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Blue Sky Olympics: Satellite Observations of Air Quality During the 2008 Beijing Olympics

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Keywords

Remote Sensing, Olympics, Pollution Regulation

Disciplines

Atmospheric Sciences | Oceanography and Atmospheric Sciences and Meteorology | Other Public Affairs, Public Policy and Public Administration | Physical Sciences and Mathematics

Comments

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蓝天奥运会： 2008 年北京市奥运会空气质量的卫星观测

by

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A thesis submitted in partial fulfillment of the requirements for the Degree of Bachelor of Arts in the Environmental Studies Major.

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I affirm that I have upheld the highest principles of honesty and integrity in my academic work and have not witnessed a violation of the Honor Code. Lincoln Butcher

DATE: May 6th, 2019

Abstract

China has imposed short-term emission control regulations on industry and transportation to quickly improve air quality during certain events, including the 2008 Summer Olympic Games. Previous research noted reductions in NO2 vertical column density, CO emissions, CO2 emissions, and Aerosol Optical Depth (AOD). NO2 and SO2 decreased in neighboring provinces, during this time period. Using MODIS level-2 atmospheric aerosol product (MYD04_L2) data, processed by the dark target algorithm, this study observes trends in regional AOD and temporal change in AOD during the Olympic emissions reduction program. 2008 observations are referenced against AOD observations from 2003 to 2013, within 9-day intervals from June 23rd to October 24th and 40 km bands extending up to 240 km from the Beijing municipal limits. During the Olympics, median AOD values were below median AOD values from the reference period. AOD levels returned to above reference period levels in the September 12th to September 20th period, before the end of the Special Olympics in Beijing. During the Olympic period, reductions in AOD values, compared to the reference period were observed in regions within 80 km of Beijing, while an increase in AOD values was present in regions 120 km to 240 km from Beijing.

1. Introduction

The growth of industry in urban areas comes at the cost of human and environmental health. Industrial pollutants mix with vehicle pollutants often creating dangerous air quality in these urban environments (Kan et. al., 2009). For the populations in these urban environments the high concentrations of particulate matter have negative health impacts: irritation of the eyes, lungs, and throat, exacerbation of preexisting conditions such as asthma, and can increase rates of heart attack, lung cancer, among other long term health issues (Kampa and Castanas, 2008). In total, an estimated 1.3 million people die each year due to outdoor air pollution (Zhi-bin et. al., 2014 as cited in Rathi et. al., 2016). In China pollution levels have increased due to the rapid development during the 21st century (Chan and Yao, 2007). Beijing, as the capital of China and the center of the Beijing-Tianjin- Hebei Economic Region, in the 21st century has seen dangerous levels of air pollution, despite central government plans to curb smog (Chan and Yao, 2007).

Countries employ different strategies to mitigate the effects of air pollution. In India, the Delhi government implemented driving restrictions allowing drivers to only drive on even or odd days of the month, thereby limiting the total number of vehicles on the road (Rathi et. al., 2016). Copenhagen plans to become carbon neutral by 2025, and as part of this effort many streets are being closed for cars and the city is increasing bike lanes (Copenhagen, 2011). China's 11th Five Year Plan (2005-2010) aimed to reduce energy consumption and SO_2 emissions by incorporating flue-gas desulfurization into 81% of coal plants (Wang et. al., 2012). Although the plan was somewhat successful, dangerous levels of pollution remain throughout many Chinese cities.

China imposed short-term emission control regulations on industry and transportation to quickly improve air quality during certain events, including the 2008 Summer Olympic Games, 2010 World Expo in Shanghai, 2010 Asian Games in Guangzhou, 2014 Asian Pacific Economic Cooperation (APEC) meeting in Beijing, and the 2015 Military Parade in Beijing. Before and during these events, factories were shut down for days, weeks, or even months at a time, and automobile use was restricted. During the 2008 Beijing Olympics, heavy polluting factories were shut down from July 20th to September 20th and driving restrictions banned vehicles with even or odd license plates on alternating days.

Previous research shows that short-term emissions control has clear effects. During the 2008 Beijing Olympics, NO_2 vertical column density decreased (Mijling et. al., 2009) (Ma et. al., 2012). Traffic restrictions reduced CO and CO_2 emissions in the Beijing area (Worden et. al, 2012). In total, factory controls and transportation controls effectively reduced Aerosol Optical Depth (AOD) during the Olympic period, reducing aerosol species by 30-50% (Gao et. al., 2011, and Liu et. al., 2012). NO_2 and SO_2 decreased in neighboring provinces south of Beijing (Witte et. al., 2009).

Other emissions control periods showed similar results. During the APEC meeting there were significant reductions in AOD and NO_2 columns decreased 21% during that same period (Huang et. al., 2015, and Meng et. al. 2015). During the 2015 Military parade levels of NO_2 dropped by 43% (Liu et. al., 2016). Studies of major emissions control events including the Olympics and APEC, show that the control period is often followed by a rebound period when factories return to full productive capacity (Witte et. al., 2009, and Huang et. al, 2015).

1.1 Objectives

The goal of this study is to identify the effects of emission control measures on air pollution in the greater Beijing area during and after the 2008 Summer Olympics. In particular, this study looked at how AOD changed compared to average conditions in the region.
This study works to answer the following research questions:

1. Were there air quality benefits beyond the borders of the pollution ban?
2. Did air quality benefits last after the ban was lifted?

I hypothesize that emission regulation during the 2008 Beijing Olympics temporarily reduced the levels of emissions, as represented by Aerosol Optical Depth (AOD), providing temporary benefits throughout the Beijing Tianjin Hebei region. The temporary reduction in AOD will return to estimated levels following the lifting of the ban.

2. Methods

This study used MODIS level-2 atmospheric aerosol product (MYD04_L2) data processed by the dark target algorithm, a high quality data product optimized for land (Levy, n.d.); to create a 10-year reference period of air quality comprising the summer months 5 years leading up to the Olympics and the 5 years after. I evaluated 9-day changes in air quality that took place after the conclusion of the Olympics. While previous studies of air quality have employed some of these strategies, none have applied all three to the Beijing Olympics. The results of this study provide useful information on the extent to which short term regulations strategies impact regional air quality conditions.

MODIS AOD observations were confirmed with ground observations using Aerosol Robotic Network (AERONET, table 1). Previous studies compared MODIS AOD during the Olympic period to AERONET observations and found a correlation between ground observations and satellite observation (Liu et. al., 2012). AERONET observations are interpolated using Multi-sensor Aerosol Products Sampling System (MAPSS) to match MODIS values observed at 550nm, consistent with previous studies (Petrenko et. al., 2012). We believe that the MODIS Aqua Collection 6 Aerosol product (MYD04_L2) used in this study will provide higher accuracy than previous studies. To confirm the accuracy of the data product I used scatter plots and a linear regression to compare the daily MODIS AOD observations with interpolated AERONET ground observations.

2.1 The MODIS AOD Product

Satellite remote sensing offers the opportunity to measure pollution where there are no ground monitoring systems (Hoff and Christopher, 2009. Lee et. al., 2011) and where pollutant sources are multiple and widespread (Duncan et. al., 2014). Aerosol Optical Depth (AOD) is one of the most widely used measures of air quality derived from remotely sensed imagery. AOD is the degree to which aerosols prevent the transmission of light through the atmosphere (Duncan et. al., 2014). AOD is highly correlated with ground based $PM_{2.5}$ mass assuming limited meteorological interference and therefore is frequently used as a measure of air pollution (Hoff and Christopher, 2009. Lee et. al., 2011. Wei et. al., 2017).

To evaluate air pollution during the 2008 Beijing Olympics I used the MODIS AOD level-2 atmospheric aerosol product (MYD04_L2) downloaded from the LAADS DAAC distribution system (Table 1). MYD04_L2 uses the Dark Target Algorithm, which provided increased target accuracy over land (Levy, n.d.). AOD is commonly measured using the MODIS sensor aboard the Aqua Satellite because of the relatively high spatial (3-10km^2) and temporal resolution (daily) coupled with a wide swath. Aqua satellite passes a site in the early afternoon showing midday pollution levels, Terra passes locations in the morning, when most pollution production is just starting (Duncan et. al., 2014). Recent studies use MODIS AOD to observe the effects of emission control during APEC events at a provincial level (Huang et. al., 2015). Other studies have used a smaller scale with 10 km^2 spatial MODIS AOD data products to convey local impacts with high spatial resolution (Meng et. al., 2015).

2.2 Image Acquisition and Processing

Previous studies of pollution during the 2008 Olympic Games (Cermak & Knutti, 2009), as well as studies of the APEC period, compared AOD observations during the event to AOD observations during a reference period (Meng et. al., 2015). Similar to previous research, I compare the levels of AOD observed before, during, and after the Olympic period to mean levels of AOD from previous and following years when restrictions were not in place (Table 2).

The Pre-Olympic period spans from June 23th to July 19th. The Pre-Olympic period is used to study AOD conditions in 2008 before the pollution ban, that began July 25 for factories and July 20 for general driving restrictions. I created a 9-day composite images showing mean AOD during the Olympics period (August 7th – September 20th). I created 9-day composite images of AOD for the period after the Olympics, September 21 – October 25. I also created one composite image displaying mean levels of AOD for the Olympics and Post-Olympics study periods using MODIS Aqua, similar to the process described in (Huang et. al., 2015).

2.3 Data Analysis

To answer the first research question, were there air quality benefits beyond the borders of the pollution ban, I calculated the average AOD levels within 40 km bands surrounding Beijing before, during and after the event (Table 2, Figure 1). I then used line graphs to compare the AOD levels within each of these bands.

To answer the second research question, did air quality benefits last after the ban was lifted, I created a difference map of the mean AOD levels by using the minus tool to subtract the mean observed levels of AOD for all of the study periods from their estimated levels in the reference periods.

3. Results

AERONET observations interpolated to 550nm using MAPSS are correlated with MODIS observations at 550nm ($p<0.05$) (Figure 2).

The average of median observations from the 2008 pre-regulation period indicate the region with the lowest AOD value is 41-80 km from Beijing (AOD=0.313). The highest AOD observations were present in regions 81-120 km from Beijing (AOD=0.5). Reference period AOD values ranged from 0.324 in regions 41-80 km from Beijing, to 0.446 within Beijing. The largest reductions in AOD was present in the 1-40 km region (AOD deviation = -0.052), while the largest increase in AOD observations was in regions 81-120 km from Beijing (AOD deviation = 0.153). 2008 AOD observations were below reference period values in regions within 40 km of Beijing, 2008 AOD observations were higher than reference period observations in regions 41-240 km outside of Beijing (Figure 3).

The average of median observations from the 2008 Olympic regulation period indicate the regions with the lowest AOD values were inner Beijing (AOD=0.189), regions 1-40km from Beijing (AOD=0.182), and 41-80km from Beijing (0.182). The highest AOD observations were present in regions 81-120 km from Beijing (AOD=0.259) and 201-240 km from Beijing (AOD=0.264). Reference period AOD values ranged from 0.229 in inner Beijing to 0.199 in regions 201-240 km from Beijing, mean reference period AOD values decreased as distance from Beijing increased. The largest reductions in AOD were present in the 1-40 km region (AOD deviation = -0.043), the largest increases in AOD observations were in regions 81-120 km and regions 201-240 km from Beijing (AOD deviation of 0.064 and 0.064, Figure 4). 2008 AOD observations were below reference period values in regions within 80 km of Beijing, 2008 AOD observations were higher than reference period observations in regions 81-240km outside of Beijing (Figure 5). Temporally, for 9-day Olympic intervals starting on August 16th, September 3rd, and September 12th, AOD values remained constant as distance increases (Figure 6). Distance had a positive relationship with AOD values during the 9-day period starting on August 7th (Figure 6). Distance had a negative relationship with AOD values during the 9-day period starting on August 25th (Figure 6). The pre-Olympic regulation period and the opening 9-day Olympic period were the only weeks in which there is a major disparity between observed values among 40 km zones, other 9-day periods showed similar values among all distance bands (Figure 6).

The average of median observations from the 2008 post-regulation period indicate the region with the lowest AOD value was 161-200 km from Beijing (AOD=0.083). The highest AOD observations were present within Beijing (AOD=0.149). Reference period AOD values range from 0.102 in regions 161-240 km from Beijing, to 0.149 within Beijing. The largest reduction in AOD was present in the 1-40 km region (AOD deviation = -0.031), while the largest increase in AOD observations was within Beijing (AOD deviation = 0.0004). 2008 AOD observations were marginally below reference period values in all regions except within Beijing (Figure 7). Variation among distance bands was present among pre-regulation 9-day interval and the August 7th-15th 9-day interval during the regulation period but limited variance among distance bands is present after the August 7th-15th 9-day period (Figure 8).

In 2008, the 9-day period with the lowest median AOD value within Beijing (0.069) was observed between July 11th and 19th, the highest 9-day median AOD value (0.888) was observed from June 23rd - July 1st (Figure 9). Both the minimum and the maximum median AOD values observed in 2008 were observed during the pre-regulation period. During the Olympic regulation program, the highest 9-day median value was present September 12th - 20th (0.263), the 9-day period with the lowest value was August 25th to August 30th (0.134, Figure 9). In the period following the Olympic regulation program, the highest AOD value (0.239) was noted during the September 30th to October 8th 9-day period, the lowest AOD value (0.079) was noted between October 18th and 26th (Figure 9). The highest median AOD value during the reference period was 0.558, during the July 11th and 19th 9-day period, the lowest observed median AOD value was 0.138, during the October 18th and 26th period (Figure 9). 2008 AOD values were below reference period average values for multiple weeks during periods between July 2nd and July 19th, as well as periods between August 7th and September 11th (Figure 9).

4. Discussion

4.1 Spatial Changes in the Beijing-Tianjin-Hebei region

Air quality regulations did not stop pollution originating in unregulated neighboring regions from entering Beijing. Emissions from the northwest and southwest of the Beijing contribute to 39% and 15% of particulate matter in Beijing (An et. al., 2007, Cited in Gao). A Community Multiscale Air Quality (CMAQ) model estimates 34% of PM2.5 comes from neighboring provinces (Streets et. al. 2007). Before the Olympics, studies advised the Chinese government to take significant regional action to attain government air quality goals (Streets et. al., 2007). In 2008 some air quality regulations, similar to Beijing were taken up in Hebei province, but they were not enforced to the same degree as Beijing regulations (Mijling et. al., 2009).

Satellite observations during the Olympic period indicate regions within 80km of Beijing, where there were higher air quality standards, represented by AOD had average observed AOD levels lower than the reference period (Figure 4). Observations in regions 81-240km outside of Beijing experienced average AOD levels higher than the reference period values. Previous studies have noted that increases in air quality standards were greatest in Beijing, when compared with Tianjin and Shijiazhuang, Hebei province (Mijling et. al., 2009)

One explanation for the observed phenomenon is pollution regulations programs centered around Beijing pushed economic production away from Beijing. At least 50 major enterprises in steel, heavy machinery, and chemical industries were forced to relocate from the Beijing region before the start of the Olympic games, other industries temporarily relocated for the games (Scientific American, Chen et. al., 2013). Enterprises had the opportunity to relocate around China, but several remained in the greater Beijing region by moving to Hebei province, where they could still participate in the Beijing-Tianjin-Hebei regional economy. Furthermore, less stringent environmental regulations in Hebei province benefitted the relocated enterprises. AOD observations among all distance bands returned close to reference period values after the Olympic regulation period, evidence that temporarily relocated production might be returning to Beijing (Figure 7).

4.2 Temporal Changes in the Beijing-Tianjin-Hebei region

The pollution regulation program during the Beijing Olympic games had temporary benefits on regional air quality. Air quality levels returned to reference period levels before the end of the Paralympic Games, and nearing the end of the pollution regulation program. In the month after the pollution regulation program, most of the Beijing-Tianjin-Hebei economic belt returned to reference period values, with slight deviations. Short term regulation schemes, are not an effective form of long term pollution regulation. During the pollution regulation program higher levels of AOD are observed in neighboring regions. Beijing, during the 2008 Olympic Games, experienced lower levels of AOD but AOD bounced back to reference period levels near the end of the Olympic period, indicating only temporary benefits. Similar to other short term pollution regulation periods, such as the 2010 World Expo in Shanghai, and the 2014 APEC conference in Beijing, air quality returned to reference period values at the end of the regulation period (Huang et. al., 2015, Huang et. al., 2013, Hao et. al., 2011). The 2008 Beijing Olympics utilized pollution restrictions over a relatively long term (July 20th-September 21st), but duration of the regulation period did not influence AOD values from returning to reference period values in the post-regulation period.

4.4 Limitations

The methodology used in this study used in this study expands current research into the spatial and temporal dynamics of AOD during the 2008 Beijing Olympics but the data does come with limitations. This study used a Beijing centered approach, that does not account for pollution present in other cities in the region, only the distance from Beijing. Economic and meteorological patterns have a significant influence on the aerosols observed through AOD. Air quality regulation is a regional issue, and air quality in Beijing is dependent on regional transport. Beijing is influenced by air quality management in the region. During poor air quality periods, Beijing receives up to 69% of air pollutants from regional sources; on better air quality days in Beijing, regional air pollution contributes as low as 12% of air pollutants (Chang et. al., 2019). City observations at different distances from Beijing could help to identify the spatial effects of air quality during the Olympic games, controlling for environment type. The current Beijing centered approach includes urban and rural environments within the same distance bands.

This study does not use a regression analysis to determine the statistical relationship between government pollution regulation data and resulting AOD observations, due to project time constraints. Instead, this study relies on deviation of observed AOD from a reference AOD value. In future studies, data products with smaller spatial resolution could be used to confirm the effectiveness of relocating industry from a certain region; regressing observations extracted from high spatial resolution zones, to see if specific policies had a significant effect on regional air quality.

Lastly, each 9-day period was given equal weighting in the creation of spatial averages, bad weather reduced the number of AOD observations during the opening week of the Olympic period. Between August 8th and September 17th 225 mm rain accumulated in Beijing over 15 rainy days (Mijling et.al. 2009). 2006 and 2007 had less rainfall, more than 73 and 91 mm in 6 and 7 rainy days over the same period (Mijling et.al. 2009). Data used in this study is "good" or "very good data", each defined by the data source (table 1). AOD observations with large amounts of cloud cover are excluded from the data set, limiting the total number of observations.

4.3 Conclusions and Policy Implications

Beijing municipality is one of the richest cities in China. Previous studies have noted trends in Olympic development discriminating against low income communities within Beijing, but this study raises potential issues of inequity and environmental justice over the larger Beijing-Tianjin-Hebei region (Shin and Li, 2013). Air quality benefits in Beijing during the Olympics coincided with increased AOD levels in regions farther from Beijing. The movement or shut-down of industry places a financial burden on some of the poorest segments of the population, forcing them to be without work or to relocate. Furthermore, the movement of industry likely relocates heavy polluting industries to poorer regions in outer Hebei province or Inner Mongolia province. The financial and environmental strains put on low-income individuals did not lead to long term benefits. The short term strategies employed by Beijing were not practical in the long term and air quality had returned to reference period levels before the end of the regulation period.

The results of this study emphasizes AOD deviation, representing the impact of government pollution regulation programs, not representing healthy levels of air quality. In spite of air quality regulations, the 2008 Beijing Olympics continue to be the most polluted Olympic games (Wang et. al., 2009). Poor air quality for athletes might cause short-term irritation of the eyes, lungs, and throat, as well as exacerbating asthma (Kampa and Castanas, 2008). The Beijing-Tianjin-Hebei regional economic structure still experiences environmental challenges similar to 2008. Aerosols have decreased in recent years, but air quality in the Beijing region remains severe (Xu et. al., 2019). The major sources of PM 2.5 in the Beijing-Tianjin-Hebei region include secondary inorganic aerosols (35.4%-42.4%), coal combustion (10.9%–18.6%), vehicle combustion (10.6%–18.6%), soil/road dust (10.6% -23.6%), and industrial emissions (8.6%-18.2%) (Xu et. al., 2019). To improve regional air quality, improving environmental and health standards, the Beijing-Tianjin-Hebei economic region needs to implement sustainable long term strategies, changing the economic structure of the region.

Tables and Figures

Table 1: Data Sources and Use		
Data source	**Description**	**Source**
Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC)	MODIS Aqua Level 2 Dark Target imagery (MYD04_L2) Spatial resolution: 10 km^2 Temporal Resolution: Daily	https://ladsweb.modaps.eosdis.nasa.gov/search/
Aerosol Robotic Network (AERONET)	Ground Observations of AOD in the Beijing Tianjin Hebei region for satellite accuracy assessment.	https://aeronet.gsfc.nasa.gov/cgi-bin/type_one_station_opera_v2_new?site=Beijing&nachal=0&year=16&aero_water=0&if_day=0&year_or_month=1&level=3&place_code=10
Multi-sensor Aerosol Products Sampling System (MAPSS)	Ground Observations of AOD in the Beijing Interpolated to 550nm for satellite accuracy assessment.	https://giovanni.gsfc.nasa.gov/mapss/#location=Beijing&data=AERONET_AOD_L2.2:AOD0550intrp:cval[None],AERONET_AOD_L2.2:AOD0550intrp:medn[None]&starttime=2004-01-01&endtime=2006-01-01T23:59:59Z&ardFlag=0&service=MAPSS_SCATTER_PLOT&portal=MAPSS

Table 2: Study time periods	
Olympic Period (2008)	**Reference Period (Mean of 2003-2007, and 2009-2013)**
Pre-Olympic Period • June 23-July 1 • July 2-10 • July 11-19	Pre-Olympic Reference Period • June 23-July 1 • July 2-10 • July 11-19
Olympic Period • August 7-15 • August 16-24 • August 25-September 2 • September 3-11 • September 12-20	Olympics Reference Period • August 7-15 • August 16-24 • August 25-September 2 • September 3-11 • September 12-20
Post-Olympic Period • September 21-29 • September 30-October 8 • October 9-17 • October 18-26	Post-Period Reference Period • September 21-29 • September 30-October 8 • October 9-17 • October 18-26

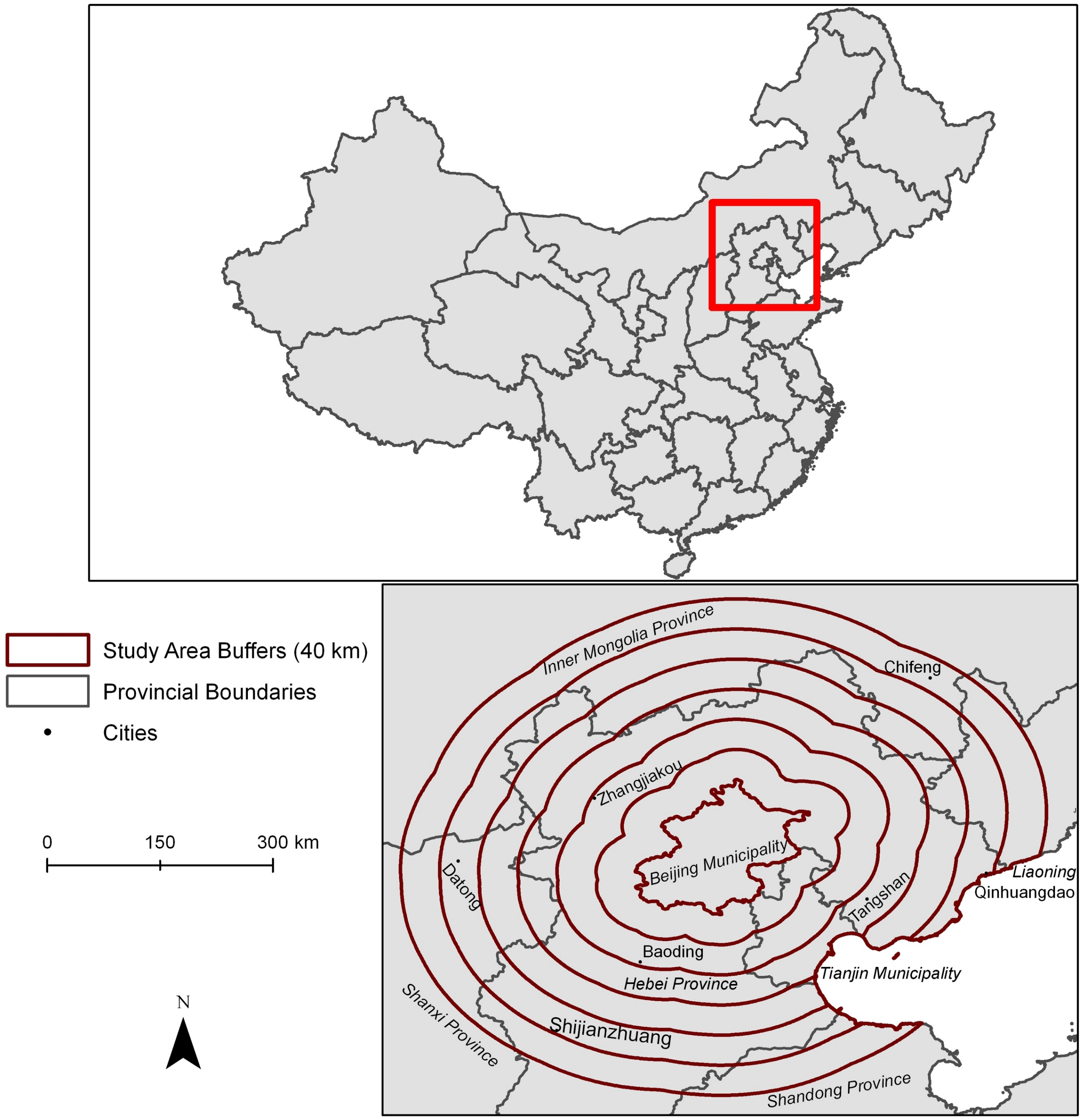

Figure 1: Map of the Study Area.

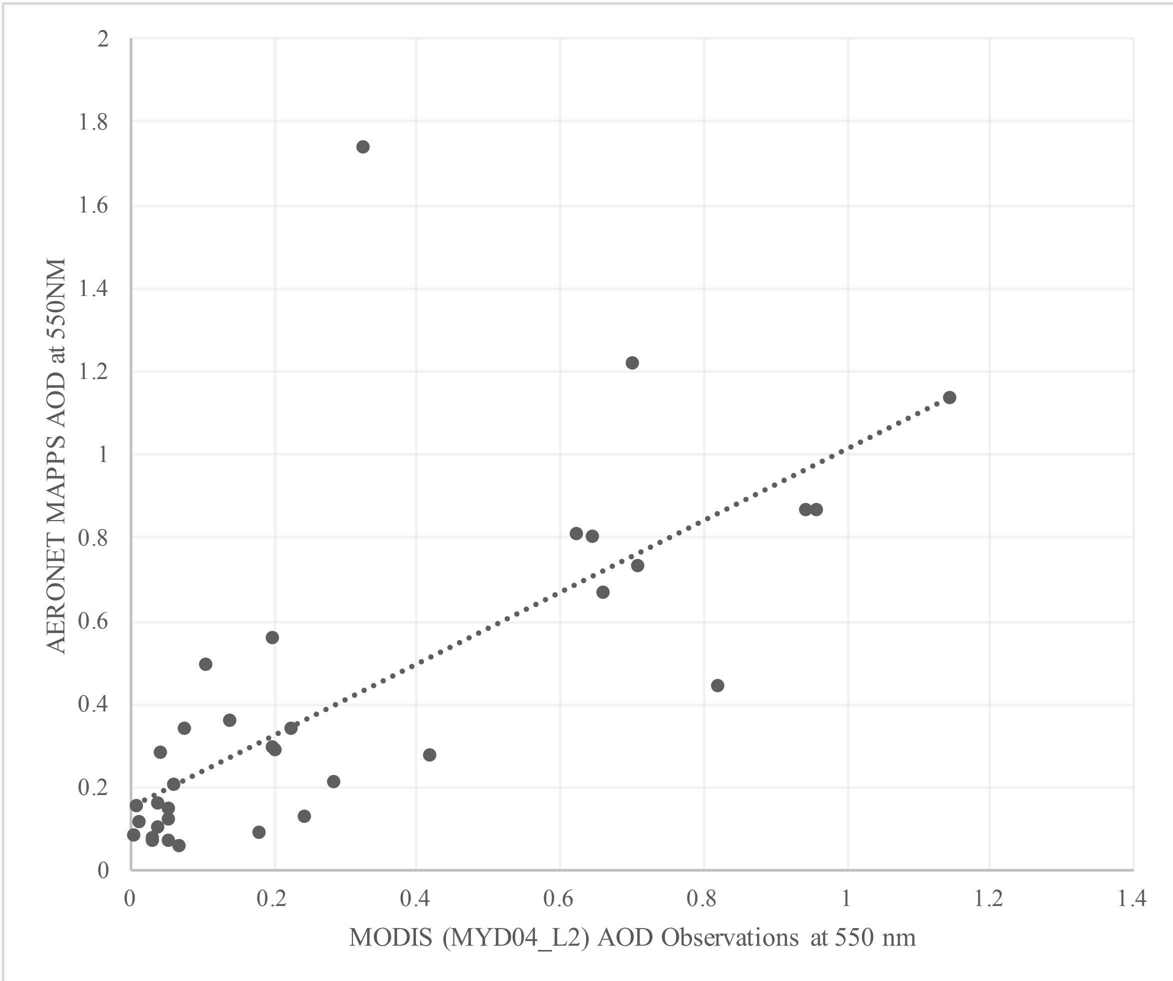

Figure 2: MYD04_L2 AOD Observation Against Ground Observation at 550 nm

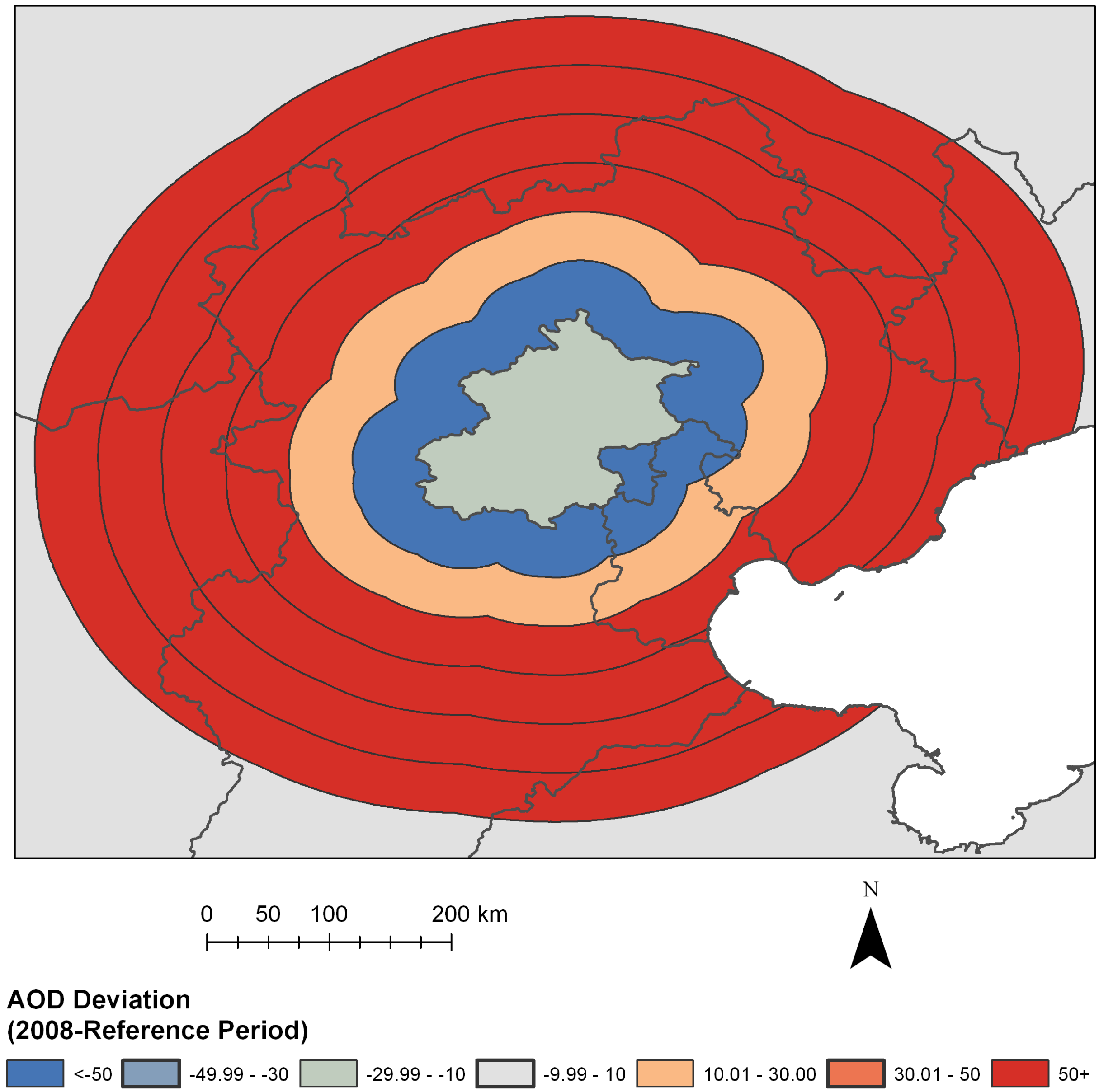

Figure 3: Pre-regulation deviation (2008 – Reference Period) of median AOD values by distance band.

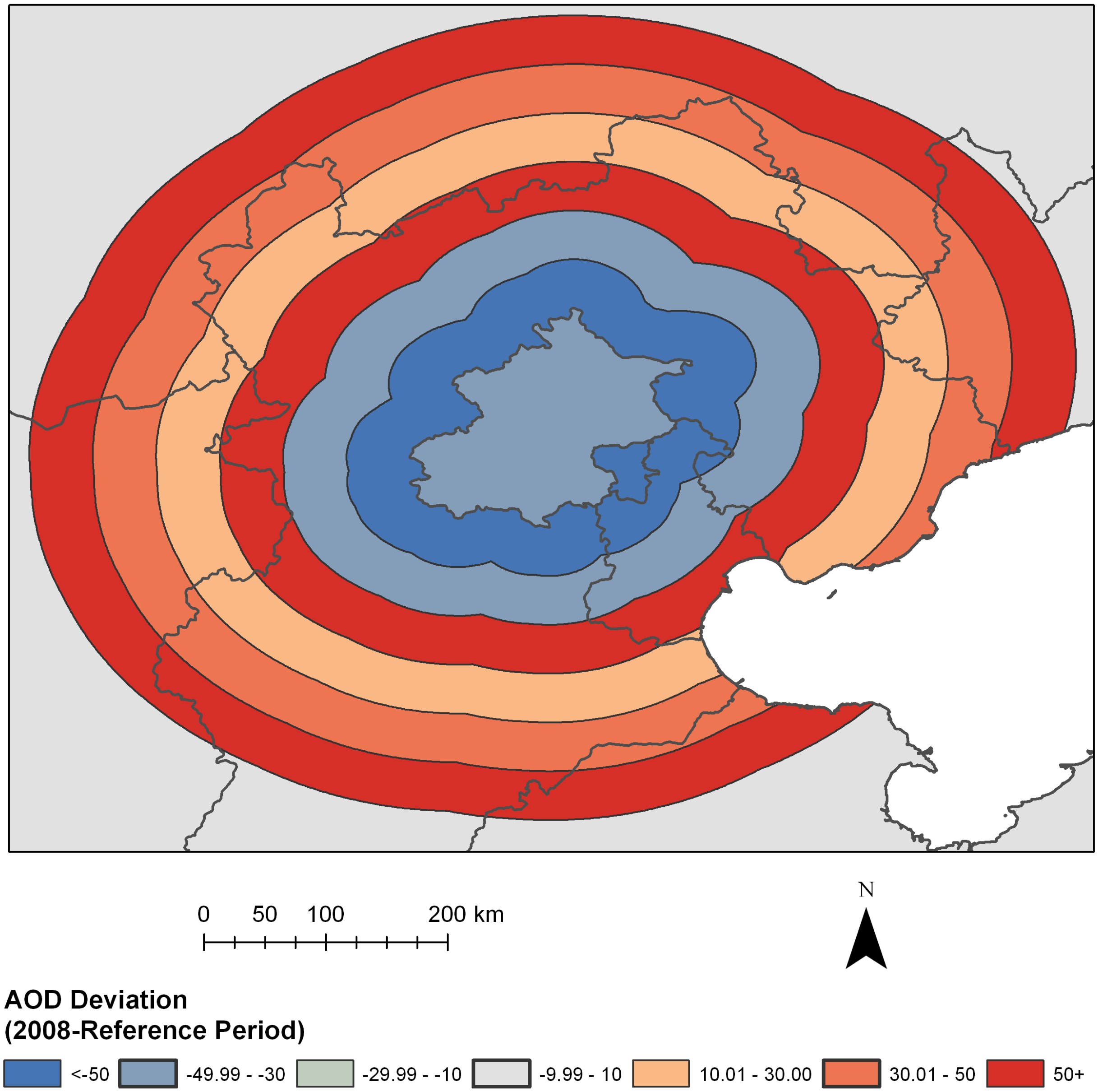

Figure 4: Regulation period deviation (2008 – Reference Period) of median AOD values by distance band.

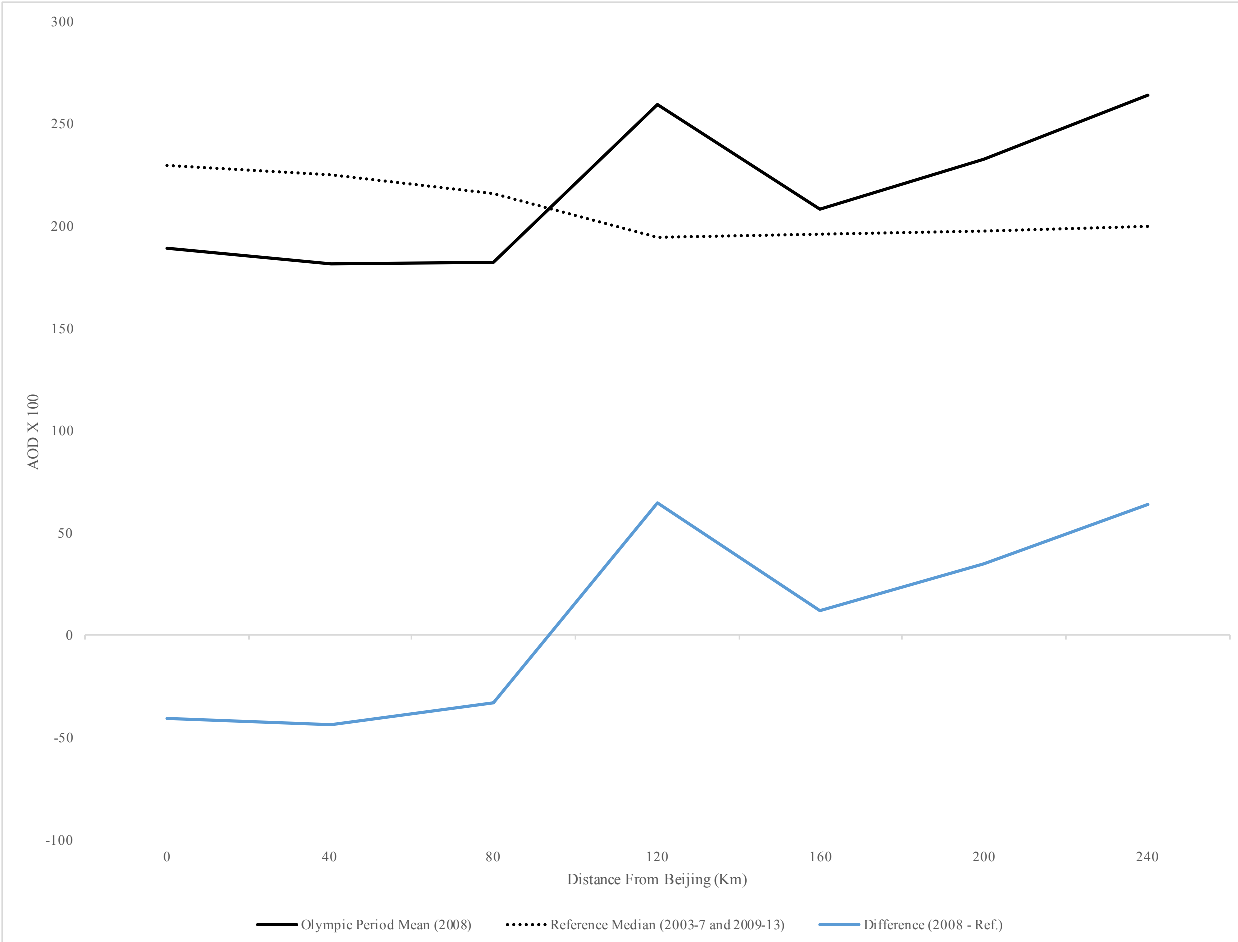

Figure 5: Median AOD by proximity to Beijing.

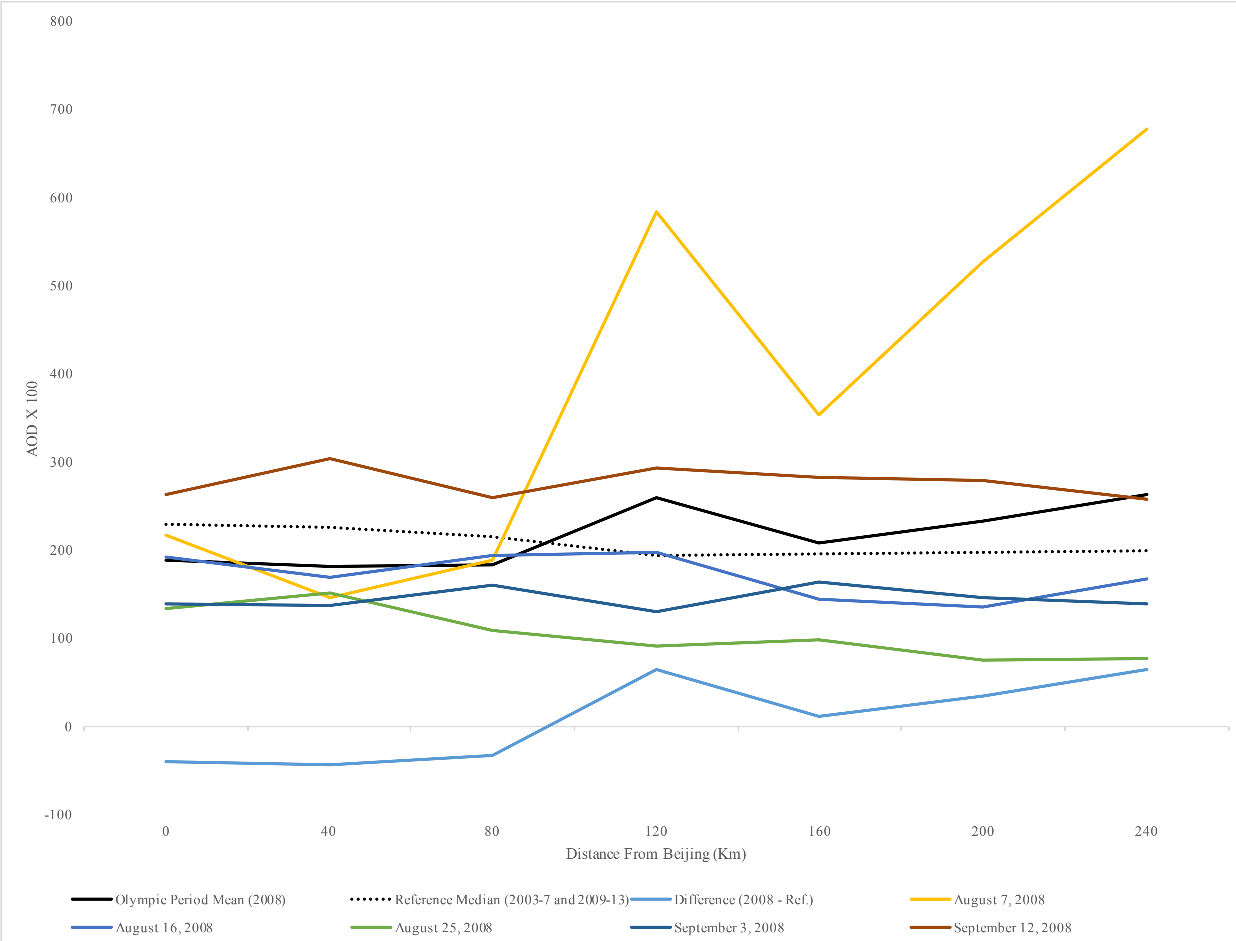

Figure 6: Median AOD by proximity to Beijing for All Olympic Weeks

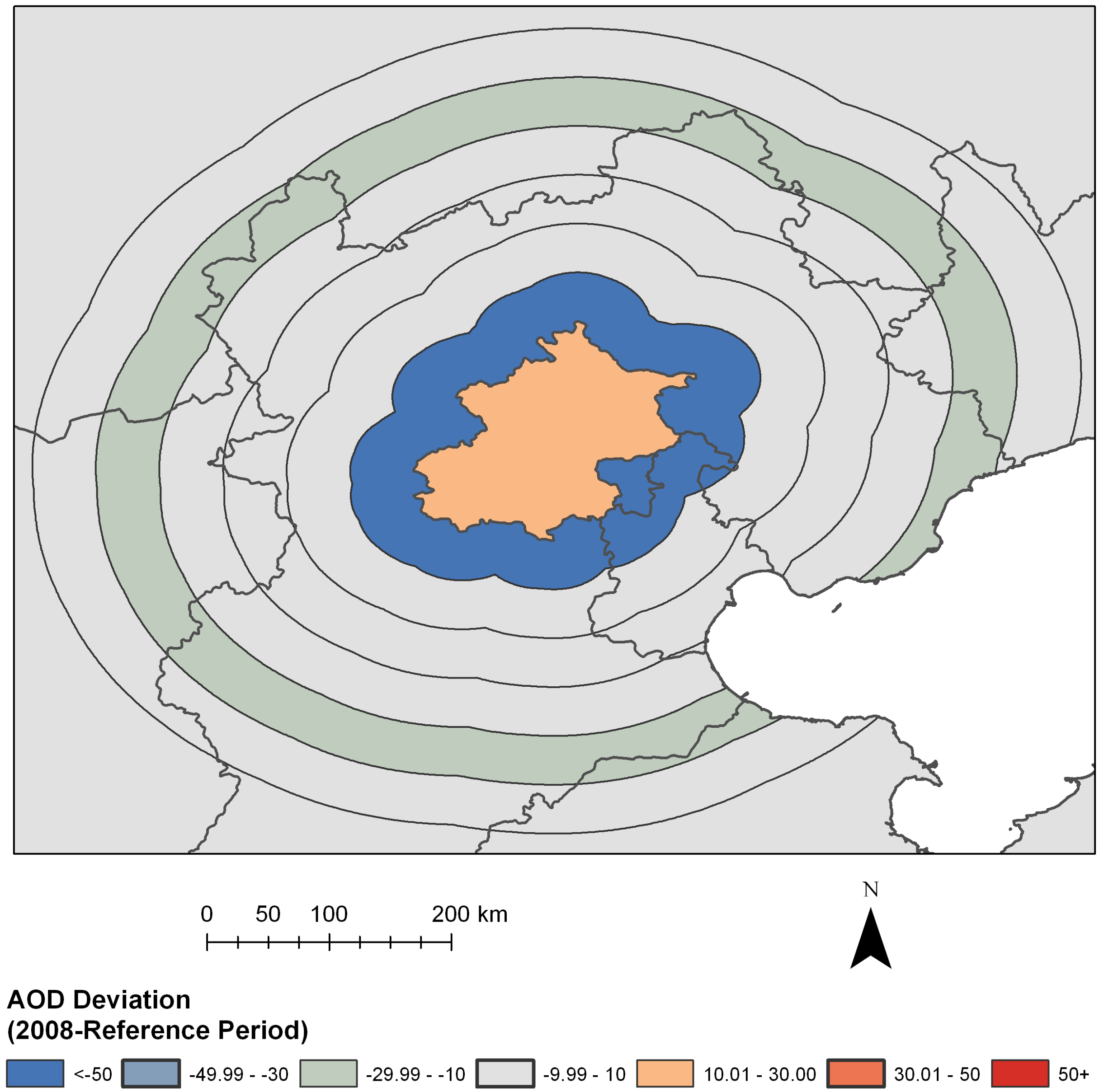

Figure 7: Post-regulation deviation (2008 – Reference Period) of median AOD values by distance band.

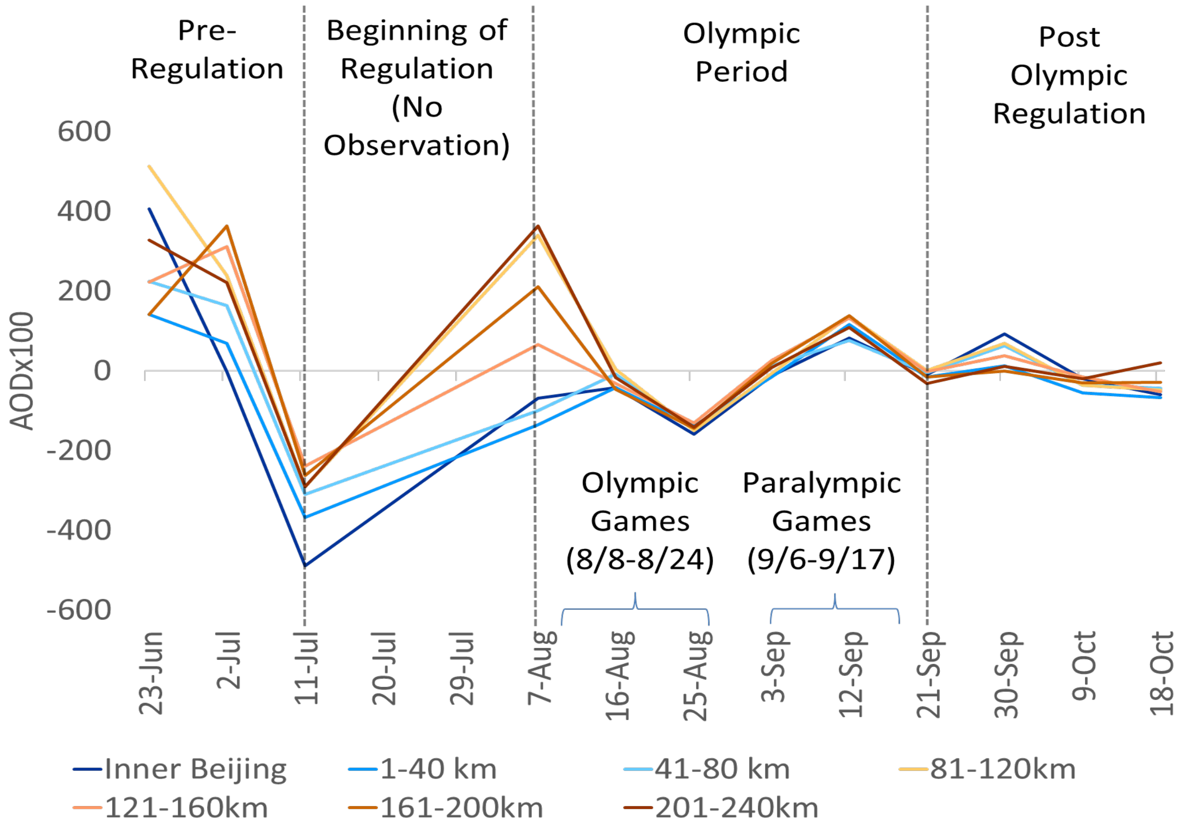

Figure 8: AOD difference from reference over time

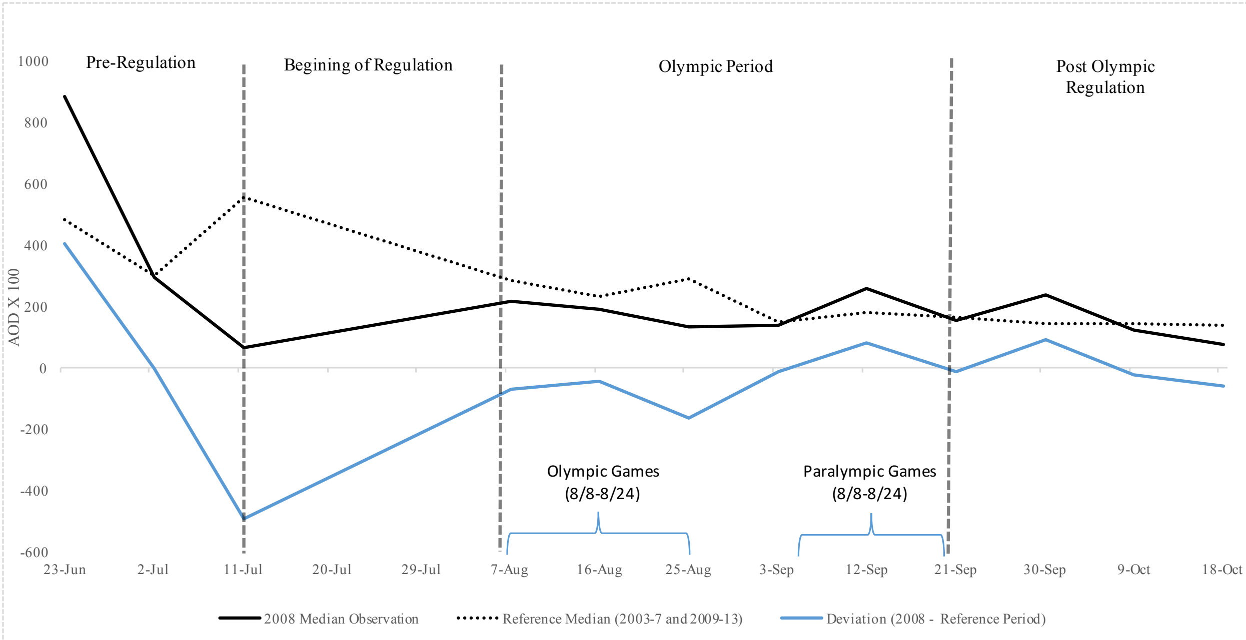

Figure 9: Temporal Change in Median Aerosol Optical Depth

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