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Relation between total-column and near-surface NO_2 based on in-situ and PANDORA ground-based remote sensing observations

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Abstract

Nitrogen dioxide (NO_2) is a major pollutant which at high concentrations may affect human health. It is also a photochemically reactive gas which is important for the oxidation potential of the atmosphere and acts as a precursor for the formation of aerosol particles and ozone. However, monitoring of near-surface (NS) NO_2 faces the challenge of spatial discontinuity due to large distances between ground-based monitoring stations, whereas satellite remote sensing provides column-integrated concentrations (total column, TC) which are related to NS concentrations in a complicated manner. In this study, the relation between TC and near-surface (NS) NO_2 concentrations is studied using TC NO_2 data from remote sensing observations using a Pandora and NS NO_2 concentrations from in-situ observations, which were located at the Beijing-RADI site (Beijing, China) during January 2022. The ratio between TC and NS NO_2 concentrations varies throughout the day with substantially different relations in the morning and afternoon. During the night and morning the atmosphere was vertically stratified, with disconnected layers which prevented vertical mixing of atmospheric constituents. In the afternoon, these layers connected allowing for vertical mixing and transport between the surface and the top of the boundary layer. Thus the prohibition of vertical transport in the morning and the mixing in the afternoon resulted in different relations between the NS and TC NO_2 concentrations. These different relationships have consequences for the use of satellite remote sensing to estimate NS NO_2 concentrations.

Keywords: Nitrogen dioxide, remote sensing, air pollution, Beijing, winter

1 Introduction

Nitrogen dioxide (NO_2) can have adverse effects on human health (Eum et al., 2022, 2019; Nordeide Kuiper et al., 2021; Kornartit et al., 2010). NO_2 plays an important role in atmospheric chemistry, and acts as a precursor for the formation of ozone and secondary aerosols in the atmosphere. The major sources of NO_2 are from fossil fuel burning such as power plants, traffic and households. Because of these anthropogenic sources, together with the relatively short atmospheric lifetime of NO_2, high tropospheric NO_2 concentrations are usually observed near highly industrialized regions (Van der A et al., 2006), densely populated agglomerations (de Souza et al., 2022), and power plants (Tang et al., 2024), as well as along major highways (Goldberg et al., 2021) and shipping lanes (Ding et al., 2018). In addition, NO_2 is produced from some natural sources such as lightning and soil emissions.

Concentrations of NO_2 in the atmosphere can be measured using satellite-based sensors providing vertical total column and tropospheric densities, ground-based remote sensing using MAX-DOAS or Pandora instruments, or in situ instruments. Satellite remote sensing is currently a widely used technique, for example using the Ozone Monitoring Instrument (OMI, Levelt et al., 2006) on the Aura satellite, and the TROPOspheric Monitoring Instrument (TROPOMI, Veefkind et al., 2012) on the Sentinel-5 Precursor (S5P) satellite. Satellite data show that the total column (TC) NO_2 concentrations are highly variable in space and time (e.g., Lamsal et al., 2014; Fan et al., 2021). Duncan et al. (2016) analyzed global NO_2 observed by OMI from 2005-2014 and found that NO_2 levels were initially high over China but had significantly decreased over the Beijing, Shanghai and the Pearl River Delta (PRD) regions in 2014, in response to pollution control measures. In particular, over the PRD region the NO_2 concentrations decreased by about 40%. Also in the following years, the NO_2 concentrations over China have been substantially reduced in response to the implementation of emission reduction policy (e.g. van der A et al., 2017; Fan et al., 2021; de Leeuw et al., 2021) and fell below the 2008 level in 2017 (Zhao et al., 2023). However, the decrease seems to have flattened in recent years (Fan et al., 2021).

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The Pandonia Global Network (PGN) of Pandora Spectrometer Instruments has been established in 2018 (http://www.pandonia-global-network.org/, last accessed: 10th July 2024) to provide "quality observations of total column and vertically resolved concentrations of a range of trace gases". The PGN data are used, for instance, for the validation of products from environmental satellites. However, the comparison of OMI TC NO_2 data with Pandora observations at 6 sites in Korea and the USA by Herman et al. (2019) showed that mean and daily Pandora NO_2 concentrations were 50% or more higher than those retrieved from OMI at sites that were frequently contaminated, such as Seoul, Busan and Washington DC. Tzortziou et al. (2018) reported that Pandora TC NO_2 observations during the KORUS-AQ coastal cruise experiment (Tzortziou, et al., 2015) were 10-50% higher than OMI-derived TC NO_2. Thompson et al. (2019), using data from the same experiment, reported that there is no consistent correlation between TC and NS NO_2 across different cases and that the relation between TC and NS NO_2 is complex. Similar results were obtained from the analysis of data from the DISCOVER-AQ campaign in the Baltimore-Washington region in July 2011; the discrepancies were suggested to be caused by the large field of view of OMI (Flynn et al., 2014; Knepp et al., 2015; Reed et al., 2015; Tzortziou et al., 2015). Preliminary validation of TC NO_2 observations from the Ozone Mapping and Profiler Suite (OMPS) aboard the joint NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP) satellite by Huang et al. (2022) in the USA showed that OMPS TC NO_2 tends to be lower in polluted urban areas and higher in clean areas/events than Pandora observations. Ialongo et al. (2020) and Zhao et al. (2020) obtained similar results from the validation of TROPOMI TC NO_2 using PGN data but the differences were significantly smaller than for the OMI and OMPS data with a coarser spatial resolution than TROPOMI. The validation of TROPOMI TC versus Pandora data at the Beijing-RADI site shows the good performance of TROPOMI (Liu et al., 2024). It is noted that Liu et al. re-sampled the TROPOMI data to a spatial resolution of 100×100 m^2, i.e. similar to that of the Pandora observation area.

Satellite-derived TC NO_2 data are often used to determine trends (e.g., van der A et al., 2017; Fan et al., 2021) but, in view of the above, the relation between TC and NS NO_2 is more complex. For instance, Fan et al. (2021) discussed the TS/NS relationship for selected major urban regions in China during the first 20 weeks after the COVID-19 lockdown and observed substantial differences (their Figure 9). Chang et al. (2022) analyzed data from the Geostationary Environment Monitoring Spectrometer (GEMS) Map of Air Pollution (GMAP) campaign conducted during 2020–2021. Their results show that TC NO_2 and NS NO_2 are better correlated in advective boundary layer conditions at high wind speeds, with a more uniform vertical distribution of NO_2, than during mixed boundary layer conditions with plumes from large point sources decoupled from the surface or transported from nearby cities, enhancing the vertical heterogeneity of NO_2. Similarly, Liu et al. (2024) show different relations between TC and NS NO_2 for low and high concentrations which are qualitatively explained in terms of transport and local emissions. Thus, to accurately assess NO_2 pollution in China and effects on air quality, accurate ground-based observations are needed.

Although a large number of ground-based NO_2 observation stations have been established in China since 2012 by the China National Environmental Monitoring Center (CNEMC) of the Ministry of Ecology and Environment of China (MEE) for the provision of the ground-based monitoring data (available at http://www.mee.gov.cn/; last access: 08 July 2024), there are still large areas for which no data are available. Satellite data can fill these gaps by converting satellite observations of aerosols and trace gases from TC to NS concentrations. Such data are usually provided from sensors flying on polar-orbiting satellites with global coverage but with a single overpass per day which at most latitudes cannot provide the daily variability of NO_2 characteristics. However, with the launch of geostationary satellites, spatial and temporal distributions of NO_2 concentrations can be obtained within the satellite field of view throughout the day. The GEO-KOMPSAT-2B geostationary satellite, launched by the National Institute of Environmental Research (NIER) under the Ministry of Environment, Korea, in February 2020, carries the Geostationary Environment Monitoring Spectrometer (GEMS), which provides high-resolution measurements of TC concentrations of key air quality components (Kim et al., 2020). With the launch of GEMS, the Asian region was the first to achieve coordinated hour-by-hour monitoring of pollutants. GEMS will form a constellation of satellites to monitor air quality globally with high temporal and spatial resolution, together with the Tropospheric Emissions: Monitoring Pollution (TEMPO) mission, launched by NASA on 7 April 2023 to cover the North American region (https://tempo.si.edu/overview.html) and Sentinel-4 planned to be launched on the Meteosat Third Generation Sounder (MTG-S) planned to be launched by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) in 2024 (EUMETSAT, 2024). Although geostationary satellites can make continuous observations of TC NO_2 during the day, the difference between TC and NS NO_2 remains an important challenge. The weak correlation between NS NO_2 concentrations and satellite-derived TC NO_2 (Lamsal et al., 2014), is closely related to their vertical distribution, lifetime in the atmosphere, and chemical reactions (Xing et al., 2017). To study the relation between TC and NS NO_2, accurate information is needed on both the TC NO_2 and the NO_2 vertical structure in the atmosphere, together with the temporal evolution, which until recently was not available for China.

The first operational Pandora instrument in China has been installed at the Beijing-RADI site in 2021, for the ground-based remote sensing of several trace gases (e.g. NO_2). The Beijing-RADI Pandora instrument is part of the PGN network and all data are publicly available via the PGN website (https://data.pandonia-global-network.org/Beijing-RADI/Pandora171s1/, last accessed: 22 Jan 2025) within one day of the observations. The aim of this study is to analyze the relationship between TC NO_2 obtained by remote sensing and NS measurements during a field experiment at the Beijing-RADI site during January 10-29, 2022. In order to better determine and understand the relation between TC and NS NO_2 concentrations, we also used auxiliary data such as simultaneous measurements of $PM_{2.5}$ mass concentrations, lidar observations, meteorological parameters, and satellite observations. Section 2 presents the experiments and data, Section 3 presents the main results, and the conclusions and discussion are presented in Section 4.

2 Materials and Method

2.1 Site description

Beijing is a metropolis with an area of 16,800 square kilometers and a population of nearly 22 million (2023) (https://worldpopulationreview.com/world-cities/beijing-population, last accessed: 22 Jan 2025). Beijing is surrounded by high mountains to the north, east, and west (Figure 1). The rapid economic development of Beijing and the topography of the area lead to emission of pollutants which may either disperse or accumulate, depending on wind direction and wind speed. During northwesterly winds, clean air is transported from the mountains, whereas during southerly winds polluted air is transported from the highly industrialized North China Plain. The southerly airflow is blocked by the mountains to the west and north and thus pollution accumulates, in particular during certain weather conditions conducive for the formation of smog, such as low wind speed. Photochemical processes may further contribute to the build-up of pollution which may result in the formation of haze.

The Beijing_RADI site is located at the roof (22 m above the surface) of the Aerospace Information Research institute of the Chinese Academy of Sciences (40.004° N, 116.379° E, elevation 59 m), which in turn is located in the north of Beijing between the Fourth and Fifth Ring Roads at the edge of the Olympic Parc. The site is representative for an urban background affected by vehicle exhaust, combustion and domestic emissions including those from heating during wintertime.

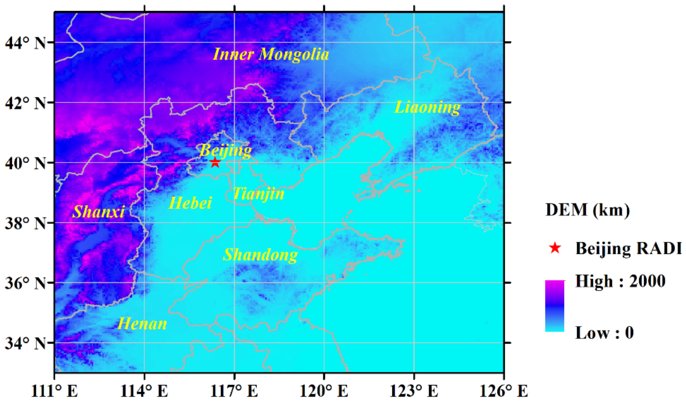

Figure 1. Digital elevation map of the study area showing the location of the Beijing-RADI site (40.004° N, 116.379° E, altitude at 59 m) (red star) and surrounding mountains.

A short-term field experiment was carried out at the Beijing-RADI long-term observation site during January 10-29, 2022. Pandora provided TC and NO_2 concentrations in 4 layers, information on the spatial distribution of TC NO_2 was obtained from TROPOMI and a lidar provided aerosol backscatter profiles showing the vertical structure and evolution of the atmospheric boundary layer. The NS parameters were measured with instrumentation mounted near the Pandora on the roof of the AirCAS building, as described in the following sections.

2.2 Observations of Column-Integrated Parameters and Vertical Profiles

2.2.1 Pandora

Pandora is a UV-visible spectrometer which can provide high-quality measurements of spectrally resolved direct-sun/lunar or sky scan radiances. It uses direct solar measurements to obtain TC NO_2, and sky measurements to obtain the vertical layer concentrations of NO_2, with a FOV of 2.6° in direct sun mode and 1.5° in sky mode (Cede et al., 2024). Based on the Beer-Bouguer-Lambert law, the spectra observed at 400~470 nm in direct-sun mode are used to invert TC NO_2 using the differential optical absorption spectroscopy (DOAS) technique of trace gas spectral fitting. Pandora's direct sun measurements depend only on the geographic location with a known solar zenith angle which simplifies the air mass factor for correction of the atmospheric light path (Chang et al., 2022). Pandora measures TC NO_2 with a clear-sky precision of 0.01 DU and a nominal accuracy of 0.1 DU Herman et al. (2009). In view of this high precision, we use TC NO_2 in this study and select products with quality control flag of L10. Diffuse (scattered) radiation is measured at 5 pointing zenith angles (PZAs) in sky mode which, together with the direct sun measurement, provides information on the tropospheric VCD and on the surface concentrations. The PZAs are 0^o, 60^o, 75^o, 88^o and a maximum angle taken as 89^o. The measurements are taken in a

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V shape (all angles are measured twice around a central angle) as described in Cede (2021). These data are used to derive vertical profiles as described in the ATBD (Cede, 2024) Section 6.7, which were downloaded from the PGN website. Pandora data are public and can be downloaded from the PGN website (https://pandonia-global-network.org, last accessed: 22 Jan 2025).

2.2.2 Lidar

A small lidar developed by the Hefei Institute of Physical Sciences, Chinese Academy of Sciences, was used for continuous measurements of aerosol backscatter profiles during day and night. The GBQ L-01 aerosol lidar consists of a laser, optical unit, control unit board, high-speed signal acquisition card, industrial motherboard and communication module. The GBQ L-01 aerosol lidar uses a high-frequency pulse laser emitting linearly polarized light at a wavelength of 1064nm. The optical unit consists of a transmitter and a receiver. The optical transmitter unit emits laser light pulses, which are expanded before they are emitted into the atmosphere. The optical receiver unit consists of a telescope which focuses the back-scattered light onto an optical detector which in turn is connected to an amplifier unit. The vertical and parallel polarized components of the back-scattered light are separated by the polarizing prism in the receiving channel. The industrial motherboard carries lidar acquisition and control software and data analysis software to control the overall operation of the system.

2.2.3 TROPOMI

The TROPOMI (TROPOspheric Monitoring Instrument) is a passive-sensing hyperspectral nadir-viewing imager aboard the Sentinel-5 Precursor (S5P) satellite, launched on 13 October 2017. S5P flies at an altitude of 817 km in a near-polar sun-synchronous orbit. The local equator overpass time in the ascending node is 13:30, and the repetition period is 17 days (KNMI, 2017). TROPOMI's four separate spectrometers cover wavelengths in the ultraviolet (UV), UV–visible (UV-VIS), near-infrared (NIR) and short wavelength infrared (SWIR) spectral bands (Veefkind et al., 2012). The TC NO_2 used in this study is derived from spectral measurements of solar radiation in TROPOMI's UV–VIS wavelength bands (van Geffen et al., 2015, 2019). Compared to the relatively small field-of-view of the Pandora instrument, the size of the TROPOMI ground pixel (3.5 km × 5.5 km; across × along track) is relatively large. Therefore, TROPOMI NO_2 products are only used as a reference for upwind concentrations during backward trajectory tracking and not for quantitative analysis. Furthermore, tropospheric NO_2 column densities are used because these are more representative of near-surface NO_2.

2.3 Near Surface Measurement

2.3.1 Trace Gas Analyzer

The Thermo Fisher Scientific Model 42i Trace Level Chemiluminescence NO-NO_2-NO_x Analyzer was used to measure NS NO_2 concentrations. This instrument first transforms NO_2 into nitric oxide (NO) using a molybdenum NO_2 to NO converter heated to about 325 °C. Then, NO and ozone (O_3) react to produce a characteristic luminescence with an intensity linearly proportional to the NO concentration (Model 42i Trace Level Manual, 2007). NO_2 values are derived by subtracting NO from NO_x measurements. Measurements were made every minute during the observation period.

2.3.2 Beta attenuation monitor

Ground-based near-surface $PM_{2.5}$ concentrations were measured using the beta attenuation monitor Met One BAM-1020 (BAM 1020 particulate monitor operation manual) equipped with a $PM_{2.5}$ inlet. The Met One BAM-1020 collects aerosol particles on glass filter tape. PM2.5 is measured using beta rays generated by a small ^{14}C source (https://metone.com/products/bam-1020/). At the start of every measurement cycle, the flux of beta rays is measured across clean filter tape, to determine a zero reading. Next, the filter tape is advanced and ambient air is sampled at the same spot, with a controlled air flow, thereby impregnating the tape with $PM_{2.5}$. After the sampling is completed, the tape retracts and $PM_{2.5}$ samples are dried (in an environment with relative humidity lower than 40% which removes most of the water content) by a built-in heater. Then the concentration of $PM_{2.5}$ collected on the filter tape is measured as described above. Samples are taken every hour.

2.3.3 Auxiliary meteorological data

In addition to the above observations, we also use weather maps, meteorological surface observations and sounding observations published by the World Meteorological Organization (WMO) to aid in our analyses. Weather maps for the Asian region are published by the Korea Meteorological Administration and can be downloaded at http://222.195.136.24/chart/kma/data_keep (last accessed: 22 Jan 2025). We downloaded the surface and sounding observations of meteorological station 54511 in Beijing, located at 39.93N, 116.28E, which is part of the WMO network. These data are available from the website of the University of Wyoming (http://weather.uwyo.edu/surface/) (last accessed: 22 Jan 2025). Although this station is far away from our experimental site (about 23 km), it is representative of the macroscopic changes of the meteorological conditions in Beijing.

2.4 HYSPLIT Model

To better understand the regional transport pathways and source regions at different altitudes, backward trajectories from the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT; Draxler & Hess, 1998) model were used. The HYSPLIT model assumes that the parcel trajectory is formed through time integration and spatial differences when moving in the wind field. The path of the air mass is mainly related to the air flow situation, pressure system movement and topography (Draxler & Hess, 1998). The HYSPLIT model has the ability to deal with a variety of meteorological input fields and physical processes, and can also be used to describe atmospheric transport, diffusion and deposition of pollutants and harmful substances (Stein et al., 2015). In this study, the backward trajectories were initialized for arrival at the Beijing-RADI site at 300, 500 m, and 1000 m. The HYSPLIT model was run at https://www.ready.noaa.gov/HYSPLIT_traj.php, with the input meteorological field data (0.25°×0.25°) provided by the Global Forecasting System.

3 Results and Analysis

3.1 Data overview

Time series of the measured NS and TC concentrations of NO_2 during the study period are presented in Fig. 2a. For comparison of NS NO_2 concentrations with Pandora observations, they are expressed in mg m^{-3}. Fig 2a shows the common diurnal variation of the NO_2 concentrations, i.e. a gradual decrease in the morning to a minimum around mid-day, followed by a gradual increase in the afternoon to a maximum value during the night. This diurnal variation is due to photochemical reactions during daytime, meteorological effects and anthropogenic emissions during certain hours (for instance during rush hour) (e.g., Atkinson, 2000; Boersma et al., 2009; Y. Zhang et al., 2016; Cheng et al., 2018; Li et al., 2021). TC NO_2 concentrations can only be measured with Pandora during day time. The diurnal variations between 8:00 and 16:00 local Beijing time (UTC+8; throughout this paper local time, LT, will be used) at the Beijing-RADI side are similar to those of NS NO_2. Based on the variation of the NS NO_2 concentrations (Fig. 2a) three periods are considered during the study period: Period I: 10 to 18 January, with strong diurnal variations and high NO_2 concentration peaks; Period II: 19 to 24 January, NS NO_2 sharply decreases and then increases with stronger fluctuations, but TC NO_2 observations are not available due to the presence of clouds; Period III: 25 to 30 January, a sudden drop occurred on January 25, and low NO_2 concentrations with some narrow peaks lasted until the 30th.

The time series of the NS $PM_{2.5}$ concentrations in Fig. 2b shows four peaks in Period I, with maximum values during the night and very low concentrations (<10 μg m^{-3}) during daytime. The maxima were relatively low on 12 and 17 January (~25 μg m^{-3}), whereas on 14 and 18 January the $PM_{2.5}$ peak concentrations were ~120 and ~70 μg m^{-3}. During Period II, the $PM_{2.5}$ concentration increased steadily from less than 25 μg m^{-3} on 20 January to more than 125 μg m^{-3} on the 24th, with similar day/night variations as in Period I. During Period III, the $PM_{2.5}$ concentrations were relatively low (<25 μg m^{-3}) and there was no clear diurnal variation.

The air temperature and relative humidity (RH) during the study period are presented in Fig. 2c and the wind speed and wind direction are presented in Fig. 2d. During Period I, air temperature, RH and wind speed all varied strongly with a clear diurnal pattern: elevated wind speed during the day, with daily maxima between about 7 and 13 m s^{-1}, and very low wind speed during the night (<2 m s^{-1}); day time air temperatures around 0^{o}C and night time temperatures around -10^{o}C; dry air during the day (RH~20%) and more humid during the night (RH of 60-80%). The wind was mostly from northerly directions (NW-NE) and veering during the night. During Period II, the air temperature increased gradually from about -5^{o}C to about 0^{o}C, with small diurnal variations, and RH increased initially from 40% to 60% on 20 January and then gradually to about 70%, with little day/night variations, whereas during the nights of 22-25 January the humidity was very high, the RH sensor saturated and reported maxima close to 100%. Wind speed during this period was low (< 3 m s^{-1}) and wind direction was mostly SE. During period III, day/night temperature and RH fluctuations occurred, with day time air temperatures above 0^{o}C and gradually rising and RH varying between 20% during the day and 60% during the night. Wind speeds were higher during the day, mostly a little higher than 3 m s^{-1}, than during the night (close to 0 m s^{-1}) and wind direction was mostly northerly.

The variations of the NO_2 and $PM_{2.5}$ concentrations were similar in the sense that the minimum and maximum peak concentrations occurred at about the same time, but with differences in the ratios between minima and maxima. The occurrence of peak concentrations during the night is consistent with the variation in meteorological conditions, with maxima during low wind speed and low air temperature, conducive for the formation of a nocturnal boundary layer in which the concentrations accumulate near the surface. This is observed during Periods I and III. During Period II, however, there were no Pandora observations during day time due the occurrence of clouds. This suggests that clouds may also have been present during the night. Hence radiative cooling was reduced and air temperature did not decrease as much as during the other periods. Wind speed was low, thus pollutants were not transported away and accumulated in the area, as also indicated by the high RH. Hence the concentrations of NO_2 and $PM_{2.5}$, as well as RH, gradually increased during period II, with relatively small diurnal variations.

For further analysis, we selected two cases for which both TC and NS NO_2 data were available, including lidar observations and air mass trajectories. The selected cases are the periods when both NO_2 and $PM_{2.5}$ concentrations were high, i.e. on 14 and 18 January, when the 24-hour average NO_2 concentrations exceeded 80 mg m^{-3}. The first pollution episode (case 1) started in the afternoon of January 14 and ended in the morning of January 15. The other pollution episode with high NS NO_2 occurred on January 18 (case 2). The diurnal variation of the NS NO_2 concentrations was similar in both cases, while the air temperature, RH, wind speed and wind direction show that also the meteorological situations were similar. However, differences are observed in the temporal variations of TC NO_2 concentrations versus NS NO_2 concentrations and in $PM_{2.5}$ concentrations.

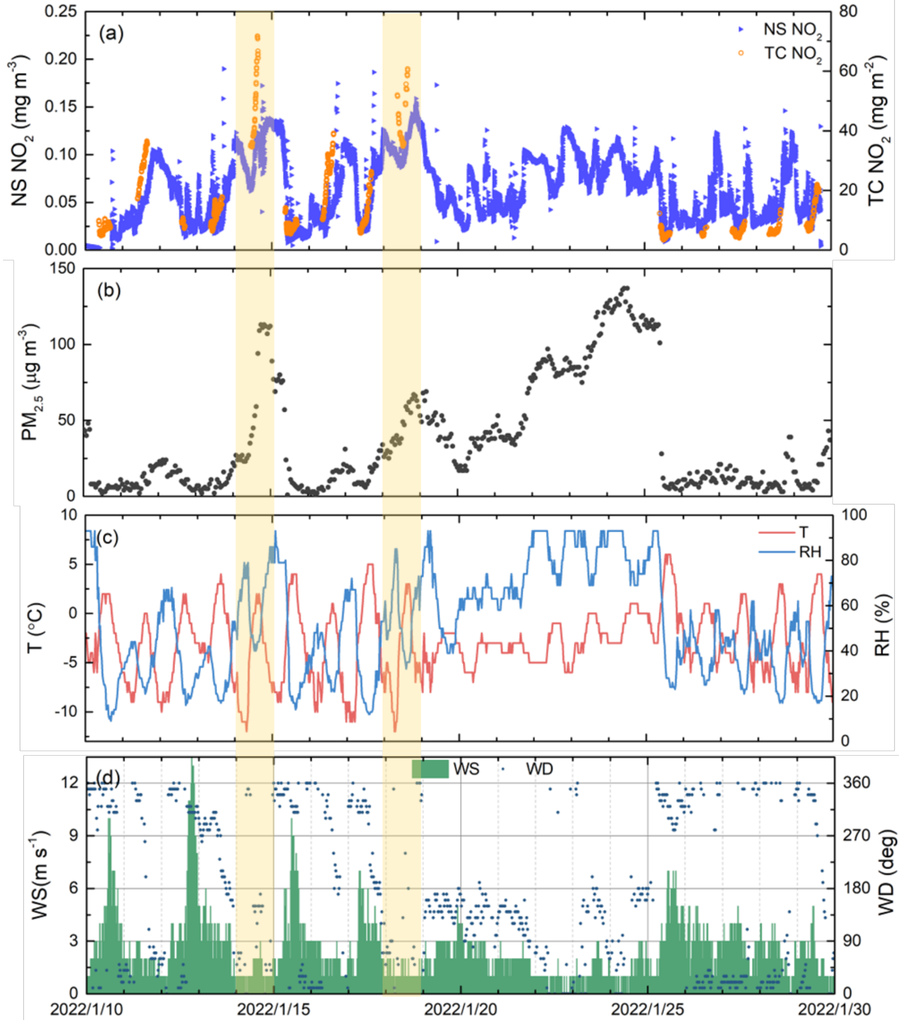

Figure 2. Time series of observed parameters from Jan 10 to 29, 2022 (a) TC and NS NO_2 concentrations, (b) NS $PM_{2.5}$ concentration, (c) temperature and related humidity, and (d) wind speed and wind direction from WMO meteorological station 54511 in Beijing.

3.2 Variations of TC and NS NO_2 during the two selected cases

The evolution of the TC and NS NO_2 concentrations and their ratio during the two high pollution episodes identified in Section 3.1 are discussed in detail. Processes influencing the concentrations and their ratio are identified based on lidar data,

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providing information on the boundary layer structure, together with large scale weather maps and air mass trajectory analyses, providing information on sources of pollutants and their transport over a wider area.

3.2.1 Case 1: Disconnected boundary layers merging (14 January, 2022)

Time series of the TC and NS NO_2 concentrations on 14 January 2022 (Fig. 3a) show their different evolution throughout the day. The NS NO_2 concentrations are available for every minute during the whole day and show a gradual decrease from about 0.11 mg m^{-3} between midnight and 04:00 to about 0.065 mg m^{-3} at 10:30. After 10:30 the concentrations increased to 0.11 mg m^{-3} at 13:30 and hardly changed until about 16:00 after which they strongly fluctuated (0.04-0.175 mg m^{-3}) and then reached a steady value of about 0.12 mg m^{-3} from 19:00 till midnight. The strong fluctuations may have been caused by emissions during evening rush hour, domestic heating and other activities producing NO_2, followed by stabilization during the evening.

Pandora uses direct sun observations and during this campaign in the winter time, high quality TC NO_2 data are only available between 10:30 and 15:30. The data in Fig. 3a show initially a similar behavior of TC and NS NO_2 concentrations, with little variation between 10:30 and 11:30. Thereafter, both NS and TC concentrations increased, initially slower for the TC than for the NS concentrations. After 13:00 the NS concentrations levelled off while the TC concentrations increased much faster. Between 12:00 and 15:00 the TC concentrations increased from 40 mg m^{-2} to 72 mg m^{-2}, almost a doubling, then decreased to 64 mg m^{-2}. The difference in the temporal behavior between the TC and NS NO_2 concentrations is amplified in Fig 3b which shows a scatterplot between the TC and NS concentrations. Observations before and after 13:00 are plotted with different symbols and color coded in blue and red, respectively. For each of these two data sets, before and after 13:00, TS and NS concentrations are well correlated with linear correlation coefficients R of 0.94 and 0.85, respectively, but with significantly different slopes.

The different behavior of the TC and NS NO_2 concentrations can be explained by

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considering the dynamical behavior of the boundary layer structure. Lidar observations reveal the vertical structure of the atmospheric boundary layer from the variation of the lidar signal as a function of height. A 3-D plot of the vertical variation of the lidar signal, measured on 14 January 2022 at the Beijing-RADI site, close to the Pandora and the ground-based measurements, is presented in Fig. 3c. The lidar signals are color-coded according to the scale to the right of Fig. 3c and each vertical line shows the variation of the lidar signal with height, plotted along the primary vertical axis. The time of measurement of each profile is plotted along the horizontal axis. The lidar signal in this figure is range-corrected, i.e. corrected for attenuation as the laser light propagates in the atmosphere away from the emitter and, after backscattering by aerosol particles, back to the receiver. The time between emission of the laser pulse and receiving the backscattered signal is a measure for the height where the backscattering takes place (after correction of the slant to a vertical optical path) and the intensity is a measure for the aerosol concentration. This is illustrated with the data in Fig 3d. For example, the data show an aerosol layer between 08:00 and 13:00, located at a height between about 800 and 900 m, as indicated by the large lidar signal (yellow and red, i.e., between about 1.2 and 2.2), with light blue above and below, indicating lower aerosol concentrations. Between about 400 and 500 m a dark blue area can be observed, which indicates very low backscatter and thus the absence of aerosol, whereas further down toward the surface, backscatter is observed with a varying intensity. The vertical variation of the lidar signal, i.e. indicating the presence of aerosol in the layer adjacent to the surface up to about 400 m, a layer with no aerosol between 400 and 500m and an elevated intense aerosol layer above, indicates a situation of a disconnected boundary structure with two layers which are not connected and thus no material can be exchanged between these layers. Such a situation can occur due to nocturnal cooling when the surface is cold due to radiation cooling and cools the layer adjacent to the surface (Stull, 1988). In this layer, no mixing occurs and material emitted near the surface accumulates. The atmospheric trace gases and aerosol in the warmer layer above are trapped in that layer and exchange with the cold layer below is prohibited due to the temperature

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gradient. Hence the two layers become disconnect and may separate.

The occurrence of such a situation is consistent with the observations discussed in Section 3.1 and Fig. 2, with low wind speed, lowest air temperature during period I (-12°C) and enhanced RH (indicating trapping of water vapor together with decreased air temperature). Also the lidar data in Fig. 3c indicate the occurrence of such a situation, with a well-mixed shallow boundary layer between midnight and 03:00, an indication of an internal boundary layer starting to form after about 04:00, disconnected from the layer above. The internal boundary layer rises gradually until about 11:00, with the clean layer above, and a new layer appears around 07:00, probably due to advection. Note that wind direction was south-easterly during a short period of time on 14 January with a wind speed of 2 m/s, slightly more than during the rest of the day when the wind direction was northerly. During south-easterly winds, polluted air may be advected to the Beijing-RADI site, whereas during northerly wind clean air is advected (Liu et al, 2024).

From 12:00, the lower layer deepened and backscatter is observed from the clean layer indicating that aerosol is gradually mixed into that layer which completely disappears around 14:00. At the same time, the lidar signal from the growing lower layer increases gradually whereas after 13:00 the lidar signal from the upper layer becomes smaller, indicating that the aerosol concentration becomes lower until both layers are mixed around 14:00 into a well-mixed boundary layer. After 15:00, the lidar signal increases, first near the surface and then growing throughout the boundary layer. The increase of the NS concentrations is consistent with the highest $PM_{2.5}$ concentrations as presented in Fig. 2b and the overall increase of the lidar signal, indicating increasing aerosol concentrations. This is confirmed by AERONET AOD observations at the Beijing-RADI site (https://aeronet.gsfc.nasa.gov/cgi-bin/data_display_aod_v3?site=Beijing_RADI&nachal=2&level=2&place_code=10) which however were only available until 16:00 LT.

The vertical variation of the NO_2 concentrations, derived from the Pandora sky radiance measurements at four elevations, is presented in Fig. 3d. Pandora data are only available during day time and therefore only the period from 08:00-16:30 can be shown. The NO_2 concentrations are available in 4 layers. Assuming that NO_2 is uniformly distributed within each layer, the data were interpolated to form a time series of NO_2 vertical distributions, similar to the lidar profiles. The data in Fig. 3d also show the similar behavior of the NO_2 concentrations and the aerosol backscatter, with increasing concentrations between 12:00 and 17:00 and their vertical mixing. In particular the increase around 15:00 is evident in both the Pandora and lidar observations. However, the Pandora observations do not show the occurrence of disconnected boundary layers in the morning. Instead, the Pandora observations show an enhanced layer between 300-800 m, rather than the more detailed structure visible in the lidar data. These differences may be due to the absence of elevated NO_2 concentrations in the aerosol layer between 800 and 900 m, while the layered structure below is not well-resolved by Pandora due to it's vertical resolution resulting in lower concentration over a large layer. The latter is in agreement with the observations later in the day.

The overall similarity between the variations in the lidar and Pandora observations supports the use of lidar observations to explain the dynamic behavior of the NO_2 concentrations. In particular, the different relations between TC and NS observations before and after 13:00 (Fig. 3b), can be explained by the occurrence of the disconnected layers. The variations of the NS NO_2 concentrations until 13:00 reflect the effects of chemical processes and emissions within the atmospheric layer near the surface and within the elevated layer where only removal processes influence the NO_2 concentrations. As a result, the temporal variation of the concentrations in both layers was in part influenced by the same processes, differences were not large (Fig. 3a) and the ratio of the TC/NS concentrations changed little (Fig. 3b). In the afternoon, such processes resulted in the increase of NO_2 concentrations while also the two layers are connected which, together with the somewhat enhanced wind speed (Fig 2d) resulted in mixing of NO_2 throughout the whole boundary layer up to about 1000 m. Hence the usual afternoon increase of NO_2 concentrations near the surface (Liu et al., 2024) was dampened by upward transport whereas the increase in TC concentrations was enhanced, as is well illustrated by the time series of both NC and TC between 13:00 and 15:00 (see Fig. 3a). As a result, also the TC/NS relationship changed substantially after 13:00 (Fig. 3b).

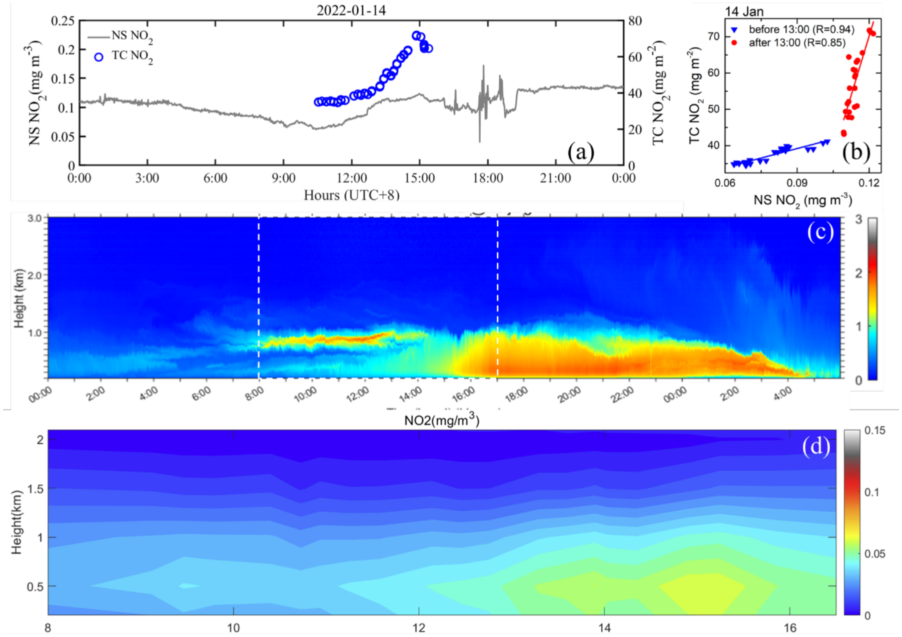

Figure 3. (a) Time series of NS NO$_2$ (grey line) and TC NO$_2$ (blue circles) at the Beijing RADI site (40.004°N, 116.379°E) on Jan 14, 2022; (b) relationship between TC and NS NO$_2$ concentrations during the morning (before 13:00) and during the afternoon (after 13:00); (c) time series of vertical profiles of range-corrected lidar signal at 1064 nm. Note that the lowest height in Fig. 3c is 100 m; (d) time series of NO$_2$ vertical profiles derived from Pandora sky radiance measurements.

The effect of transport on the NO$_2$ concentrations at the Beijing-RADI site on 14 January 2022 was analyzed using the data presented in Fig. 4: the spatial distribution of tropospheric NO$_2$ columns derived from TROPOMI data (overpass time 13:30), the synoptic weather map at 00 UTC and 24-hour backward trajectories for arrival at the Beijing-RADI site at altitudes of 300 m, 500 m and 1000 m, at 10:00, 13:00 and 16:00 LT. The TROPOMI data show the relatively high tropospheric NO$_2$ concentrations over

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the study area, in particular over an elongated area stretching from the SW to the NE over Hebei Province, including Beijing (compare with Fig. 1), and from Beijing eastward. This area is bounded by the Taihang mountains in the west and by the Yan mountains in the north, blocking transport of pollutants. The weather map in Fig. 4b shows the pressure distribution and location of low pressure areas resulting in wind from the SW, i.e. along the direction of the elongated area with elevated NO_2 concentrations (see Fig. 4a). This is confirmed by the air mass trajectories in Fig. 4c, all showing overall transport from the SW. However, the trajectories arriving at 10:00 LT show that during the last 8h, the air mass arriving at 300 m came from the NE at low wind speed and the airmass arriving at 500m came from the NW at even lower windspeed. The airmass arriving at 1000 m came from the SW during the last 14 h before arrival and from the NW during the earlier 12 hours. The airmasses arriving at 13:00 show similar trajectories. These trajectories are consistent with the lidar observation of disconnected layers, with different air mass trajectories during the last hours before arriving at the Beijing-RADI site and thus possibly different composition. The air mass arriving at 1000 m had been at high elevations during its entire 24 h trajectory and originated from higher than 1500m, but those arriving at 300 and 500 m originated from the surface at different locations separated by tens of km and may thus have been influenced by different sources.

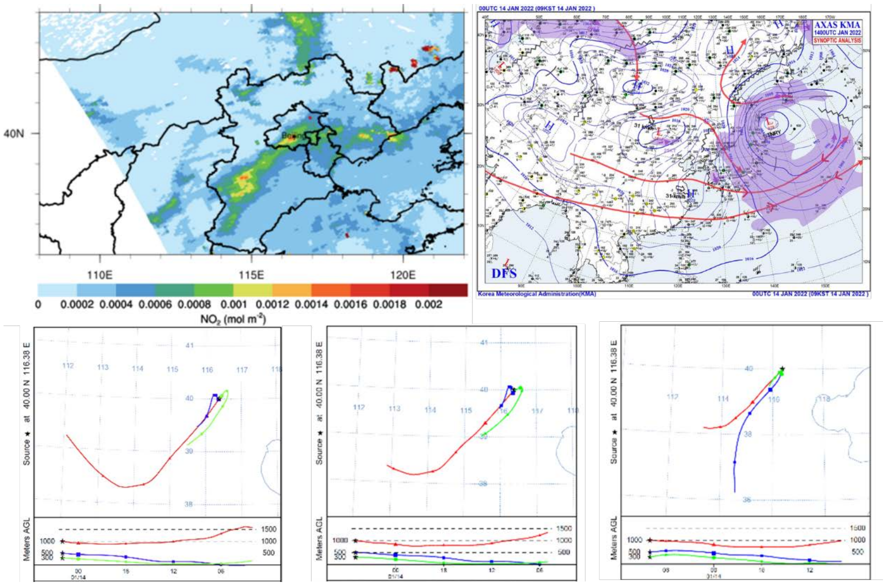

Figure 4. (a) Spatial distribution of tropospheric NO_2 in the study area derived from TROPOMI data on 14 January 2022; (b) Synoptic weather map at 00:00 UTC (08:00 LT); (c) 24-hour backward air mass trajectories arriving at the Beijing-RADI site at 10:00, 13:00 and 16:00 LT, at heights of 300, 100 and 1000 m, calculated using the HYSPLIT model with 6h time steps (00, 06, 12 and 18) and a shorter time step to the arrival time.

3.2.2 Case 2: Multi-layer structure on 18 January, 2022

Time series of the TC and NS NO_2 concentrations on 18 January 2022 are shown in Fig. 5a, together with a scatterplot between the TC and NS concentrations in Fig. 5b and 3-D plots of the vertical variation of lidar backscatter coefficients in Fig. 5c and of NO_2 concentrations in Fig. 5d. The NS NO_2 time series in Fig. 5a show that the concentrations were higher than on 14 January, but their variation was initially similar, with a decrease to a minimum around 11:30 (later than on the 14th) followed by an increase. However, on 18 January, the increase continued non-linearly until about 14:30 when the concentrations plateaued at a value of about 0.12 $mg\ m^{-3}$ during about 1 hour and then increased further, likely due to increased emissions during rush hour and decreasing photochemical sink when the solar radiation intensity decreased in the afternoon. After 18:00 the concentrations plateaued at 0.13-0.14 mg m^{-3}, fluctuated up to about 0.14 mg m^{-3} around 21:00 and decreased somewhat toward the end of the day.

The TC NO_2 concentrations decreased faster than on 14 January, from the initial 54 mg m^{-2} around 08:30 to the minimum of 36 mg m^{-2} around 12:30, with a smaller decrease after 11:00. Hence, similar to the situation on 14 January, the TC NO_2 concentrations initially decreased while also the NS NO_2 concentrations decreased, but in contrast to the 14th, after 11:30 the TC NO_2 concentrations continued to decrease while the NS NO_2 concentrations increased. As a result, there was no clear correlation between TC and NS NO_2 concentrations before 13:00, as on 14 January. These morning data could be separated into two groups, before 11:30, when there was no TC/NS relation, and after 11:30 where the data in Fig. 5b suggest a non-linear relation. Hence, in this situation, it may be difficult to determine NS NO_2 concentrations from satellite data. After 13:00, the TC NO_2 concentrations increased from about 37 mg m^{-2} to almost 60 mg m^{-2} at 16:30, with a plateau around 15:00. The scatterplot in Fig. 5b shows a good correlation between TS and NS NO_2 concentrations.

The lidar data in Fig. 5c, with lower intensity than on 14 January, indicate smaller aerosol concentrations on 18 January than on 14 January, consistent with the smaller $PM_{2.5}$ concentrations (in Fig. 2b). The lidar data show the occurrence of multiple layers during the night and morning, with sharp boundaries indicating that aerosol particles are trapped in rather shallow layers with little or no exchange between these layers. After 10:30, the boundaries between layers become less sharp indicating the onset of vertical transport, although the very shallow clear layer (dark blue) between 500 and 600 m indicates a clear separation between the lower and upper layers, prohibiting vertical transport. Around 13:00 this shallow layer disappeared and after 15:00 the atmospheric boundary layer appears well-mixed up to the top at about 800m.

The time series of the NO_2 vertical distributions in Fig. 5c shows that NO_2 concentrations were lower on the 18th than on the 14th, and concentrated below 1000 m.

The NO_2 concentrations and their vertical distributions varied between 08:00 and 12:30, with an initial increase between 08:00 and 10:00 with a broad elevated maximum centered around 500 m and another small maximum around 11, Apart from these, the NO_2 concentrations were rather homogeneously distributed up to the top of the atmospheric boundary layer at about 800 m as also indicated by the lidar data. After about 12:00 the NO_2 concentrations increased with a significant enhancement after 14:00.

The evolution of the atmospheric boundary layer, as shown in detail by the lidar data, and the variation of the NO_2 concentration profiles provide a plausible explanation for the evolution of the TC and NS NO_2 concentrations and their ratios, with changes around 11:30 and 13:00. The plateau in the NS NO_2 concentrations may be indicative of the dilution near the surface due to upward transport and vertical mixing, at the same time increasing the TS NO_2 concentrations.

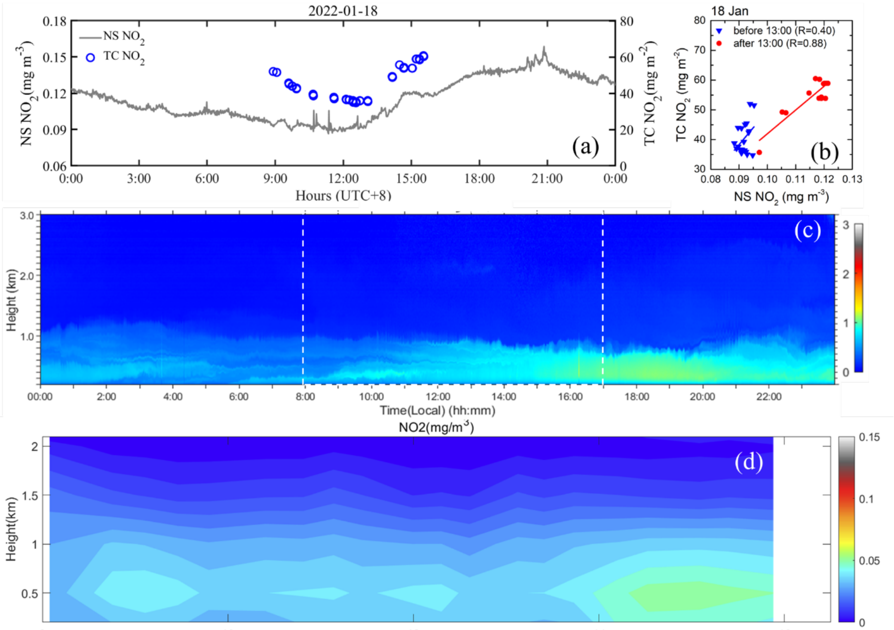

Figure 5. Same as Fig. 3 but for 18 January, 2022.

Fig. 6 shows the large scale situation for the study area on 18 January. The TROPOMI data in Fig. 6a show the spatial distribution of the tropospheric NO_2 VCDs which are highest to the SE of Beijing, in Hebei/Tianjin and over the Yellow Sea. Over Beijing, the tropospheric NO_2 VCDs, as indicated by TROPOMI, are substantially lower than in case 1. This can be explained by the transport from clean areas to the W and WNW as indicated by the air mass trajectories arriving in Beijing at 300m, 500 m and 1000m, at 10:00, 13:00 and 16:00 LT (Fig. 6c). The trajectories of the air masses arriving at 10:00 LT show a clear difference between the lower and higher layers visible in the lidar data: where the air arriving at 1000 m originated from the WNW and had traveled during the last 24 h over clean areas (Fig. 6a) over a distance of 1000 km (10°), between heights of 1000-1500 m, the lower air mass was influenced by local air from SSW (at 300 m) and SW (500m) that had traveled during the last 24 h near the surface at heights up to 500 m over moderately polluted areas. Hence the lidar data show higher aerosol content in the lower layer (<500 m) than in the layer above (>600m) and both disconnected layers are from different origin.

This situation changed as indicated by the air mass trajectory arriving at 12:00 LT. The air mass arriving at 300 m had the same characteristics as at 10:00 LT, had traveled an even shorter distance and the layer adjacent to the surface was more stagnant. However, the air mass arriving at 500 m now came from the west, had traveled over clean areas (Fig 6a) at heights between 500 and 1000 m and thus was distinctly different from the layer below. The air mass arriving at 1000 m originated from a bit further north and further away (in Inner Mongolia) than at 10:00 LT, and had travelled at heights between 750 and 1000 m. Hence all three air masses suggest that the layers originated from different regions and likely had different composition.

The trajectories of the air masses arriving at 16:00 LT indicate that the situation had changed, i.e. the pollution episode was finished and pollution was replaced with cleaner air transported from the W to WNW over distances of hundreds of km and originating from elevations of 500-1000 m for air masses arriving at 300m and 500m, whereas the air mass arriving at 1000 m had actually followed a lower trajectory.

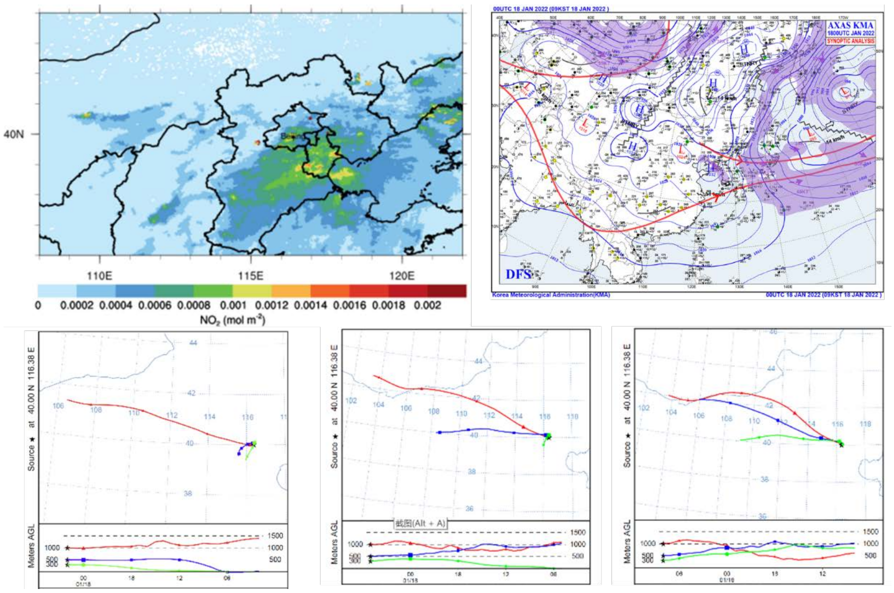

Figure 6. Same as Fig. 4, but for 18 January, 2022.

3.3 Ratio of TC vs NS NO_2

The two pollution cases discussed above show that the ratio between TC and NS NO_2 in the morning (before 13:00) is different from that in the afternoon (after 13:00) during the study period in the winter in Beijing. In order to better understand the relationship between TC and NS NO_2, we calculated the ratio of TC and NS NO_2 concentrations for each day, while we also differentiated between the morning and afternoon using 13:00 as the split time. The results are presented as violin plots in Fig. 7, for each of the 12 days for which data are available. The data in fig. 7 show that the mean and median values of the NO_2 ratio during Period I (10-18 January were substantially higher than those during Period III (25-30 January), with the exception of 25 and 29 January. During these two days, at the beginning and end of Period III, signify the transition from polluted to clean days (see fig. 2b). On most days the ratio was smaller in the morning than in the afternoon. The difference between the morning and afternoon ratios was small during the two days (14th and 18th) with accumulated pollution, while during the four days when wind speed increased, on 13, 15, and 17, the differences were relatively large, with the largest difference of 192 m on the 13th.

During Period III the difference between the morning and afternoon ratio was basically smaller than 50 m, with a gap of more than 100 m only on the 29th. There were no valid observations of TC NO_2 concentrations during Period II, so it is not possible to judge the changes in ratio over multiple consecutive days of pollution. Throughout the observation period, the standard deviations of the ratio were overall larger in the morning than in the afternoon, when the winter boundary layer was well-mixed and the relationship between TC and NS NO_2 concentrations was relatively stable. However, in the morning, when the boundary layer was developing, the day-to-day variations in the standard deviation imply relatively large changes in the ratio. The box plot in fig. 7b illustrates the difference between the morning and afternoon ratios. The mean values are lower in the morning (364m) than in the afternoon (428m), and the upper quartile in the afternoon are closer to their median value, suggesting that the ratio is more stable in the afternoon when it is well mixed vertically. However, although the ratio is quite stable in the afternoon with well mixing, there are still unpredictable extreme values (e.g. 771 m).

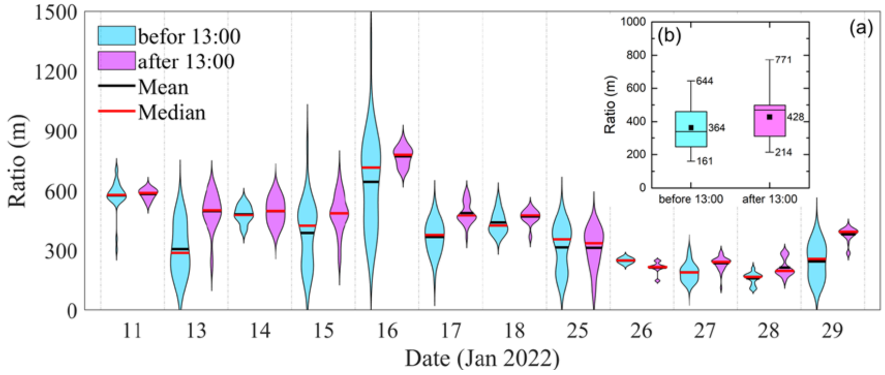

Figure 7. (a) Violin plots of the ratio of TC and NS NO_2 concentrations for each day when observations were available in January 2022, where the data were differentiated between morning (before 13:00 LT) and afternoon (after 13:00LT). (b) The box-whisker plot of the ratio averaged over all observations before and after 13:00 in January 2022. The horizontal lines in the boxes and the top and bottom edges represent the mean and

upper and lower quartile values of the Ratio, the solid square dots represent the median values, and the bars represent the minimum and maximum values.

4 Conclusion and Discussion

Total column and near surface NO_2 data observed during the winter field experiment from Jan 10 to Jan 29, 2022, at the Beijing RADI site were analyzed together with lidar, $PM_{2.5}$ and meteorological data, satellite data, weather maps and air mass trajectories. Based on these observations, the experimental period was sub-dived into three periods: intermittent pollution days, persistent pollution days and clean days. The analysis of the TC and NS NO_2 concentrations shows substantial differences between the first and third period, while during the second period with persistent pollution no TC NO_2 observations were available due to the presence of clouds. During the first period, two episodes with high pollution were identified and analyzed in detail with a focus on the ratio between the variations of the TC and NS NO_2 concentrations and their ratio. The relations between the TC and NS NO_2 concentrations in the morning and in the afternoon, split at 13:00 LT, appear to be significantly different. These differences have been explained in terms of boundary layer dynamics, using lidar data showing the vertical stratification with disconnected boundary layers at different heights in the morning which connected as the boundary layer develops in the afternoon. In addition, the 4-layer NO_2 column concentrations obtained from Pandora show good agreement with the lidar signal in terms of the temporal and vertical variations of the NO_2 concentrations, with differences attributed to the vertical resolution of the Pandora and lidar observations, as well as physical properties of NO_2 and aerosols. From this, together with air mass trajectories, weather maps and TROPOMI satellite observations of the NO_2 spatial distribution, a consistent picture was created showing different source regions for disconnected airmasses arriving at different heights and different times of the day.

Data from the full experimental period, with 12 days for which valid data are available, were analyzed in detail to obtain more insight into the variation of the ratio between the TC and NS NO_2 concentrations. This ratio appears to be overall smaller in the morning

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than in the afternoon, with larger standard deviations. In addition, the ratios and their standard deviations were overall larger during the more polluted episode I than during the relatively clean period III.

Time-continuous remote sensing observations of Pandora were used in this study and the results confirm its possible importance in understanding changes in the distribution of NO_2 in the vertical direction. The NO_2 vertical distribution has been analyzed using less than 3 weeks of observation data, which has some limitations, but the research idea is worthy of reference and promotion. In the future, the implementation of larger-scale experiments in different typical regions and seasons will help to provide further understanding of the ideas presented in this study and improve the shortcomings.

The overall conclusion from this study during a relatively short period of almost 3 weeks in the winter in Beijing is that the variation between the total column and near surface NO_2 concentrations varies with the concentration level and the time of day. In the afternoon the boundary layer is well developed and satellite observations are sensitive to the NS concentrations, whereas in the morning this depends on meteorological conditions. Hence, satellites with an afternoon overpass are capable to measure TC NO_2 which is representative for NS concentrations, whereas observations earlier in the day may not be. This could possibly affect the interpretation of diurnal variations derived from observations using geostationary satellite.

Data availability. Data will be made available on request.

Author contributions. YZ and YW conceived and designed the study. OL processed the Pandora data. YC collected and processed the meteorological data. YL processed the Lidar data. YZ and GL prepared the paper with contributions from all coauthors. Y-XZ and ZL provide project funding.

Competing interests. The authors declare that they have no conflict of interest.

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