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Research Article

Anthropogenic Activities and Spatio-Temporal Patterns of Tropospheric NO_2 over the Gandaki Province in Nepal during 2005-2020

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ABSTRACT

Gandaki Province is located in the mid-region of Nepal, encompassing an area of 21773 km², which is approximately 14.66% of Nepal's total land area. The province experiences a diversity of climate variability. A massive glacier in the Himalayas is a crucial part of the freshwater and water ecosystem. Over the past two decades, anthropogenic activities within and near the boundary regions have degraded the regional ecosystem of the province. We investigate the Spatio-temporal characteristics and long-term trends derived from satellite measurements of tropospheric NO_2 from the Ozone Monitoring Instrument (OMI) for the period 2005-2020. Tropospheric NO_2 over the Gandaki province varies from 0.4-0.7 x 10^{15} molec. cm^{-2} with higher values > 0.7 x 10^{15} molec. cm^{-2} over the southern region of the province and comparatively small < 0.7 x 10^{15} molec. cm^{-2} over the high-altitude region. We use a linear regression model to find the trend. There is a significant increasing trend in NO_2 up to 0.1 × 10^{15} molec. cm^{-2} yr^{-1}, with slightly higher values in the southern region of the province. The trends are seasonally more prominent in autumn (0.1 × 10^{15} molec. cm^{-2} yr^{-1}). The main sources of NO_2 in the regions are road transport, followed by agriculture. This study reveals that the high mountainous, pristine areas of the province are becoming gradually polluted due to the high anthropogenic activities within the region and the influence of nearby regions in recent years, indicating the impact of socioeconomic changes in the province.

KEYWORDS: Air pollution, tropospheric NO_2, spatio-temporal patterns, anthropogeny

INTRODUCTION

The major trace gases in the earth's atmosphere, Nitric oxide (NO) and Nitrogen dioxide (NO_2) are two prime constituents of nitrogen oxides (NO_X). These trace gases are detrimental to human health, ecosystems and climate (Schraufnagel et al., 2019; Gaffin et al., 2018; WHO, 2005). NO is the primary emission of NO_X sources, which rapidly oxidises the available oxidants such as oxygen (O_2), ozone (O_3) and Volatile organic compounds (VOC) in the ambient conditions to form NO_2. Therefore, NO_2 in the atmosphere is considered a primary toxic pollutant. The identified natural sources of NO_X are lightning, combustion, and microbial processes (Singh et al., 2020; Hilboll et al., 2017). On the other hand, the power plants, road transport, and waste disposal systems are major anthropogenic sources (Sharma et al., 2023a; Seinfeld and Pandis, 2006). Previous studies have indicated that NO_2 is a reliable indicator of traffic pollution due to its strong correlation with various mobile exhaust components. Figure 1 illustrates the various emission sources and their impacts on the ecosystem and human health. Photolysis and wet deposition are the major sinks of NO_2 (Sharma et al., 2023a; Demirel et al., 2014). The oxides of nitrogen are precursors of a greenhouse gas, the tropospheric ozone (Sharma et al., 2025; Kuttippurath et al., 2023; Gopikrishnan and Kuttippurath, 2024). NO_2 is primarily associated with adverse health effects and plays a crucial role in forming secondary aerosols, a type of particulate matter (Sharma et al., 2023b; Kuttippurath et al., 2021; Kang et al., 2019). NO_X indirectly affects the regional and global climate, which fascinates researchers in the study of NO_X (Kuttippurath et al., 2024b; Monks et al., 2015).

Gandaki Province is located in the mid-region of Nepal, on the southern incline of the Third Pole. The northern region of the province is characterised by a complex topography, which includes high mountains in the Himalaya, such as the Dhaulagiri and Annapurna ranges. This area is also home to an enormous amount of fresh ice mass, which is the primary source of freshwater resources for nearly 3 million individuals in the downstream. The mountains of the Himalayan region are a crucial component of the freshwater and water ecosystem of the province (Kuttippurath et al., 2024a). Tropospheric NO_2 over the Gandaki province largely depends on local emissions, climatic conditions, energy consumption, meteorological conditions and seasonal cycles (Sharma et al., 2023a; Zhou et al., 2012). In the southern foothills of the Himalayas, transportation is the primary contributor to NO_X emissions, followed by industries and biomass burning (Sharma et al., 2025, 2023a).

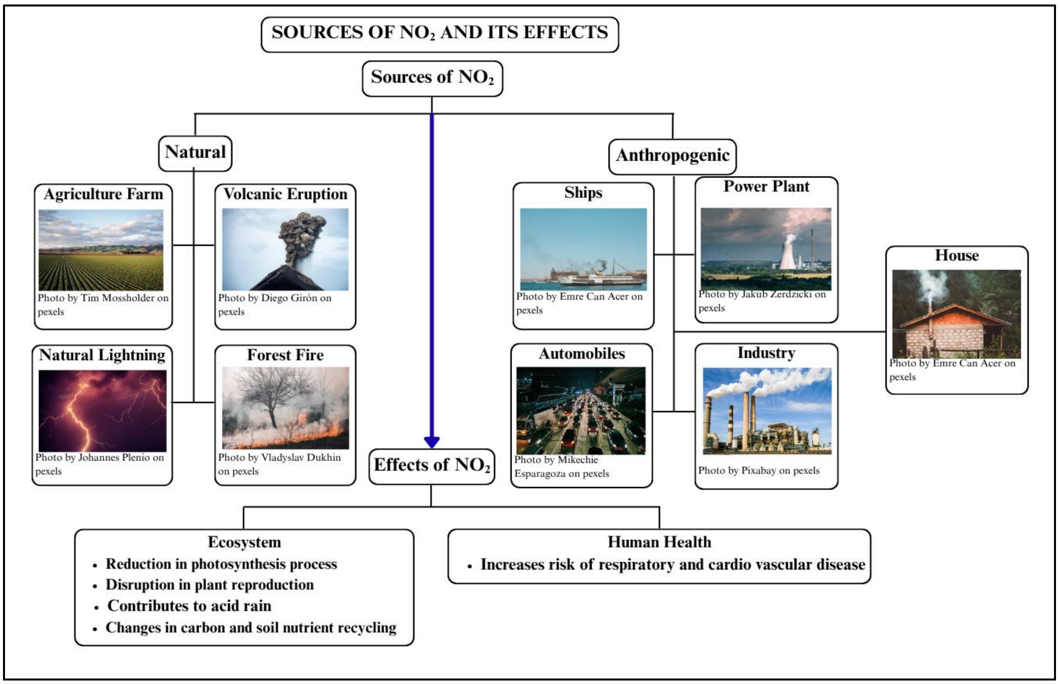
A previous study shows a global NO_X emission increase by 22.3% during the period 2000–2015 (Cripa et al., 2018). However, studies have reported that pollution-weighted NO_2 emissions decreased in the United States and Western Europe but increased in South Asia and East Asia between 1996 and 2012 (Geddes et al., 2016). A recent study by Sharma et al (2023a) found a positive trend of NO_2 over most of the Third Pole region. Pavel et al (2021) reported a strong increasing trend in the Ganges-Brahamaputra-Meghna Delta region in India. However, no comprehensive study of tropospheric NO2 has been found to focus on the provincial level in Nepal.

Given the importance of the study region, it is essential to consistently monitor NO_2 levels in Gandaki Province with high accuracy. The intricate topography limits the establishment of a comprehensive ground-based NO_2 monitoring network in this region (Sharma et al., 2023a). However, the NO_2 spectrum in the visible and near-ultraviolet range (300–700 nm) makes measurement possible through satellites (Fan et al., 1995). Since the mid-1990s, various space-based instruments to monitor the tropospheric NO_2 are available, including the Ozone Monitoring Instrument (OMI) and Global Ozone Monitoring Experiment–2 (GOME–2) (Liu et al., 2017). OMI has the longest measurements from 2004–to date and GOME-2 from 2006– to date (Munro et al., 2016; Levelt et al., 2006). More recent observations from the Tropospheric and Monitoring Instrument (TROPOMI) have better resolution, but the data are only available for a short period (Zhao et al., 2020).

Therefore, this study is the Spatio-temporal variation of tropospheric NO_2 over the Gandaki Province from space using OMI measurements. The spatial-temporal patterns of any atmospheric species help to identify pollution hotspots and trends over time in the region. Therefore, this kind of study are crucial for understanding air pollution and its impacts on health and the climate. Many studies indicate that NO_2 levels on the southern slope of the Third Pole have increased in recent decades, coinciding with the economic development of the region (Sharma et al., 2023a). However, no such comprehensive study of NO_2 has been conducted in Nepal in provincial level. This is the first comprehensive study of its kind in this region. As an important precursor of a direct climate forcer (O_3 in the troposphere), the increase in NO_2

Figure 1

Schematic of various emission sources and the effect of tropospheric NO_2 on human health and ecosystems



potentially influences the regional ice mass. The goal of this type of long-term study is to help policymakers and scientists to determine the sources of pollution and their impact on climate change as the climate change often first appears in the remote mountain regions of the Himalayas.

RESEARCH METHODS

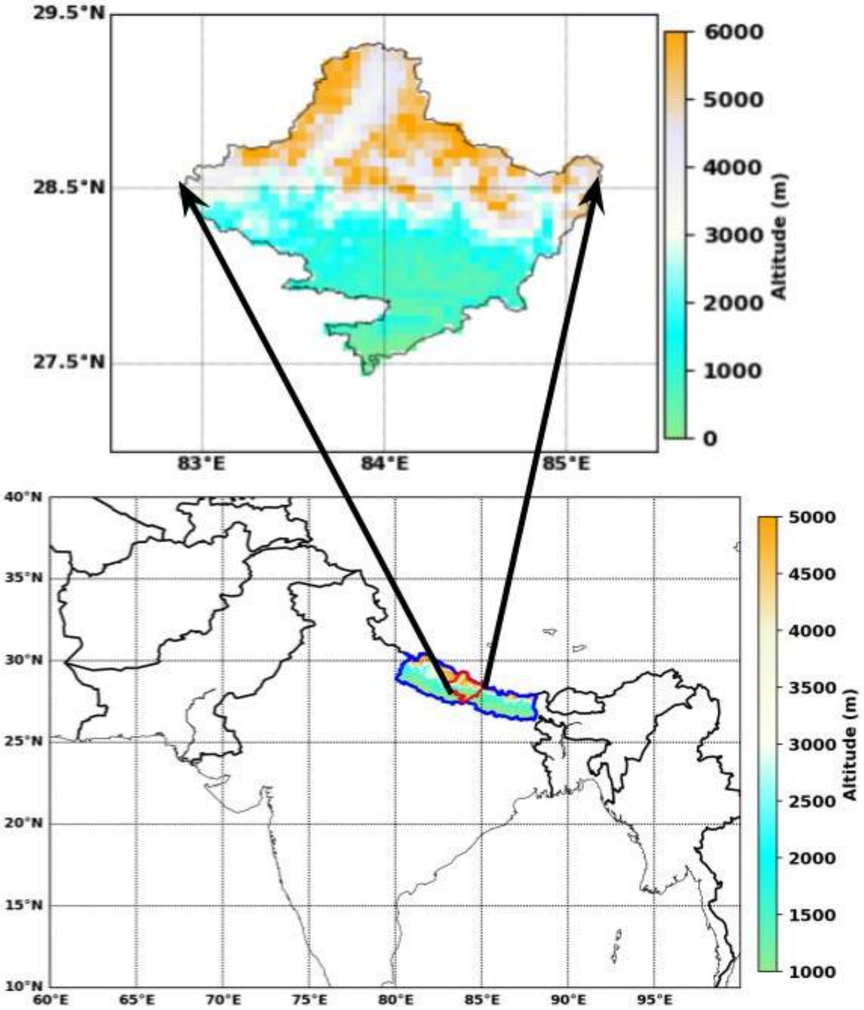
Nepal is a landlocked, mountainous country situated between China and India in South Asia, encompassing an area of 147181 km^2. Within a limited latitudinal span, elevation ranges from 70 m (Terai plain) in the south to Mount Everest (8848.86 m) in the north, and the province spans 885 km east-west and 140–250 km north-south (Talchabhadel et al., 2019). Nepal falls in the subtropical climate zone globally; however, it possesses many microclimates within the region due to its complex topography (Karki et al. 2016). The study area is the Gandaki province in the mid-region of Nepal, bordered to the east by Bagmati Province, to the west by Karnali and Lumbini Provinces, to the north by the Tibetan Autonomous Region of China, and to the south by India. Figure 2 shows the study area with an altitude map. The region experiences a temperate climate within an altitude range of 1,500 to 3,000 meters above the mean sea level (msl) and an alpine climate in the mountain regions at altitudes of 3,000 to 4,500 meters above the msl. In the high-altitude Himalaya region of the province, we can find Tundra climatic conditions. About 80% of the annual precipitation occurs during the summer (Talchabhadel et al., 2019; Shrestha, 2000). Four distinct seasons are recognised in Nepal as winter (December to February, DJF), spring (March to May, MAM), summer (June to September, JJAS), and autumn (October to November, ON) (Talchabhadel et al., 2019; Shrestha, 2000). Total population of the province is 2466427, with the highest population of about 600051 in Kaski district (NSO, 2023). The climatic features and geographical accessibility seem to be major reasons for the increasing population. However, Manang and Mustang have the lowest population. Gandaki Province, with its expanded potential in the tourism sector, is experiencing significant growth in tourism activities, which is one of the key drivers of growth in the economic, technological, and industrial sectors, as well as emissions.

We have used the monthly mean Tropospheric NO_2 column derived from OMI onboard Aura satellite launched in 2004 (Levelt et al., 2006). The OMI satellite provides daily NO_2 measurements on a global scale. Details about OMI can be found in Levelt et al (2006). The OMI NO_2 measurements (2004–present) are made in three channels between 264 and 504 nm (Schoeberl et al., 2006). The spectral resolution of OMI is 0.5 × 0.5 nm and spatial resolution of 13 × 24 km^2 at nadir. OMI provides daily global coverage with a field of view of 114° and a cross-track swath of 2600 km (Boersma et al., 2004, 2011).

For inventory analysis, we used EDGARv6.1, a bottom-up approach that estimates emissions. It is a 0.10 x 0.10 gridded emissions inventory of aerosols and trace gases that covers the period 1970–2018. Emissions from each source and nation are calculated annually using the activity data and emission factors. We have considered the emissions from various sources, including energy, industrial operations, product consumption, agriculture, waste and other anthropogenic activities (Itahashi et al., 2019).

Figure 2

The geographical location of the study area, Gandaki Province is marked by the red line with an altitude map



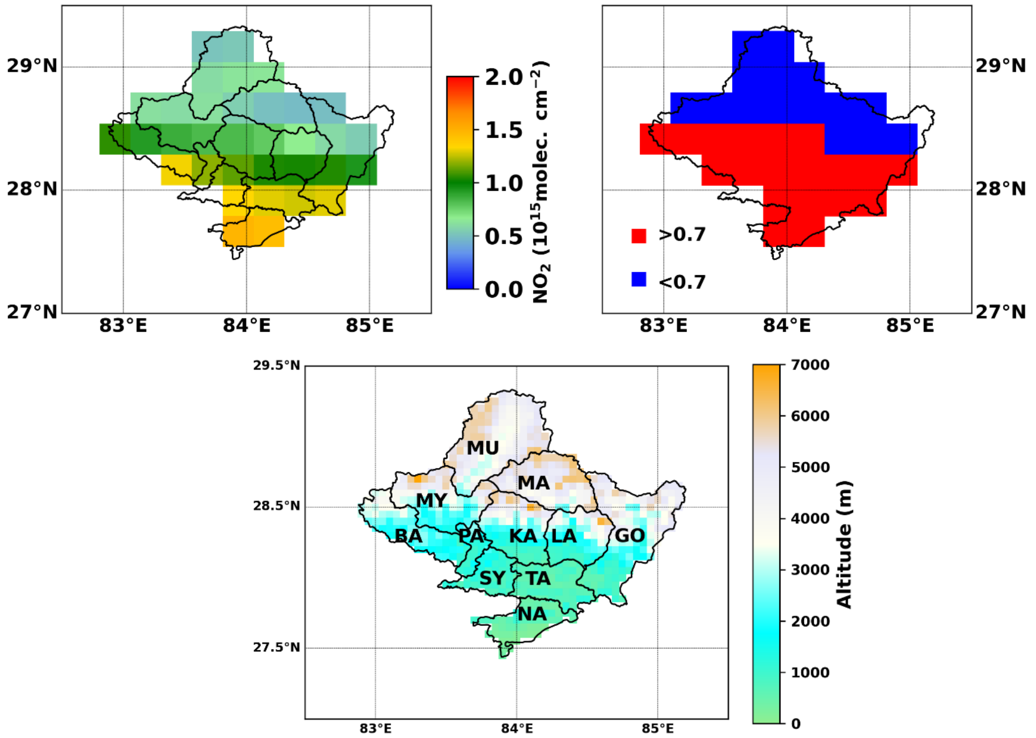
RESULTS AND DISCUSSION

Spatial Distribution of Mean Tropospheric NO_2

The spatial distribution of mean (2005–2020) Tropospheric NO_2 over the Gandaki Province, derived from OMI is shown in Figure 3 (top left). Tropospheric NO_2 in the Gandaki province varies from 0–2 × 10^{15} molec. cm^{-2} with higher values over the southern region of the province, particularly over east Baglung, Parbat, Syanga, Tanahu and Nawalpur districts. The southern region is predominantly a low-altitude region (<1500 m, msl), which is densely populated and economically dynamic; consequently, higher NO_2 levels are observed there, as NO_2 is highly sensitive to socioeconomic changes and economic activities (Badarinath et al., 2006). The complex topographical configuration of the southern slope of the Himalaya and the prolonged dry season favours the accumulation of air pollution in the lower basins (Sharma et al., 2024). NO_2 concentration is gradually decreasing from south to north. In the sparsely

Figure 3

TOP (Left): *Mean distribution of tropospheric NO_2 over the Gandaki Province averaged for the period 2005–2020.* ***TOP (Right):*** *Mean (2005–2020) tropospheric NO_2 over TP with two distinct ranges of NO_2: Regions with NO_2 greater than 0.7×10^{15} molec. cm^{-2} (red colour) and less than 0.7×10^{15} molec. cm^{-2}(blue colour).* ***Bottom:*** *Elevation map of the study region, Gandaki Province, with district boundaries. The districts are shown in brackets for each abbreviated form, i.e MU (Mustang), MA (Manang), MY (Myagdi), BA (Baglung), PA (Parbat), KA (Kaski), LA (Lamjung), GO (Gorkha), SY (Syangja), TA (Tanahun), NA (Nawalpur)*

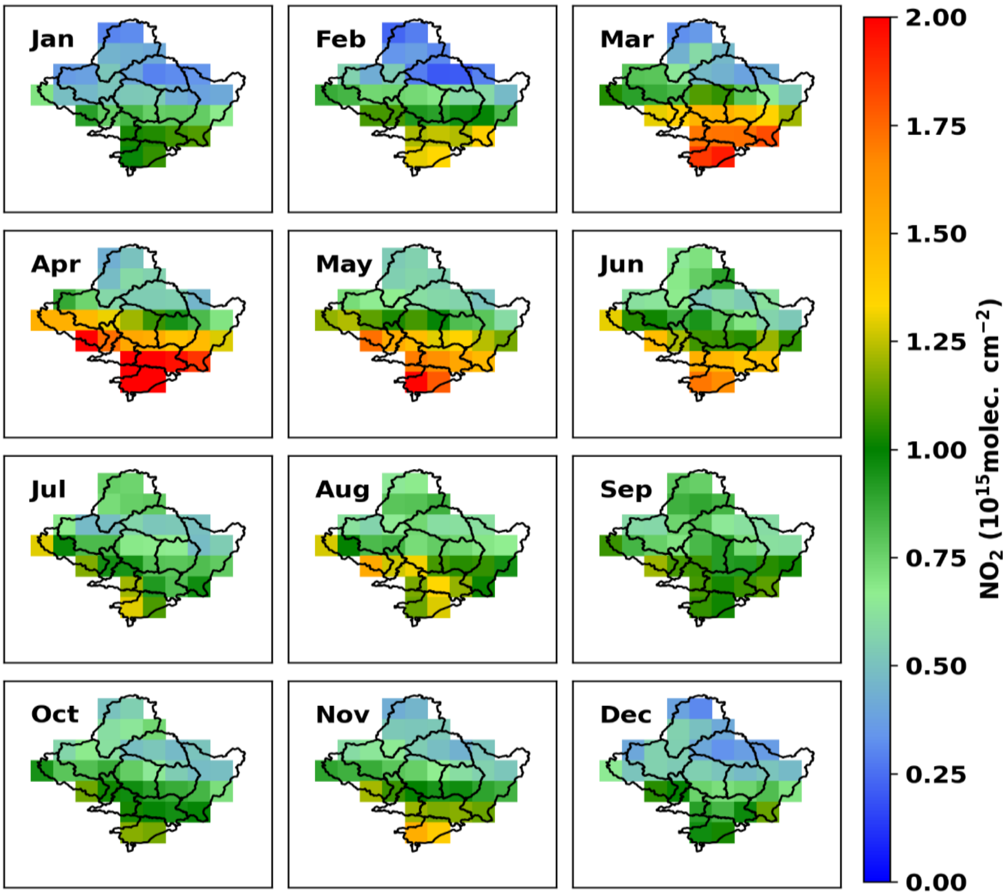


populated central mountainous hill regions of west Baglung, the southern regions of Myagdi, Kaski, Lamjung, and Gorkha districts in the province, the NO2 concentration is small, within the range of 0.5–1 × 10^{15} molec. cm^{-2}. However, regions above 4000 m from msl particularly over the west Myagdi, Mustang, Manang, and northern region of Kaski, Lamjhung and Goarkha are among the cleanest, with small anthropogenic activity; consequently, lower (< 0.7×10^{15} molec. cm^{-2}) tropospheric NO_2 there. Furthermore, for the assessment of spatial and temporal variations of NO_2 based on the mean distribution, the study area is divided into two regions: high concentrations (> 0.7×10^{15} molec. cm^{-2}) region marked as R1, and the low concentrations (< 0.7×10^{15} molec. cm^{-2}) region as R2, as shown in Figure 3 (top right) in red and blue colours, respectively.

Figure 4 shows the monthly mean tropospheric NO_2 over the Gandaki Province for the period 2005–2020. We find a higher tropospheric NO_2 ranging from 1×10^{15} molec. cm^{-2} to 2×10^{15} molec. cm^{-2} mostly in the southern Gandaki province, including the districts Baglung, Parbat, Syanja, Tanahu, Lamjhung and Nawalpur district during March – June. A

Figure 4

Monthly variation of the mean tropospheric NO_2 column over the Gandaki Province for the period 2005–2020



higher tropospheric NO_2 column is also observed in this region in the month of November. Numerous studies have shown that significant biomass burning occurs on the southern slope of the Himalayan basin, mostly between March and May and October and November (Wester et al., 2019; Tariq et al., 2014; David and Nair, 2013). Biomass burning contributes a significant amount of NO_2 in the region; consequently, higher levels of NO_2 are found in the region. There is a significant decrease in NO_2 (from 1.75–2 × 10^{15} molec. cm^{-2} to 1 × 10^{15} molec. cm^{-2} with the onset of the monsoon (Sharma et al., 2023a). The southwest monsoon carries cleaner air from the ocean to land (Sharma et al., 2025). In addition, higher NO_2 over the high-altitude region during May–August is associated with natural emissions from soil and lightning, which are significantly influenced by variations in temperature, soil conditions, and precipitation (Van der A et al., 2006).

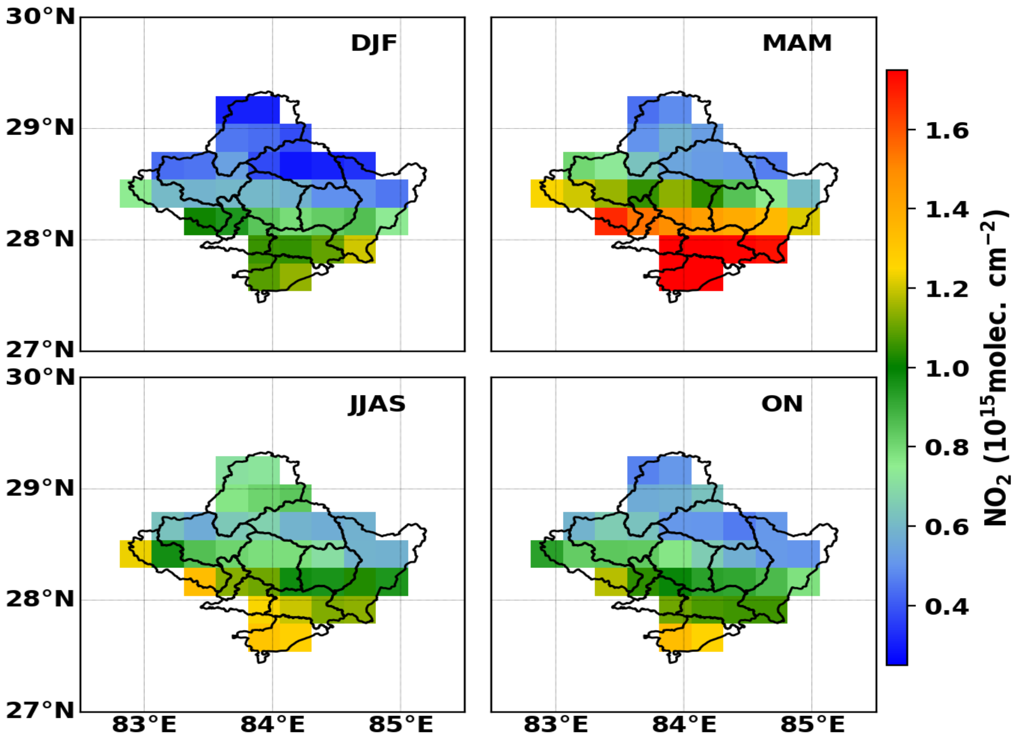
Seasonal Variation of Tropospheric NO_2

Figure 5 shows the seasonal mean distribution of tropospheric NO_2 for the period 2005–2020. The changes in wind, humidity, and temperature with the seasons are the primary causes of the seasonal variation in tropospheric NO_2 in the southern slope of the Himalayas (Bian et al., 2020). The climate of the Gandaki Province is primarily influenced by the Asian monsoon in summer and the westerlies in other seasons, which in turn affects the transport of pollutants (Sharma et al., 2023a; Bian et al., 2020). Tropospheric NO_2 in the Gandaki Province ranges from 0.5×10^{15} molec. cm^{-2} to1.8×10^{15} molec. cm^{-2} in spring, with higher values of $1.5–1.8\times 10^{15}$ molec. cm^{-2} over the southern regions.

surrounding regions, including the Indo-Gangetic Plains (IGP) (Sharma et al., 2023a; Kuttippurath et al., 2023). An increase in NO_2 in the southern region of the province can be attributed to stubble burning within the IGP and the input of pollutants during the wheat-rice rotation period (Sharma et al., 2023b; Rupakheti et al., 2018). The complex topography of the southern slope of the Himalaya and various meteorological factors, including higher temperatures, low humidity, and slow wind speeds, provide favourable

Figure 5

Seasonal changes in tropospheric NO_2 column over the Gandaki Province. The seasons are defined winter (December to February, DJF), spring (March to May, MAM), summer (June to September, JJAS), and autumn (October to November, ON)



The increase in NO_2 in spring over the southern region of the province particuly over Baglung, Parbat, Syanja, Tanahu, Lamjhung and Nawalpur is attributed to the enhanced biomass burning associated with agricultural activities within and

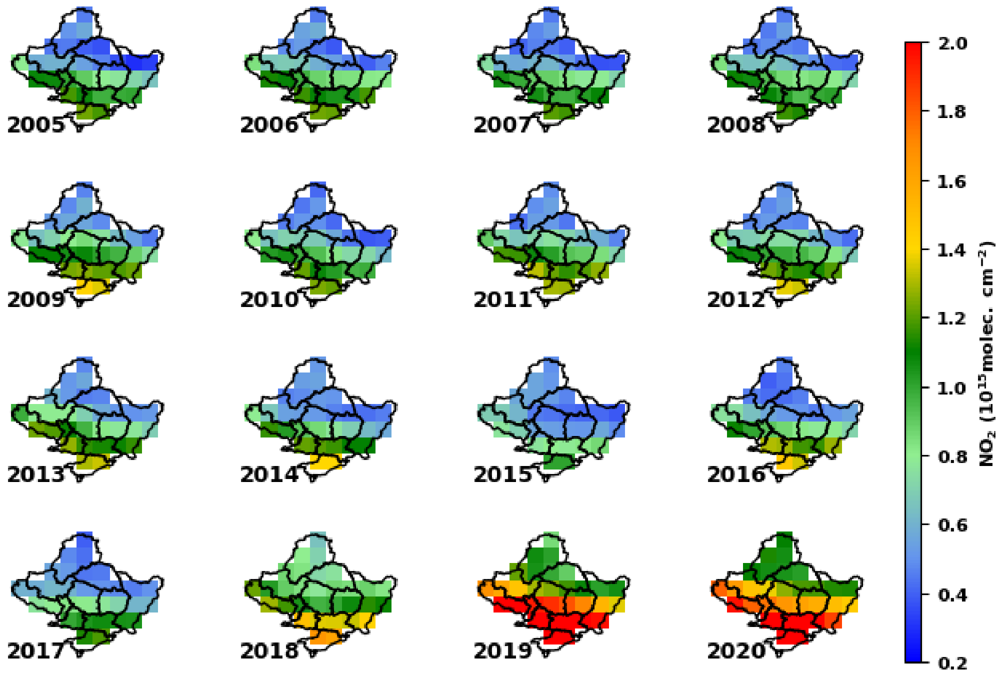
conditions for the transport and accumulation of pollutants there during spring (Adhikari et al., 2024; Bian et al., 2020). Likewise, NO_2 in the troposphere ranges from 0.6×10^{15} molec. cm^{-2} to 1.4×10^{15} molec. cm^{-2} during summer with elevated levels of 1.4 × 10^{15} molec. cm^{-2} in the southern region. Gandaki Province is dominated by the Asian monsoon in the summer and the westerlies in other seasons (Sharma et al., 2023a; Bian et al., 2020). Therefore, a significant decrease in tropospheric NO_2 from 2 × 10^{15} molec. cm^{-2} to 1.2 × 10^{15} molec. cm^{-2} in summer due to the effect of the southwest monsoon. In summer, air masses from surrounding areas converge towards the high mountainous region of South Asia, carrying various pollutants to the northern region of the province; consequently, the NO_2 levels are higher, at about 1 × 10^{15} molec. cm^{-2} there (Bian et al., 2020). The tropospheric NO_2 concentration further decreases from summer to autumn, ranging from 0.6 × 10^{15} molec. cm^{-2} to 1.2 × 10^{15} molec. cm^{-2}. During winter, the NO_2 levels fall below 0.7 × 10^{15} molec. cm^{-2} over the entire province, with lower values in the northern region < 0.4 × 10^{15} molec. cm^{-2}. A clear seasonal variation in tropospheric NO_2 is observed in the Gandaki Province, with higher values in summer and lower values in winter.

Inter-annual Variation of Tropospheric NO_2

Figure 6 shows a spatial map of the time evolution of tropospheric NO_2 from 2005 to 2020. A notable and distinct interannual variation in the regional distribution of NO_2 has been observed throughout the study period. Comparatively, Tropospheric NO_2 is higher in the southern regions, particularly over Baglung, Parbat, Syanja, Tanahu, Lamjhung and Nawalpur and decreases

Figure 6

Interannual variation of tropospheric NO_2 column over the Gandaki Province for the period 2005–2020



towards the mountainous regions in the north. The NO_2 concentration gradually increased in the province from 2006 to 2014. However, it decreased in 2015. After 2017, the increase is sharp, almost doubling the entire province compared to 2016.

Furthermore, we have also examined the time evolution of the changes in monthly mean NO_2 over the regions R1 and R2 from 2005 to 2020 (see Figure 8 (top). The tropospheric NO_2 concentration consistently increases from 2006 to 2009, reaching a maximum of about 2–2.3 × 10^{15} molec. cm^{-2} in R1 in 2009. Subsequently, there is a gradual decrease in NO_2 from 2.3–1 × 10^{15} molec. cm^{-2} between 2012 and 2015, possibly due to the enforcement of various air pollution regulation laws in the country and its neighbouring regions. The policies encompass the Environment Protection Act, 2076 in Nepal (EPA, 2019), the Chinese government's State Council air pollution prevention and control action plan (CAAC, 2013) and Pollution Control Acts, rules, and notifications (Saheb et al., 2012) in India. A sharp increase in NO_2 from 1 to 3 × 10^{15} molec. cm^{-2} is observed after 2018. In region R2, a consistent annual variation in NO_2 of about 0.6 × 10^{15} molec. cm^{-2} is found from 2004 to 2018. A sudden increase in NO_2 from 0.6 to 2 × 10^{15} molec. cm^{-2} between 2018 and 2020 indicates the influence of anthropogenic emissions reaching the pristine high mountainous region of the province.

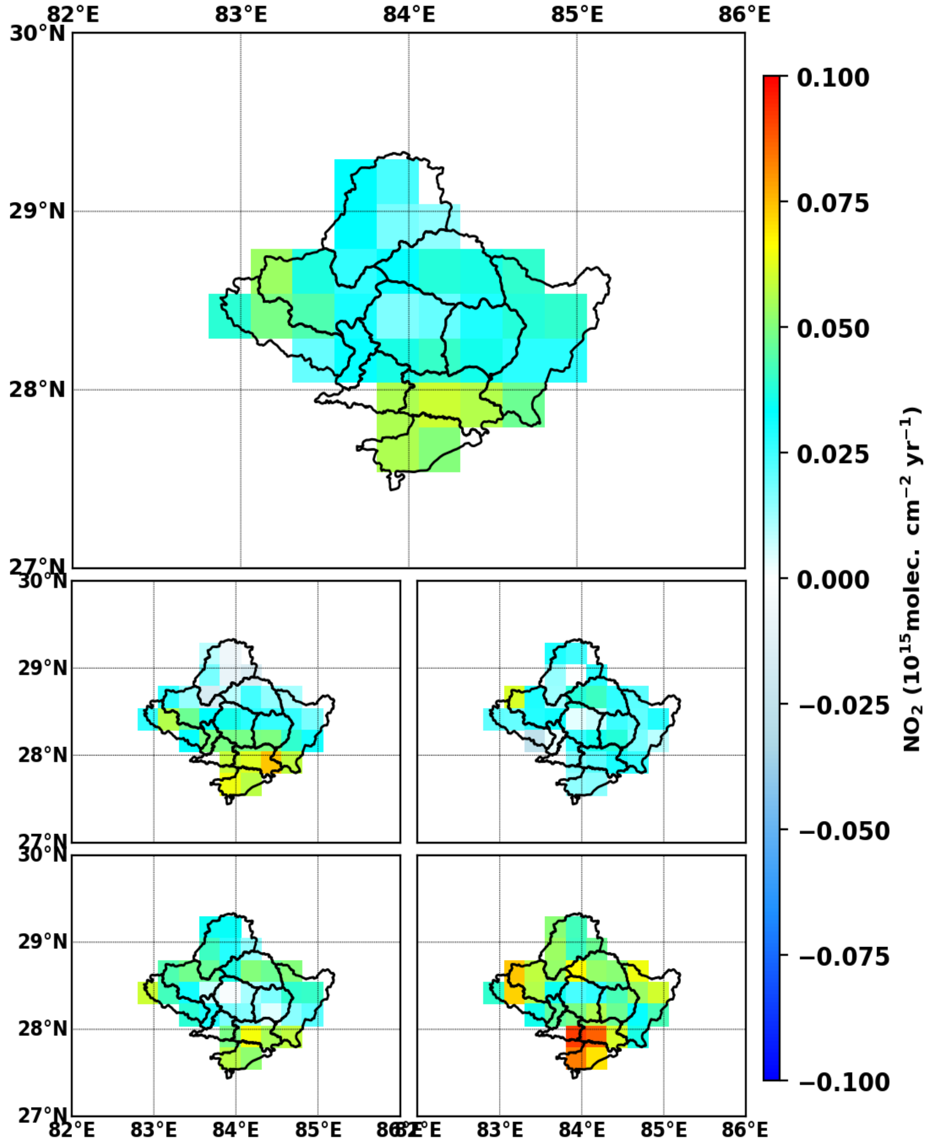
Trends in Tropospheric NO_2

Figure 7 shows tropospheric NO_2 trends for the period (2005–2020) in the Gandaki province in Nepal. Annual trends are positive, varying from 0.025 to 0.075 × 10^{15} molec. cm^{-2} yr^{-1}. Comparatively, trends are higher (i.e. ≥ 0.05 × 10^{15} molec. cm^{-2} yr^{-1}) over southern regions of the province. However, there is a large variation in seasonal trends. Observed trends are higher up to 0.05 × 10^{15} molec. cm^{-2} yr^{-1} in Autumn and small about 0.025 × 10^{15} molec. cm^{-2} yr^{-1} in spring in the province. Our results agree with some previous studies in the region. Sharma et al (2023a) found a positive trend up to 1 × 10^{15} molec. cm^{-2} yr^{-1} in the southern slope of the Third Pole using a combined dataset from OMI and GOME-2B for the period 2005–2020, and Rupakheti et al (2018) found NO_2 trend up to 0.016 × 10^{15} molec. cm^{-2} yr^{-1} over the Tibetan Plateau in summer and 0.052 × 10^{15} molec. cm^{-2} yr^{-1} in IGP in winter using the OMI measurements during 2004–2015.

We analysed the emission inventory EDGARv6.1 available from 1970 to 2018 to investigate the impact of NO_2 sources. We find major emission sources in the province are road transport, power and refinery, followed by agriculture. Figure 8 (bottom) shows the spatial distribution of anthropogenic NO_2 from road transport (bottom left) and agricultural activities (bottom right). Agricultural activities are spread throughout the province, except in the high mountainous region in the northern part. We find a significant contribution of NO_2 up to 1 × 10^{-9} kg m^{-2} s^{-1} in the southern region of the province. However, the contribution from road transport is confined to the highways, as seen in Figure 8, **(**bottom). The contribution from road transport varies from 2–10 × 10^{-9} kg m^{-2} s^{-1} with higher values 10 × 10^{-9} kg m^{-2} s^{-1} over the Mahendra highways, Prithvi highways and Siddartha highways. A higher contribution of NO_2 is also observed from road transport in the capital city of the province, Pokhara Metropolitan City.

Figure 7

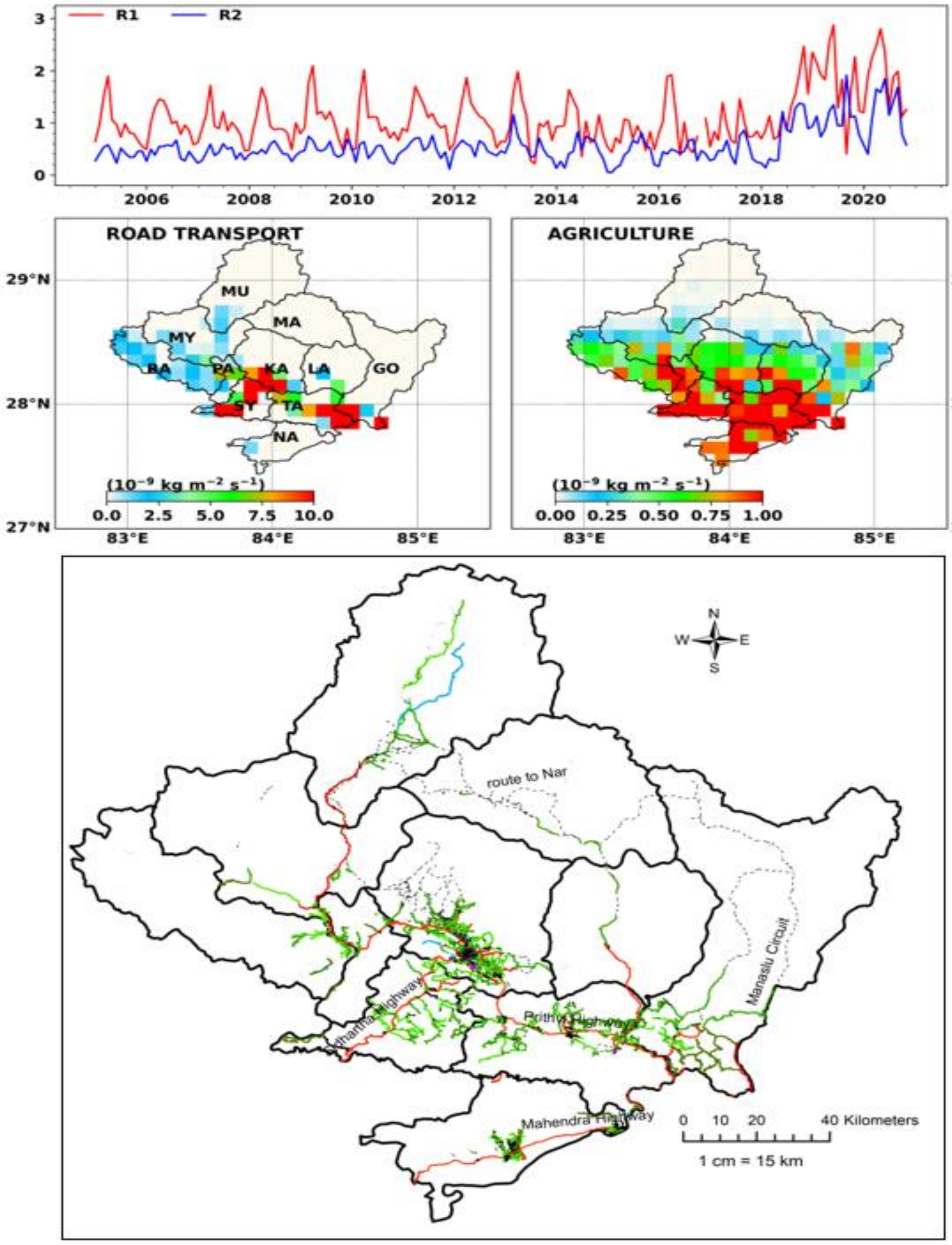
Annual (top panel) and seasonal (the four panels in the bottom) trend of tropospheric NO_2 in the Gandaki Province estimated for the period of 2005–2020. The trends are statistically significant at the 95% CI ($p < 0.05$). The seasons are defined as winter (December to February, DJF), spring (March to May, MAM), summer (June to September, JJAS), and autumn (October to November, ON)



Anthropogenic activities have severely degraded the environment of the province. The key findings of this research are: (1) Tropospheric NO_2 in the Gandaki Province has substantially increased in the last 15 years; however, an alarming change has been observed after 2018. (2) Major contributing sources are road transport and agriculture. Regions containing major contributing sources have alarming levels of tropospheric NO2, which is a great concern.

Figure 8

Top: Temporal evolution of tropospheric NO_2 over two distinct NO_2 regions. Middle: Spatial representation of NO_2 emissions from the agriculture sector and road transport during the period 1970–2018 derived from the EDGAR inventory. Bottom: The road transport map of the Gandaki Province. The districts of the Gandaki province are shown in brackets for each abbreviated form, i.e MU (Mustang), MA (Manang), MY (Myagdi), BA (Baglung), PA (Parbat), KA (Kaski), LA (Lamjung), GO (Gorkha), SY (Syangja), TA (Tanahun), NA (Nawalpur)



CONCLUSIONS

This work presented the spatiotemporal variation of tropospheric NO_2 based on OMI measurements from 2005 to 2020 across the Gandaki Province in Nepal. The increase in anthropogenic activities is mainly responsible for high tropospheric NO_2 in the region. We find lower NO_2 ($< 0.7 \times 10^{15}$ molec. cm^{-2}) over the high-altitude mountainous regions in the north and high NO_2 ($> 0.7 \times 10^{15}$ molec. cm^{-2}) over the southern region of the province, particularly the regions close to IGP. A clear seasonality of tropospheric NO_2 is observed. We have computed the linear trends of tropospheric NO_2 at a 95% Confidence Interval in the Gandaki province. We find positive annual trends during (2005–2020) over most regions in the Gandaki province with higher values ($\geq 0.05 \times 10^{15}$ molec. cm^{-2} yr^{-1}) in the southern part. However, there is a large variation in the seasonal trends. NO_2 trends are positive in all seasons with higher values of about 0.05×10^{15} molec. cm^{-2} yr^{-1} during autumn and small up to 0.025×10^{15} molec. cm^{-2} yr^{-1} in spring. Although this study identifies the major hotspot regions in the province and their sources. The southern urban regions of the province are the major hotspots of NO_2, with road transport and agricultural activities being the major sources. The positive trends of NO_2 over most regions in the province, as well as in high-altitude pristine areas, suggest a decline in air quality. The significant rise in tropospheric NO_2 after 2018 nearly doubled across all regions compared to 2016, indicating climate and environmental change in the province, which, amidst ongoing global warming, is an important issue that accentuates the importance of this study. Therefore, strong policy enforcement is required at the provincial level to control emissions in the region. However, the datasets used for this study are NO_2 vertical columns, which cannot be interpreted as NO_2 exposure. Therefore, an exposure model study is also needed to assess the health impact, which we will focus on in a future study.

DATA AVAILABILITY

We have used the data from various sources, which are publicly available:
Tropospheric NO_2: www.temis.nl
Topography: https://www.shadedrelief.com/
EDGAR inventory: https://edgar.jrc.ec.europa.eu/
The data can be provided on request.

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