and fuels two of the largest power plants in the country.

Fig. 5 Ekibastuz Google map. Ekibastuz is located in the Pavlodar region of the Republic of Kazakhstan.

Fig. 6 An increase in population was observed for Ekibastuz from 2006 to 2016 by 8.6%.²⁵

Fig. 7 The population of Astana increased by 65% from 2005 to 2016.²⁴

While 72% of electricity in Kazakhstan is produced by thermal power plants, Ekibastuz State District Power Plant-1 (SDPP-1) contributes to 12% of the demand.^{28,29} High-ash coals with inadequate ash collectors at local plants lead to significant emissions of harmful substances, such as NO_x and SO₂ into the atmosphere. Since Ekibastuz uses brown coal with a high content of minerals (more than 30%), pollutant emissions from coal thermal power plants extend to

Fig. 8 Astana Google Map. This shift in capital, construction, and transport by roads and railways increased dramatically, introducing increased sources of dust and air pollutions.

the entire northeast of Kazakhstan, Siberia, and Mongolia.³⁰ Minor industrial activities account for ~20% of the emissions.³¹ SO₂ and NO_x were detected at a distance of 119 km.³²

In December 1997, Kazakhstan's capital city changed from Almaty to Astana (51.16°N, 71.47°E). As a result industrial outputs and the gross regional products have increased by 11 and 90 times, respectively. While the trend of migration to Almaty did not decrease from 2005 to 2016, the population migrating to the new capital, Astana, increased. Figure 7 shows the population increase by 65% from 2005 to 2016 in Astana.²⁴ This shift in capital, construction, and transport by roads and railways increased dramatically, introducing increased sources of dust and air pollutions. To offset air pollution, the government organized projects such as the construction of a large (190 ha) forest park. In addition, the area of landscaping in Astana increased from 67.9 ha in 1997 to 1061.5 ha in 2009.³³ Figure 8 shows the current map of Astana.

4 Results and Discussion

Annual averages of OMI columns over Kazakhstan from 2005 to 2016 show the high NO₂ vertical tropospheric columns over the megacities (Almaty, Shymkent), as well as the towns with big thermal power plant (Ekibastuz) (Fig. 9). The annually averaged NO₂ vertical columns over Kazakhstan are low, $\sim 0.8 \times 10^{15}$ molecules/cm². However, there exists “hotspots” in the country, such as the southern cities of Almaty, Shymkent, and the northern city Ekibastuz (Fig. 9).

The city of Almaty showed the most striking changes in NO₂ density from 2005 to 2016 ($k = 0.0236$). As shown in Fig. 10, the vertical columns peak annual average increased from 4.8×10^{15} molecules/cm² to 6.4×10^{15} molecules/cm². Another striking increase ($k = 0.0151$) came from another major city in the south, Shymkent (Fig. 10), where the vertical columns increased from 1.4 to 3.1×10^{15} molecules/cm².

Overall increase in NO₂ concentrations between 2005 and 2016 over Almaty and Shymkent cities could be attributed to the rise in the population (Figs. 2 and 3, respectively) and vehicle count. Another reason for increased NO₂ levels can be credited to the growing number of chemical factories and power plants.

In 2013, the government implemented two big projects: emission trading system (ETS) and Euro-4 standard for cars.^{34,35} When observing total NO₂ columns, the ETS and ICAP potentially contributed to the decrease in NO₂ over Almaty (20%) and Ekibastuz (17%) from 2012 to 2014

Fig. 9 Twelve-year average of NO₂ averaged from 2005 to 2016.

(Fig. 10). When the government transferred the Combined Heat and Power-2 (CHP-2) to the Almaty city territory in 2015, the NO₂ is shown to slightly increase in this area (14%).³⁶ After 2015, the optimization of technical processes power stations and employing natural gas-driven buses stabilized NO₂ level in hot spot cities, such as Almaty (19% change of NO₂ over the Almaty).³⁶

In comparing the urban area of Almaty with the rural area of Esik (43.35°N, 77.46°E), satellite data show that NO₂ density in the rural area of Esik is four times lower than Almaty city for the period of 2005 to 2016.

In the capital city of Astana (formerly Akmola), located in the northern part of the country, shows an 11% decrease from 2005 to 2016 (Fig. 10). Despite Astana's relatively high population, the observed average NO₂ column during 2005 to 2016 is 1.2×10^{15} molecules/cm², which is as low as rural areas elsewhere in the country (Table 1).

Figure 11 shows the monthly NO₂ tropospheric column over Kazakhstan in year 2014. During winter time there are some gray patterns, specifically in the north part, which shows missing data due to the extended snow cover. Therefore, in this study the evaluation of NO₂ concentration over northern part of country during winter is not reliable. Another important point from Fig. 11 is that NO₂ level changes over the whole country and hotspots during the year. The overall pattern over country changes from blue (low NO₂) to light blue (high

Fig. 10 NO₂ column trend over Kazakhstan and its cities between 2005 and 2016.

Table 1 The trend line equations for NO₂ variations from 2005 to 2016 for different cities of Kazakhstan.

Cities	Almaty	Esik	Shymkent	Ekibastuz	Astana	Kazakhstan
Trend line equation	$y = 0.0236x + 5.0668$	$y = -0.0007x + 0.9395$	$y = 0.0151x + 1.8624$	$y = 0.0042x + 2.8616$	$y = 0.0008x + 1.0405$	$y = -0.0005x + 0.8033$

Fig. 11 Illustration of the monthly NO₂ tropospheric column over Kazakhstan in year 2014. December shows missing data due to extended snow coverage.

NO₂) as season changes from winter to summer, while pattern over hot spots changes from yellow (very high NO₂) to light blue (high NO₂) during this period. Figure 11 also shares valuable information regarding the impact of majorly polluted neighbor countries including China and Russia on NO₂ density in Kazakhstan. It is understood from Fig. 11 that from October to February, Kazakhstan is influenced by the border regions of China and Russia.

Fig. 12 Average seasonal variation of NO₂ column over Almaty, Shymkent, Ekibastoz, Astana, Esik, and Kazakhstan.

Figure 12 shows the seasonal behavior of NO₂ retrievals in cities, as well as the country average. The maximum NO₂ peak for Almaty, Shymkent, and Ekibastuz occurs during wintertime (at 9.85×10^{15} molecules/cm², 5.30×10^{15} molecules/cm², and 4.25×10^{15} molecules/cm², respectively), which is consistent with Ref. 22. Two factors account for this wintertime peak in Kazakhstan: the heavier use of combustion power plants for heating and the longer lifetime of NO₂ in the atmosphere. In the summertime, urban to rural NO₂ density may vary by a factor of 4. This ratio is amplified in the winter, with urban areas showing 20× more NO₂ density than rural areas (Fig. 12). Rural regions are typically at the national average of NO₂ concentration, as the majority of Kazakhstan's area is rural. As seen in Fig. 12, the rural areas stay relatively stagnant in their NO₂ concentrations, with the maximum NO₂ occurring in the summertime, though the difference between maximum and minimum value is low (0.5×10^{15} molecules/cm²).

5 Conclusion and Future Work

In this study, Kazakhstan is suggested as a case study for applying satellite data to assess air quality and energy sectors. As a country with rapid industrial and social growth, and without an established air quality monitoring network, the value of satellite data to assess emissions is particularly high.

This study analyzed retrievals of the vertical column density of NO₂ from the OMI over atmosphere of Kazakhstan between 2005 and 2016. Observations are coincided with other papers: (1) the dominant NO₂ source regions correspond primarily to areas with high population and large industry; (2) hot spots are strongly correlated with electricity usage and fuel sources; and (3) in northern hemisphere hot spots peak NO₂ is much higher during winter. OMI observations have shown that hotspot cities in Kazakhstan are industrial megacities with high population (Almaty, Shymkent) and a small town with thermal power plants providing 72% of electricity in Kazakhstan (Ekibastuz). The rest of the country has approximately the same amount of NO₂ concentration. From the rural sample region of Esik, the NO₂ levels stayed much lower year round, having concentrations that are 1/4 (in summer) to 1/20 (in winter) of its urban neighbor, Almaty. Significant increase in NO₂ over 2005 to 2016 was recorded in the growing cities of Almaty and Shymkent, while NO₂ columns in the rest of the country fluctuated insignificantly. From analyzing the seasonal behavior of NO₂ over Kazakhstan, we show a wintertime peak for hotspot cities due to the increased need for heat and increased lifetime of NO₂. In comparing the annual columns in 2012 and 2014, it was possible to estimate that the implementation of the Euro-4 standard and the ETS reduced NO₂ up to 40% in Almaty, the city with the highest number of automobiles in country. Discrepancies for other two cities can be used to identify specific areas needing further studies.

This work could be expanded by a comparison with ground-based monitoring data, model estimates of column NO₂, and/or other satellite data products. As next-generation NO₂ data become available—include the Netherlands Space Office and European Space Agency Tropomi instrument launched in 2017, and the upcoming geostationary Sentinel 4 geostationary satellite will offer new sources of NO₂ over Kazakhstan and the region to improve our characterization of energy and emissions in this rapidly changing country.

The transboundary influence from other countries can be investigated in the future using modeling tools, such as GEOS-Chem. Particularly, biomass burning in China (East of Kazakhstan) during the winter time can introduce NO₂ to Kazakhstan as shown in Fig. 11, although the global wind in Kazakhstan is westerly wind. We will address this point as our future work using GEOS-Chem study.

Acknowledgments

The authors of this study would like to acknowledge Nazarbayev University for providing the Faculty Small Grant (No: 090118FD5315) to the authors of this paper (MAT, LK, ZD, and AM) to conduct this study. Participation of TH was supported by the NASA Health and Air Quality Applied Sciences Team. We appreciate the helpful comments of Anastasia Montgomery and Mary Spraggs of the Holloway Group at the University of Wisconsin—Madison. We acknowledge the free use of tropospheric NO₂ column data from the OMI sensor from www.temis.nl.

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