ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

INVESTIGATION OF THE CHANGE OF NO_2 POLLUTION DURING THE PANDEMIC PERIOD USING SATELLITE RETRIEVALS IN MARMARA REGION

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSU

MARMARA BÖLGESİNDE UYDU VERİLERİ KULLANILARAK NO_2 KİRLİLİĞİNİN PANDEMİ DÖNEMİNDE DEĞİŞİMİNİN İNCELENMESİ

YÜKSEK LİSANS TEZİ

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"The future is in the sky."
-M. Kemal Atatürk

FOREWORD

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ABBREVIATIONS

NO_x	: Nitrogen Oxides
NO_2	: Nitrogen Dioxide
NO :	: Nitrogen Monoxide
O_3	: Ozone
PM	: Particulate Matter
TROPOMI	: Tropospheric Ozone Monitoring Instrument
TUIK	: Turkish Statistical Institute
WHO	: World Health Organization
Molec	: Molecules
BAL	: Balikesir
BIL	: Bilecik
BUR	: Bursa
EDI	: Edirne
KIR	: Kirklareli
KOC	: Kocaeli
IST	: Istanbul
SAK	: Sakarya
TEK	: Tekirdag
YAL	: Yalova

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INVESTIGATION OF THE CHANGE OF NO_2 POLLUTION DURING THE PANDEMIC PERIOD USING SATELLITE RETRIEVALS IN MARMARA REGION

SUMMARY

Air pollution has been a great problem during the history of mankind with its effects on human health and the environment. Among the major air pollutants, nitrogen oxides (NO_x=NO+NO_2) are still an issue with significant emissions, and their contribution especially on urban areas to ozone (O_3) and secondary particulate matter formation. Satellite-based measurements have been used for monitoring of the air pollutants for obtaining information on the global distribution of these pollutants in the last decade, and their performance was increased in terms of both resolution and data reliability.

In addition to being a leading country in Europe and Asia with its increasing industry and population, Turkey is struggling with air pollution with high ambient levels. Past studies showed that air pollution reaches dangerous concentrations, especially in city centers.

This thesis aims to analyze the NO_2 pollution in the Marmara Region, which is the most populated and developed Region of Turkey, with the help of satellite retrievals and ground-based measurements. The effect of human activities and restrictions on NO_2 during the pandemic period, which is the study time interval, was also examined, and the study showed the effects of urbanization, industrialization, increasing human population, and the NO_2 pollution of these parameters.

A deductive approach was used in the study and Turkey, Marmara Region, and Istanbul province were examined in terms of NO_2 pollution with detailed analyses, respectively. With this aspect of the study, both the high-resolution data technology of the TROPOMI instrument and the technology of measuring large areas were used. These measurements were supported by the ground-based measurements, the relationship between them was examined and the differences were interpreted.

TROPOMI is an instrument onboard ESA's Sentinel-5. TROPOMI NO_2 retrievals obtained from ESA were processed, and gridded monthly NO_2 tropospheric columns were calculated to a uniform spatial distribution.

In this thesis, both satellite and ground-based measurements were investigated for two years: 2019 and 2020. Differences between the examined periods were analyzed and the effect of restrictions during the pandemic period and different urban indicators (such as traffic density or natural gas usage for domestic heating) on NO_2 pollution was examined.

Ground-based measurements were also used for Marmara Region, which are located in provinces of Istanbul, Kocaeli, Bursa, Canakkale, Balikesir, Sakarya, Tekirdag, Yalova, Edirne, Bilecik and Kırklareli. Ground-based measurements were selected according to the overpass time (around local time 13:00) of TROPOMI. Also, the Marmara Region, which is the study area, was divided into 1×1 km^2 grids and satellite retrievals were selected only for the grids which have urban residences and 1 km around them for further comparison with ground-based measurements.

All the data used in the study were eliminated according to the measurement criteria determined by the ESA, the days deemed invalid for comparison (with less than 75%

data) were eliminated, and the data obtained as a result of the process were processed and/or visualized with programming and mapping programs, and possible errors were analyzed and interpreted.

Firstly, national NO_2 pollution levels over Turkey were examined. As a result of the examinations performed using satellite retrievals, Marmara was found to be the most polluted Region of Turkey in terms of NO_2 pollution. The most polluted provinces are Istanbul, Kocaeli, Ankara, and Izmir, and for Marmara Region, those are Istanbul, Kocaeli, Bursa, and Yalova, respectively. It was found that the winter months have noticeably higher values than the summer months of 2019 and 2020 possibly because of domestic heating in period and meteorological factors, and the most polluted month is November 2019 for all of Turkey. In addition, it has been observed that NO_2 pollution in various cities in Turkey, especially in Mugla, during the summer months is equivalent to and sometimes higher than, the crowded provinces due to point sources such as thermal power plants.

When an analysis was made based on districts with the clustering method using monthly averaged measurements, it was seen that the districts of the provinces with dense vehicles and populations such as Istanbul were included in the same cluster. In addition, it has been observed that the central districts of cities with less population have close pollution and show the same seasonal variation. When the same clustering method was performed using ground-based measurements and satellite retrievals separately, it was seen that the ground-based measurements did not show seasonality, and many Regions were found to have high NO_2 pollution levels whereas satellite retrievals were clustered as less polluted.

As a result of the correlation analysis performed using satellite retrievals and ground-based measurements, it was observed that Ground-based measurements of the Marmara Region were not correlated with satellite retrievals. They were measuring lower signals than satellite retrievals in the time intervals when the data was not missing. Especially the low correlation values of the stations in the densely populated areas have revealed that the difference in the NO_2 pollution measurements of the Region is high and that improvements should be made. With the statistical analyses performed, it was observed that the highest rate of change was observed in the Istanbul Region and the NO_2 pollution decreased by 60% for March, April, November, and December months compared to the previous year. When comparing the same months of 2019 and 2020 throughout Turkey decrease rates were found to be decreased in direct proportion as the population and industrialization rates of cities, while increases were seen in some eastern provinces of Turkey such as Mugla and Aydin. It is thought that the most important reason for these increases, which are intense in the winter period, is the decrease of seasonal temperatures.

Both satellite retrievals and ground-based measurements showed elevated concentrations of NO_2 in and around highly populated areas. When the pollution changes of the Marmara Region were examined during the COVID-19 pandemic, the effects of human behavior on pollution were observed, especially in the days of full restriction and in the associated months. Districts grouped by clustering method, from districts with dense industry to districts with high population, were interpreted with the help of these groups and examined in terms of both provincial and urban status during the pandemic period. The study has shown that situations such as domestic heating, a change in the number of vehicles, and the closure of some businesses have caused a visible effect on NO_2 pollution. During the study period, a comparison was made between the pre-pandemic period and the pandemic period for the densely populated cities of Marmara provinces. As a result of the comparison, a decrease in NO_2 pollution was observed in the districts, especially in November and December 2020 (weekend curfew period) compared to November and December 2019. As a result of the calculations, the decrease between 10-20% is proportional to the population.

Lastly, urban indicators and NO_2 pollution in Istanbul were also examined in detail for 2019. As a result of the correlations made with indicators such as population, natural gas use, socio-economic status of the districts, a high correlation was found between NO_2 pollution and population and natural gas use (R = 0.81 and 0.83 respectively), and a moderate correlation between socio-economic score (R = 0.35). The fact that the strong relationship between urban indicators and NO_2 pollution is high in mega cities such as Istanbul results in taking precautions, and making more detailed analyses. As shown in the thesis, Istanbul is the largest province in the whole of Europe in terms of population, urbanization, and traffic, and the study showed the NO_2 pollution that the people of Istanbul are exposed to in daily life under these conditions, district by district. In addition, in this section, the correlation between ground-based measurement and satellite retrievals in Istanbul were examined, and it was understood that the Ground-based measurements had lower levels than satellite retrievals in many districts. These low levels, especially in regions with high population and vehicle traffic, were attributed to the non-representativeness of the ground-based measurements. As a result of the study, the highest NO_2 values in Istanbul were found as 6.44×10^{15} molecules/cm^2 (Gungoren) and 94.12 μg/m^3 (Aksaray) annual average on a monthly basis satellite retrievals and ground stations, respectively. The results showed the extent of NO_2 pollution in Istanbul, proved to be directly related to urban factors, and created an initial analysis for future studies to be repeated in more detail for the future years.

In conclusion, this thesis showed TROPOMI can detect temporal variation of NO_2 pollution over different districts, and the impact of COVID-19 pandemic restrictions over Turkey, specifically in Marmara Region. The results also gave important information about the evaluation and status of ground-based measurements, the relationship between urban indicators and NO_2 pollution, and the changing NO_2 pollution during the pandemic period. The thesis also showed that NO_2 pollution in dense urban areas decreased during the pandemic period with the help of satellite retrievals. The study examined important points in this respect and prepared a basis for future studies and it explained, interpreted, and discussed the seasonal distribution of pollution and the effects of the districts with statistical analyses and spatial distribution of NO_2. This thesis is the first study in terms of applied Region, high-resolution satellite retrievals, and time interval.

MARMARA BÖLGESİNDE UYDU VERİLERİ KULLANILARAK NO_2 KİRLİLİĞİNİN PANDEMİ DÖNEMİNDE DEĞİŞİMİNİN İNCELENMESİ

ÖZET

Hava kirliliği, insan sağlığı ve çevre üzerindeki etkileri ile insanlık tarihi boyunca büyük bir sorun olmuştur. Başlıca hava kirleticileri arasında olan NO_x ($NO+NO_2$), artan emisyon değerleri ve özellikle kentsel alanlarda O_3 ve ikincil partikül madde oluşumuna etkisi yüzünden büyük bir sorun olmaya devam etmektedir. Son on yılda bu kirleticilerin küresel dağılımı hakkında bilgi veren hava kirleticilerinin izlenmesi için uydu verileri kullanılmaya başlanmış ve hem çözünürlük hem de veri güvenilirliği acısından performansları artmıştır. Uydu verilerinin kullanımı oldukça etkili olsa da geliştirilmesi ve tam performans alınması için yer ölçüm istasyonları ile birlikte kullanılmasının daha etkili olduğu görülmüştür.

Türkiye artan sanayisi ve nüfusu ile Avrupa ve Asya kıtalarında ileri gelen bir ülke olmasının yanı sıra yüksek değerlere sahip hava kirliliği ile mücadele etmektedir. Yapılan geçmiş çalışmalar hava kirliliğinin özellikle şehir merkezlerinde tehlikeli konsantrasyonlara ulaştığını göstermekte ve bu hususta yapılan geliştirme çalışmaları devam etmektedir.

Bu tezin amacı, Türkiye'nin en kalabalık ve gelişmiş bölgesi olan Marmara bölgesindeki NO_2 kirliliğini uydu verileri ve yer ölçüm istasyonları yardımıyla analiz etmektir. Çalışma zaman aralığı olan pandemi döneminde insan faaliyetleri ve kısıtlamaların NO_2 üzerindeki etkisi de incelenmiş ayrıca çalışma kentleşme, sanayileşme, artan insan nüfusu ve bu parametrelerin NO_2 kirliliğine etkisini göstermiştir.

Çalışmada tümdengelim yaklaşımı kullanılmış ve sırası ile Türkiye, Marmara Bölgesi ve İstanbul şehri detaylı analizler ile NO_2 kirliliği acısından incelenmiştir. Çalışmada bu yönü ile hem TROPOMI enstrümanının yüksek çözünürlüklü veri teknolojisi hem de geniş alanları ölçebilme teknolojisi kullanılmıştır. Yapılan bu ölçümler, yer ölçüm istasyonu verileri ile desteklenmiş aralarındaki ilişki irdelenmiş ve farklar yorumlanmıştır.

ESA'nın Sentinel-5 uydusunda yer alan ve NO_2 ölçümleri için kullanılabilen bir enstrüman olan TROPOMI verileri ve T.C. Çevre ve Şehircilik Bakanlığı'nın yer ölçüm istasyonlarının mevcut verileri bu çalışmada karşılaştırılmıştır. Tezde 2019 ve 2020 yılları için hem uydu hem de yer ölçüm verileri seçilmiştir. İncelenen zaman periyotları arasındaki farklar analiz edilmiş ve farklı kentsel faktörlerin (pandemi döneminde uygulanan kısıtlamalar gibi) NO_2 kirliliği üzerindeki etkisi incelenmiştir.

Bir bölge ve 11 il için yer ölçüm istasyonu verisi kullanılmıştır. Çalışmada incelenen şehirler İstanbul, Kocaeli, Bursa, Çanakkale, Balıkesir, Sakarya, Tekirdağ, Yalova, Edirne, Bilecik ve Kırklareli'dir. Yer ölçüm verileri bölge için Sentinel-5 uydusunun geçiş saatine (13 :00) göre seçilmiştir. Ayrıca çalışma alanı olan Marmara bölgesi 1×1 km^2'lik gridlere ayrılmış ve uydu verileri kentsel alanlarda NO_2'nin en önemli kaynağının evsel ısınma ve kara araçları olması sebebi ile sadece kentsel konutların bulunduğu ve 1 km civarındaki gridler seçilmiştir.

Çalışmada kullanılan tüm veriler ESA'nın belirlediği ölçüm kriterlerine göre elendikten sonra kıyaslama için geçersiz sayılan günler (%75'ten az veriye sahip) elenmiş ve

eleme işlemi sonucu elde kalan veriler programlama ve haritalandırma programları ile işlenmiş ve/veya görselleştirilmiş ayrıca olası hatalar analiz edilmiş ve yorumlanmıştır.

Uydu verileri kullanılarak yapılan incelemeler sonucunda, Marmara'nın NO_2 acısından Türkiye’nin en kirli bölgesi olduğu ve en kirli illerinin sırasıyla İstanbul, Kocaeli, Bursa ve Yalova olduğu, Tüm Türkiye için ise bu illerin İstanbul, Kocaeli, Ankara ve İzmir olarak sıralandığı tespit edilmiştir. 2019 ve 2020 döneminde kış aylarının evsel ısınma nedeniyle yaz aylarına göre belirgin şekilde daha yüksek değerlere sahip olduğu ve hemen hemen tüm Türkiye için en kirli ayın Kasım 2019 olduğu tespit edilmiştir. Bunun yanı sıra yaz mevsimi aylarında Türkiye’de Muğla basta olmak üzere çeşitli şehirlerde NO_2 kirliliğinin termik santraller gibi noktasal kaynaklar yüzünden kalabalık şehirlere denk hatta zaman zaman daha yüksek olduğu gözlemlenmiştir.

Kümeleme yöntemi ile ilçe bazında bir analiz yapıldığı zaman görülmüştür ki İstanbul gibi yoğun araç ve nüfusa sahip şehirlerin ilçeleri aynı kümeye dahil olmuştur. Bunun yanı sıra daha az nüfusa sahip şehirlerin merkez ilçelerinde yakın kirliliğe sahip olduğu ve aynı mevsimsel değişimi gösterdiği gözlemlenmiştir. Uydu verileri ve yer ölçüm istasyonları arasında yapılan korelasyonlar sonucunda Marmara Bölgesi’nin yer ölçüm istasyonlarının uydu verileri ile korele olmadığı bunun yanında verinin eksik olmadığı zaman aralıklarında çok düşük değerler ölçtüğü gözlemlenmiştir. Aynı kümeleme yöntemi yer ölçüm istasyonları ve uydu verileri ile ayrı ayrı yapıldığı zaman yer ölçüm istasyonlarının mevsimsellik göstermediği bunun yanı sıra uydu verilerinde yüksek NO_2 kirliliğine sahip olduğu görülen pek çok bölgenin az kirli olarak kümelendiği görülmüştür. Özellikle yoğun nüfusun yasadığı bölgelerdeki istasyonların düşük korelasyon değerlerine sahip olması bölgenin NO_2 kirliliği ölçümlerinde hata payının yüksek olduğu ve geliştirmelerin yapılması gerektiği sonucunu ortaya çıkarmıştır.

Yapılan istatistiksel analizler ile Türkiye genelinde yapılan 2019 ve 2020 yılları aynı aylarının kıyaslanmasında en yüksek değişim oranının İstanbul bölgesinde görüldüğü ve NO_2 kirliliğinin bazı aylarda (Mart, Nisan, Kasım ve Aralık) bir önceki seneye göre %60 düştüğü gözlemlenmiştir. Bu düşüş oranları şehirlerin nüfus ve sanayileşme oranları düştükçe doğru orantılı olarak azalmakta Türkiye’nin bazı doğu illerinde ise artışlar görülmektedir. Kış döneminde yoğun olan bu artışların en önemli sebebinin mevsime bağlı sıcaklık derecelerindeki düşüş olduğu düşünülmüştür.

Hem uydu hem de yer ölçümleri, yoğun nüfuslu alanlarda ve çevresinde yüksek NO_2 konsantrasyonları göstermiştir. Marmara Bölgesi’nin COVID-19 pandemisi sırasında kirlilik değişimleri incelendiği zaman özellikle tam kısıtlama olan günlerde ve takip eden aylarda insan davranışlarınım kirlilik üzerinde etkileri görülmüştür. Yoğun sanayiye sahip ilçelerden yüksek popülasyona sahip ilçelere kadar kümeleme yöntemi ile gruplandırılan ilçeler bu gruplar yardımı ile yorumlanmış ve hem il hem ilce değişimi Pandemi döneminde incelenmiştir. Çalışma göstermiştir ki evsel ısınma, araç kullanım sayılarının artması, bazı işletmelerin kapatılması gibi durumlar NO_2 kirliliğine gözle görülebilir etkiye sebep olmuştur. Çalışma suresinde Marmara İllerinin yoğun nüfusa sahip şehirleri için pandemi öncesi donem ve pandemi donemi ayları arasında karşılaştırma yapılmıştır. Karşılaştırma sonucunda ilçelerin özellikle 2020 Kasım ve Aralık aylarında (hafta sonu sokağa çıkma yasağı olan donem) 2019 yılı Kasım ve Aralık aylarına göre NO_2 kirliliğinde düşüş gözlemlenmiştir. Aynı düşüş oranları ilk kapanma donemi olan Mart ve Nisan donemi içinde gözlemlenmiş olsa da özellikle evsel ısınmanın önemli bir kaynak olduğu kış aylarında yapılan incelemeler pandemi dönemi ve NO_2 kirliliği hakkında daha detaylı sonuçlar vermiştir. Yapılan hesaplamalar sonucunda %10-20 arasında düşüş pek çok ilçede nüfus ile orantılıdır.

Özellikle ilce bazında yapılan incelemelerde yoğun nüfusun yanında ulaşım ve sanayi merkezleri olarak bilinen (örneğin İstanbul Kadıköy ve Kocaeli Dilovası) ilçelerde pandemi nedeni ile görülen yüksek düşüş oranları kırsal veya düşük nüfuslu kentsel bölgelerde gözlemlenmemiş hatta bazı aylarda artışlar görülmüştür.

Çalışmada ayrıca 2019 yılı için İstanbul kentindeki kentsel faktörler ve NO_2 kirliliği de incelenmiştir. İlçelerin nüfus, doğalgaz kullanımı, sosyo-ekonomik durumu gibi göstergelerle yapılan korelasyonlar sonucunda NO_2 kirliliği ile nüfus ve doğalgaz kullanımı arasında (sırasıyla R = 0.81 ve 0.83) ve sosyo-ekonomik puan arasında (R = 0.35) yüksek korelasyonlar bulunmuştur. Kentsel indikatörler ve NO_2 kirliliği arasındaki güçlü ilişkinin İstanbul gibi mega şehirlerde yüksek olarak görülmesi, önlem alınması ve daha detaylı analizlerin yapılması sonucunu çıkarmaktadır. Tezde gösterildiği gibi İstanbul gerek nüfus gerek kentleşme gerekse trafik acısından Avrupa'da en büyük şehirdir ve çalışma bu koşullar altında İstanbul halkının gündelik hayatta maruz kaldığı NO_2 kirliliğini ilce bazında göstermiştir. Ayrıca bu bölümde İstanbul'daki yer ölçümü ile uydu verileri arasındaki korelasyon incelenmiş ve birçok ilçede yer ölçüm verilerinin uydu verilerine göre daha düşük değerlere sahip olduğu anlaşılmıştır. Bu düşük değerler özellikle nüfus ve araç trafiğinin yoğun olduğu bölgelerde yer ölçüm istasyonlarının hatası olarak değerlendirilmiştir. Çalışma sonucunda İstanbul'da en yüksek NO_2 değerleri ay bazında yıllık ortalama cinsinden uydu verisi ve yer ölçüm istasyonları için sırasıyla 6.44×10^{15} molekül/cm^2 (Güngören) ve 94.12 µg/m^3 (Aksaray) olarak bulunmuştur. Sonuçlar İstanbul'un NO_2 kirliliğinin boyutlarını gösterdiği gibi kentsel faktörler ile doğrudan ilişkisi olduğunu kanıtlamış ve gelecek çalışmaların daha detaylı tekrarlanması için altyapı oluşturmuştur.

Sonuç olarak, bu tez TROPOMI'nin Türkiye'de NO_2 kirliliğini tespit edebildiğini ve zaman ile değişiminin hem uydu hem yer ölçümü istasyonu analizleri ile göstermiştir. Sonuçlar ayrıca yer ölçüm istasyonlarının durumu hakkında bilgi vermiştir. Tez ayrıca yoğun kentsel bölgelerin pandemi döneminde NO_2 kirliliğinin azaldığını uydu verileri yardımı ile göstermiştir. Ayrıca kirliliğin mevsimsel dağılımı ve ilçelerin etkilenme durumlarını istatistiksel analizler ve görseller ile açıklanmış, yorumlanmış ve tartışılmıştır. Çalışma bu açıdan önemli noktaları irdelemiş ve gelecek çalışmalar için altyapı hazırlamıştır. Kentsel göstergeler ile NO_2 kirliliği arasındaki ilişki ve pandemi döneminde değişen NO_2 kirliliği hakkında önemli bilgiler sunan bu tez, uygulanan bölge, yüksek çözünürlüklü veriler ve zaman aralığı acısından yapılmış ilk çalışmadır.

1. INTRODUCTION

Air pollution has been a big problem for human beings, especially since the industrial revolution. It is seen as the main environmental factor of many health problems (lung cancer, asthma, respiratory distress, etc.) and millions of people get sick or die every year because of air pollution. Due to the global economy and globalization, air pollution is now a problem not only for developed countries but also for the whole world (WHO, 2016).

Access to clean air is a basic human right (WHO, 2021). The Organization for Economic Cooperation and Development (OECD, 2021) and the World Health Organization (WHO rank air pollution among environmental problems as the leading cause of premature death and have concluded that by reducing air pollution since 2014, countries can reduce the burden of disease to can alleviate the benefits of both economic and public health (WHO, 2019).

Ozone (O_3), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), sulfur dioxide (SO_2), and volatile organic compounds (VOCs) have been known as major air pollutants (WHO, 2015). With developing new technologies for combustion and industrial processes along with the treatment of air pollutants, significant improvement of air quality is observed. Yet NO_x is still an important issue for the environment because of transportation and non-industrial sources. NO_x is also important because of their reactions in the atmosphere that cause secondary pollutants such as O_3 and secondary PM.

The year 2020 was spent against the COVID-19 virus, which will be remembered as a disaster for the whole world. But the pandemic period has also given us a chance to understand the changing human habits and the impact of these changes on air pollution levels.

Remote sensing techniques were used mostly in geosciences and meteorology. However, in the last decade studies which used remote sensing for analyzing and understanding air pollution have been increased. NO_2, CO, SO_2, PM, CH_4, and O_3 can currently be monitored by instruments on the satellites that allow global coverages. Instruments on satellites provides great convenience in understanding and analyzing the air pollution levels on a global scale with better coverage than ground-based monitoring networks.

1.1 Aim and Scope

This thesis aims to analyze and interpret the NO_2 pollution in urban areas, investigate the impact of urban parameters on NO_2 pollution with a specific focus on COVID-19 pandemic period. The study was conducted in the Marmara Region, which is the most populated, developed, and industrialized Region of Turkey, and the time interval before and during the COVID-19 pandemic was chosen. In the study, the effect of the restrictions imposed during the pandemic period and the change of daily human routines on NO_2 pollution were examined.

NO_2 tropospheric columns are related to NO_x emissions because of the short lifetime of NO_x and this provides an opportunity to have information about the nearby emissions. Similar studies have been carried out in many Regions, especially in the USA, China, and Europe. In particular, there were several studies investigated the change in pollution levels using satellite retrievals and focused on the pandemic period. However, the study period and the instrument used are the first for the Marmara Region where this study was conducted.

In this context, NO_2 pollution was analyzed with satellite retrievals as well as additional parameters such as ground-based measurements from air pollution monitoring stations, population, natural gas used for domestic heating, and the results were discussed.

This thesis is composed of three research parts. In the first part, the NO_2 pollution of the whole of Turkey was interpreted with satellite retrievals and ground-based observations. In the second part, the NO_2 pollution of the Marmara Region during the pandemic period was examined extensively with ground-based measurement and satellite retrievals, and in the last part, the relationship between the NO_2 pollution in Istanbul using ground-based measurements, satellite retrievals and urban indicators was examined on district level.

2. BACKGROUND INFORMATION

Air pollution is defined by EPA as "one or more chemicals or substances in high enough concentrations in the air to harm humans, other animals, vegetation, or materials". Such chemicals (such as ozone, carbon monoxide, nitrogen dioxide, particulate matter, sulfur dioxide) are known as major criteria air pollutants or physical conditions (such as excess heat or noise) (EPA, 2017).

2.1 COVID-19 Pandemic

On March 11, 2020, the WHO evaluated coronavirus disease (COVID-19) as a public health emergency, and the pandemic period began worldwide (WHO Guideline, 2021). The first case of COVID-19 was announced in Turkey on March 11, 2020, which is the same date as of 2021, the number of cases is over 360 million in the world and over 11 million in Turkey (WHO-C, 2021).

2.2 NO_x

Oxidized Nitrogen species are nitrogen monoxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), dinitrogen trioxide (N_2O_3), dinitrogen tetroxide (N_2O_5), dinitrogen pentoxide (N_2O_5) (Uyar, 2006). NO and NO_2 are known as NO_x (NO_X = NO+NO_2) together (Cardu and Baica 2005).

Main sources of nitrogen oxides, are combustion processes, in addition every process which use air as oxygen source for combustion generate NO_x because approximately %78 of the air taken is nitrogen. The sources can be examined in two groups; anthropogenic and natural sources.

Natural sources are;

- Lighting,
- Forest fires,
- Microbiological process

Anthropogenic main sources of NO_x are;

- Transportation,

- Industrial process,
    - Energy production (most using with natural gas),
    - Biomass burning,
    - Domestic heating.

NO_x formed in combustion processes either due to thermal fixation of atmospheric nitrogen in the combustion air or to the conversion of chemically bound nitrogen in the fuel. For most external fossil fuel combustion systems, over 95 percent of the emitted NO_x is in the form of NO (EPA, 1995), but NO quickly oxidized to NO_2 after released to the atmosphere.

NO_x affects human and environmental health like other air pollutants. It causes acid rains with low pH levels and it can be caused damage to materials, plants, and the aquatic ecosystem. Nitrogen monoxides are not dangerous because of low concentrations in the atmosphere. However, nitrogen dioxides have serious effects on human health. Respiratory irritation, headaches, lung diseases eye irritations and loss of appetite are well-known health effects. In addition, NO_x play a key role in tropospheric ozone formation with VOCs which causes asthma and several respiratory diseases. The most vulnerable groups are young children, asthmatics, as well as individuals with chronic bronchitis (UNEP, 2013).

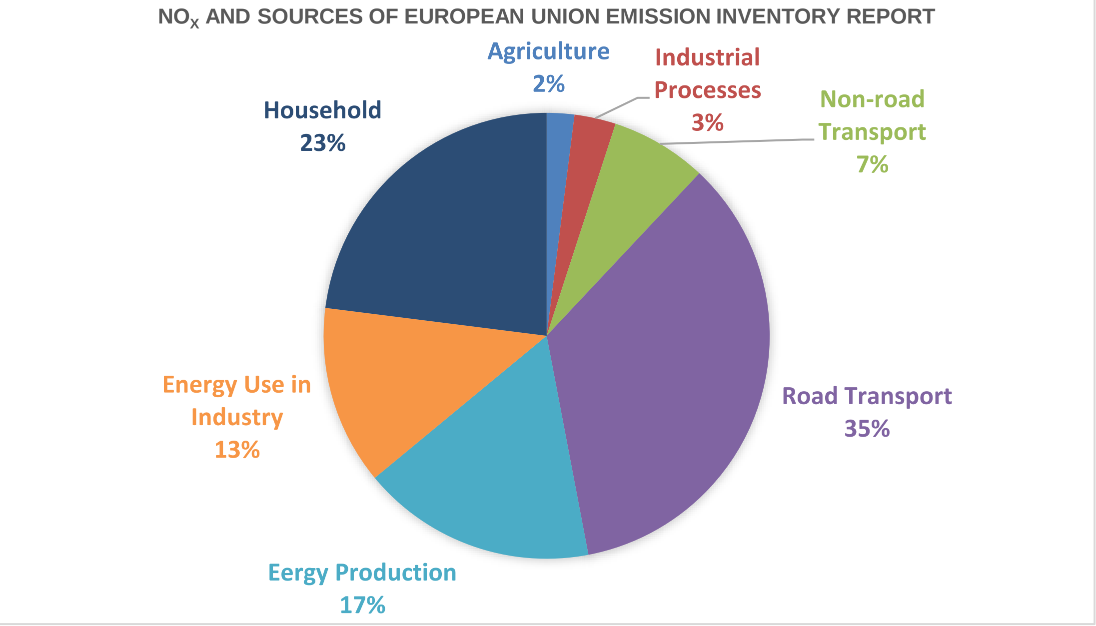

Figure 2.1 : NO_x and sources of European Union emission inventory report 1990–2018 under the UNECE (adapted from EU, 2018).

2.3 Satellite and Remote Sensing

"Remote sensing is the practice of driving information about the earth's land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation in one or more Regions of the electromagnetic spectrum, reflected or emitted from the earth's surface without direct contact" (Campbell, 2011). Satellite instruments are the most common and effective way in some air pollution measurements. Satellite retrievals enable measurements over an area at a time to give information about the conditions remotely. With this method, large areas can be measured in a very short time (whole world coverage in a day) interval and provide continuous spatial coverage unlike ground-based measurements.

The use of satellite systems to evaluate air pollution on a global scale and to create action plans has been a preferred method, especially in recent years. Even though the consistency rates of ground-measurement stations are high, it is seen that they are not sufficient for wide range measurements of air pollution, which is the fastest increasing pollution in the world, when considering a limited area and installation costs. With the developing technology, satellites that can measure many types of pollutants throughout the entire atmosphere can measure the whole world in a short time like 24 hours, especially on clear days. NO_2 measurements in the troposphere started with the Global Ozone Monitoring Experiment (GOME) instrument, which started to work in 1995, and in the following years, SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIMACHY) in 2002, Ozone Monitoring Instrument (OMI) in 2004, Global Ozone Monitoring Experiment-2 (GOME-2) in 2006 and last but not the least Tropospheric Monitoring Instrument (TROPOM)I in 2019 continued to work in the same order. Satellite measurements, which started with 30×60 km^2 as spatial resolution with GOME, developed up to 7×3.5 km^2 resolution with TROPOMI.

The instrument to be used in the study, TROPOMI, (Figure 2.2 bottom) is the air pollution measurement instrument on the Copernicus Sentinel-5 (Figure 2.2 top) satellite of the European Space Agency (ESA), which was sent to space on 13 November 2017. It has the highest spatial resolution (7×3.5 km^2 and the spatial resolution has been further increased to 3.5×5.6 km^2 starting from 6 August 2019) among the sun synchronous remote sensing instruments used for air pollution measurement in today's technology (J.P. et al, 2012; Rozemeijer and Kleipool, 2019). The fact that it can measure many pollutants such as NO_2, SO_2, HCHO, CO, CH_4 and

O_3 with high resolution globally makes the instrument the most useful remote sensing instrument available in the recent days.

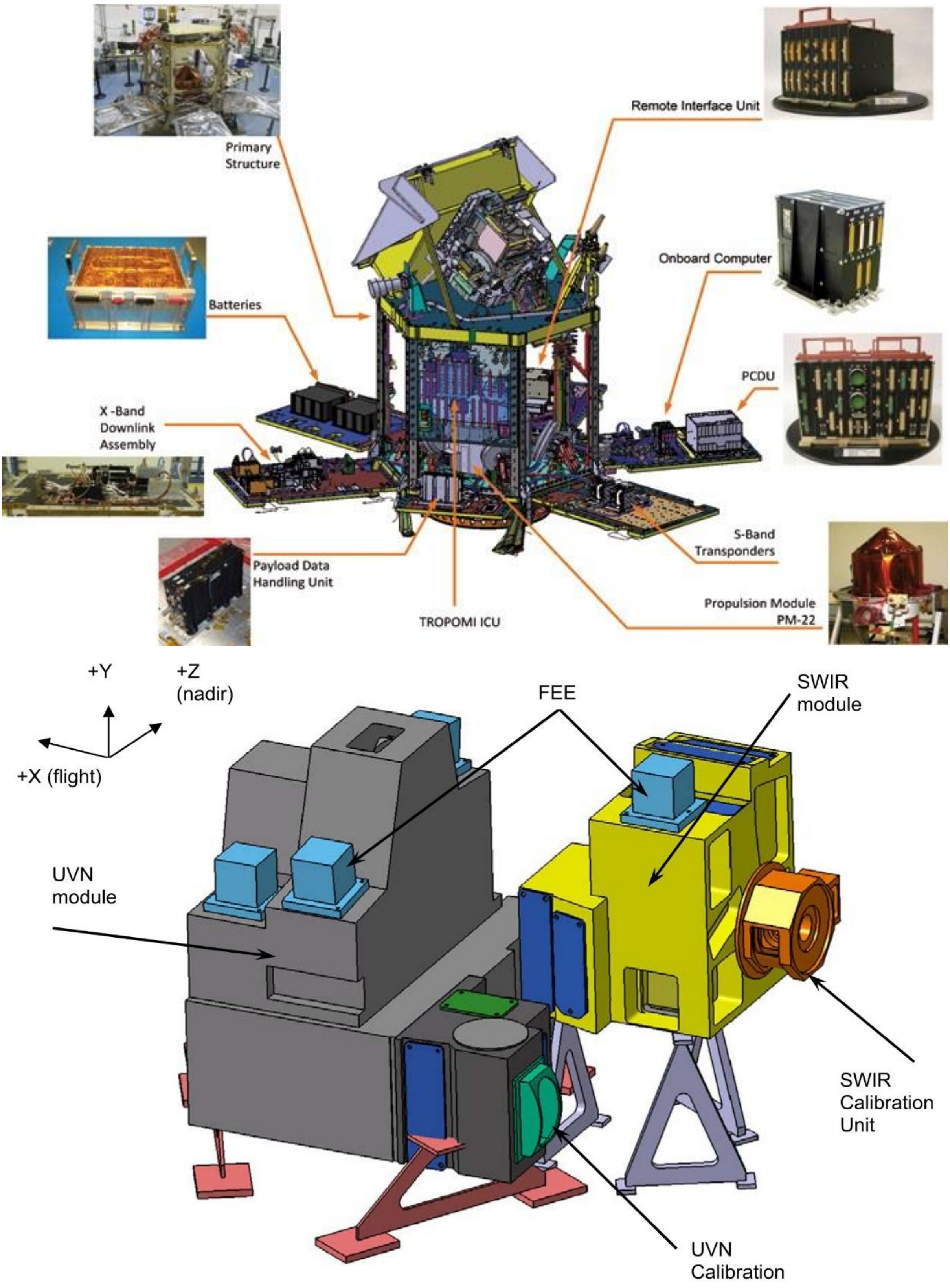

Figure 2.2 : Sentinel-5 Satellite (top) and TROPOMI instrument (bottom). (adapted from ESA, 2018)

2.4 Ground NO_x Measurements

Ground-based measurements are often preferred by countries for measurements of NO_x along with other criteria pollutants. The biggest disadvantage of ground-based measurements, which are generally used in important and long-term projects such as modeling studies, is the limited area they can measure. Ultraviolet method (UV), electrochemical cell method, chemiluminescence method, Fourier Transform Infrared Spectroscopy (FTIR), and nitrogen dioxide absorption (SALZMAN) method are used technologies as direct measurement methods to determine nitrogen oxides. Most of the ground-based measurements use chemiluminescence method. Chemiluminescence analyzers, which measure NO_2 as the difference between alternating measurements of nitric oxide (NO) and nitrogen oxides ($NO_x \equiv NO+NO_2$) (EPA, 2017). This method allows to measure NO_2 with characteristic chemiluminescence that allows to measure NO and NO_2 separately.

2.5 Geographic Information Systems

Burrough and McDonnell (1998) have defined Geographic Information System (GIS) as “a powerful set of tools for collecting, storing, and retrieving, before transforming and displaying spatial data from the real world for a particular set of purposes”. ArcGIS is the most used GIS software all over the world and uses Python which is highly developed modeling and programming language. (Url-2; ESRI, 2021)

In GIS, the real world is represented as two data elements: geographic and attribute. The geographical elements can be accepted as a reference of attribute elements (Figure 2.3). There are also two ways to store vectors and raster. The most important thing about map cartography is determining the projections and coordinate systems. In general, ideas about GIS can be divided into three different areas: map, database, and spatial analysis view. In the map view, each dataset is represented as a layer or theme and new featured maps are created using the old map data.

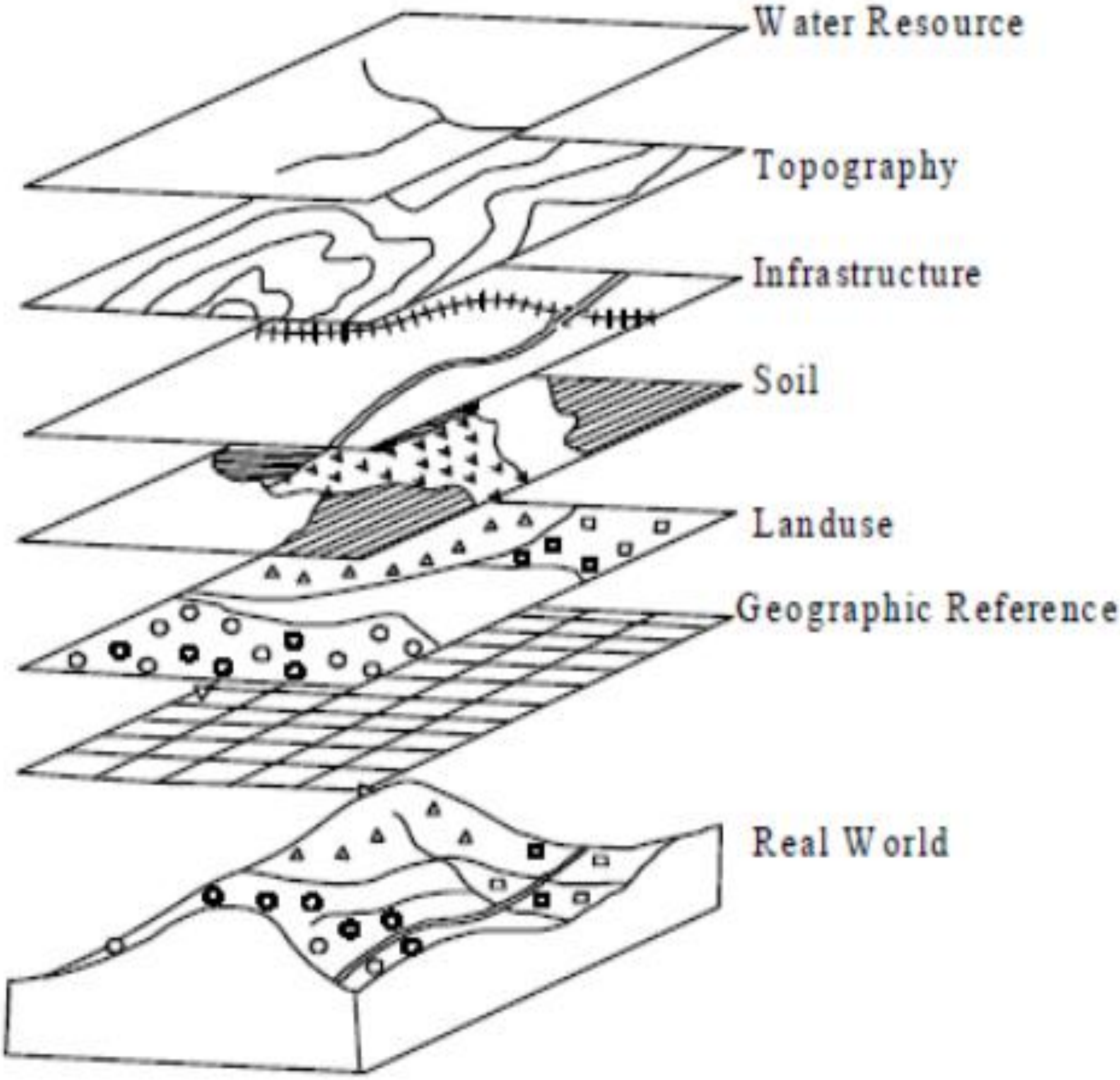

Figure 2.3 : Real world and its symbolization in ArcGIS (adapted from Burrough, 1998)

3. LITERATURE REVIEW

Before TROPOMI, remote sensing method and NO_2 measurements were performed with various instruments such as OMI, GOME-2, and SCIAMACHY. Thus, there have been important studies where other instruments were used.

Study in China, used SCIAMACHY, GOME-2, and OMI tropospheric NO_2 retrievals to evaluate changes in emissions of NO_x from October 2004 to February 2010, identifying the impacts of the economic downturn in China. Emissions decreased, close to the reduction of 18% in NO_x emissions from thermal power generation that occurred over the same interval (Lin et al, 2012). Among these three instruments, OMI stands out with its high resolution, for changes in emission levels on the scale months due to driving forces have been observed in a study, and OMI retrievals indicated reductions of about 40% in associated emissions of NO_x in Beijing at the time of Sino-African Summit in November 2006 due to traffic limitations (Wang et al, 2007).

A study using SCIAMACHY tropospheric NO_2 columns for three different types of regions: urban, rural, and rural-point and compared these Regions for tropospheric NO_2 column magnitudes and weekly profiles and observed that rural Regions did not show any weekly pattern however, in urban areas, the model revealed a certain pattern with satellite retrievals (Kaynak et al, 2009).

Remote sensing instruments have always been important in measuring large-scale Regions and significant time intervals. A study during 2008 Olympic and Paralympic Games in Beijing (8 August-17 September 2008) used tropospheric NO_2 column measurements from GOME-2 and OMI. They compared these retrievals against simulations from the regional chemistry transport model CHIMERE, based on an emission inventory, and found a reduction of approximately 60% of NO_2 concentrations during these events (Mijling et al, 2009). A similar study in China concentrated on the specific episode in Beijing, and found that satellite measurements over Beijing between July and September showed 43% reductions of tropospheric NO_2 column compared to the past three years (Witte et al, 2009). Another study observed the changes of OMI NO_2 vertical tropospheric columns over Europe during

2004-2009. They found significant negative changes in areas with large anthropogenic sources over Western Europe (Zhou et al, 2012).

After ESA announced Sentinel-5 and TROPOMI, the first years of the studies on TROPOMI (2012) were limited and generally included theoretical information about what the instrument could do (Butz et al, 2012; Veefkind et al, 2012).

Using TROPOMI satellite retrievals following important pollutants can be monitored: NO_2, SO_2, CO, CH_4, formaldehyde, and particulate matter (Pardini et al, 2018; Xu et al, 2018; Du et al, 2018; Nabavi et al, 2018; Goronoff et al, 2019; Lin et al, 2019; Goldberg et al, 2019). Also, parameters that other satellites cannot measure, such as the problems caused by UV rays, have begun to be investigated with TROPOMI (Fujinava et al, 2019).

The studies are spread over very wide time intervals, especially when NO_2 is in question. Especially in studies conducted in China, research time intervals such as the last 30 years are observed (Ito et al, 2019). The study areas of studies using TROPOMI on NO_2 can vary greatly. Thanks to TROPOMI, which provides high-resolution measurements, analysis of an entire country or even a continent can be performed, while analysis of cities and even districts can be performed (Xue et al, 2020; Beloconi et al, 2020; Gao et al, 2020). Also, studies that only investigate specific areas like large point sources, TROPOMI retrievals showed high correlation values in studies conducted with large point sources such as natural gas sources and thermal power plants (Maasakkers et al, 2021; Saw et al, 2021; Hakkarainen et al, 2021).

Ground-based measurements, meteorological measurements, or air quality models were used in some studies (Bassani et al, 2021; Wyche et al, 2020; Solberg et al, 2021; Griffin et al, 2020). A study was conducted in the US; besides satellite retrievals, mobile device measurements were used for tracking and analysis of people's movements (Straka et al, 2021). As mentioned, the fact that TROPOMI being high-resolution and powerful has enabled both small cities (Rosu et al, 2021) and large-scale analysis to cover the entire continent (Vîrghileanu et al, 2021). The support of remote sensing measurements with ground-based measurement and air quality models, which is an integrated way of assessing air pollution, has also taken place in many studies and TROPOMI retrievals has contributed significantly with its high-resolution data (Liu 2021; Cui et al, 2021; Johson et al, 2021; Dumka et al, 2020; Wang et al, 2021). For statistical analysis, TROPOMI retrievals were used on a global scale to understand the hot points for NO_2 pollution using several statistic methods, and the study showed a global tree-based model for NO_2 (which was generated with a high-resolution TROPOMI dataset) obtained similar accuracy to national models but higher than traditional linear-based regressions which only used ground-based measurement s at day time. The study said TROPOMI datasets ranked as one of the most important variables in the statistics about air pollution (Lu et al, 2020).

Recently, the remote sensing instrument used in all of the studies was TROPOMI, but to compare the data obtained, evaluation and comparison with another remote sensing instrument (for example OMI) were also performed (Wang et al, 2021). Another study that used previous instruments to measure PM such as MODIS, was used in a study on desert dust in China and and it was found that the pollution was up to 1500 $\mu g/m^3$ in some cities (Filonchyk, 2022).

TROPOMI retrievals were also used to investigate and try to find the connection between tropospheric NO_2 over United Arab Emirates (UAE) and population. Results showed between UAE's most populated cities and NO_2 are highly correlated (R^2 = 0.838) and air quality index of UAE's ground-based measurement of air pollution supported this relation around 70% (Bhatkar et al, 2020). Similarly, much more grand scale research examined the US, China, and India (the three most populated countries in the world) and Europe. The correlation of OMI NO_2 retrievals with population is significant for the three countries and one continent: United States (R=0.71), China (R=0.69), India (R=0.59), and Europe (R=0.67), (Lamsal et al, 2003).

Another recent study in India which is a growing third world country like Turkey showed Socioeconomic Status (SES) and NO_2 pollution had a relationship (R^2 = 0.56) with using Land Use Regression (LUR) / kriging model (Amruta et al, 2020). A global study which explained 16 years of NO_2 pollution and the World's economic relationship (including extreme events like COVID-19 lockdown) with using Principal Component Analysis (PCA) and total variability of the personalized series, and 40% of the variability in this mode can be attributed to the economy, especially for the US and China. However, the study also indicated there were other indicators of NO_2 pollution such as traffic, meteorology, and urban habits (Andrey et al, 2021).

Especially in the last year, studies have been carried out in many Regions using TROPOMI regarding the reduction of air pollutants during the COVID-19 pandemic period. The period focused on in these studies is the time intervals with the COVID-19 pandemic and related restrictions. Although studies generally focus on the NO_2 measurement, there are also studies on pollutants such as SO_2, HCHO, and CO (Cheng et al, 2020; Sun et al, 2021; Masoud et al, 2021). In the studies, it has been analyzed with satellite retrievals that there are decreases in pollutants in various

Regions such as the US, China, Europe, Japan, Iraq, especially in the Regions where there are restrictions such as curfew due to the COVID-19 pandemic, especially in the densely populated areas (Bhishma et al, 2021; Bassim et al, 2021; Bassani et al, 2021; Bo et al, 2020; Henry et al, 2020; Guanyu et al, 2020; Otmani et al, 2020; Ding et al, 2020; Vadrevu et al, 2020; Naeger et al, 2020; Goldberg et al, 2020; Cerosimo et al, 2020; Muhammad et al, 2020; Dutheil et al, 2020; Corlett et al, 2020; Selvam et al, 2020).

In the study conducted for 20 cities, decreases in air pollution were observed during the pandemic period, when vehicle traffic, especially PM and NO_2, decreased. (Sannigrahi et al, 2021). In another study conducted in Spain, it was found that the relationship between O_3 and NO_2 increased visibly during the pandemic period using TROPOMI retrievals (Veld et al, 2021). TROPOMI retrievals were used to understand NO_2 pollution changes and their relationship with ground-based measurements over China, study showed 25% of the population of China were lived areas that exceed NO_2 limit values (40 $\mu g/m^3$) even in the COVID-19 pandemic which is the lowest emission time in the whole two years for China. Also, the study found that TROPOMI retrievals and China's NO_2 ground-based measurements were correlated 85% (Fan et al, 2021). Study in 2020 was used TROPOMI retrievals for the same COVID-19 timeline but in different cities. The study showed in 2020 for the US (New York and Boston) and France (Milan, and Paris) NO_2 levels decreased associated with the pandemic (8-19%) but most importantly study showed in highly developed urban areas, policies must be changed in terms of environment, society and economic-growth because of the air pollution like NO_2 may decrease because of the pandemic, but for a long term, it is still a problem especially highly crowded and economically strong urban areas (Bar et al, 2020).

As can be understood from the literature, TROPOMI and all other remote sensing instruments have been used for the study of air pollution, from province to continent levels, from daily or weekly studies to decade-long studies. In studies, only satellite receptions can be used, as well as in very comprehensive multiple models. Satellite retrievals have proven their quality many times, both in terms of their correlations with other data and its consistency.

In this study, satellite retrievals were used to examine the NO_2 pollution change in the Marmara Region (Turkey) during the pandemic period. Although there are similar studies within the scope of the reviewed literature in different regions, there is not such a high-resolution study for Turkey in general or for a specific region.

4. METHODOLOGY

The methodology used in this thesis is summarized into five different parts. The following sections describe the study area, time interval, processing of satellite retrievals, ground-based measurements, and statistical analysis, respectively.

4.1 Study Area

The Marmara Region is the most developed and most populated Region of Turkey. The Region is located in the westernmost part of Turkey and has a border with Bulgaria and Greece via Edirne, and a maritime border with Greece via Canakkale. There are eleven cities in the region: Balikesir, Bilecik, Bursa, Canakkale, Edirne, Istanbul, Kocaeli, Tekirdag, Sakarya, Yalova. The Region has more than 25 million people.

Marmara provinces generally have a central structure and the majority of the population live in the central districts. Although most of the cities are classified as industrial cities, there are cities such as Tekirdag, where both industry and agriculture are seen. Undoubtedly, the largest and most important province of the Region is Istanbul, the most populated province in Turkey and Europe. With a population of more than 15 million, Istanbul contains 20% of Turkey's population (Figure 4.2). Unlike other Marmara provinces, Istanbul has more than one center. Istanbul, which consists of two sides, Anatolian and European, has three bridges connecting these two sides and over the Bosphorus Strait. In Istanbul, which has a dense population in almost every Region, the densest population is around the shores of the Marmara Sea and the Bosphorus. In addition, Turkey's largest industrial cities such as Kocaeli and Bursa are in this Region. The Marmara Region has the Marmara Sea, which is surrounded by the cities of Marmara and two straits connecting the sea to other large bodies of water (Figure 4.1), the Dardanelles and the Bosphorus, are open to international maritime traffic, and the Bosphorus, in particular, is exposed to heavy traffic with domestic and international trade ships. Marmara Region, which was known to use intense coal for domestic heating before 1990, uses natural gas at a rate of 60-70% today. In addition, there are many thermal power plants in the Region, especially in Canakkale, that produce electricity with both natural gas and coal. In the Marmara

Region, where every province has at least one industrial zone, the air pollution caused by this need has affected almost the entire Region in the Region where energy production and consumption are the most important among the needs. This information becomes more important when it is considered that NO_2 pollution can occur from a combustion reaction with any oxygen.

Although the plans made were to keep the industrial zones outside the province, the rapidly increasing population and intense industrial demand disabled this plan. Today, it has a medium-large level of industry in the vicinity of the densely populated Marmara district (For example, Kocaeli Gebze or Tekirdag Corlu).

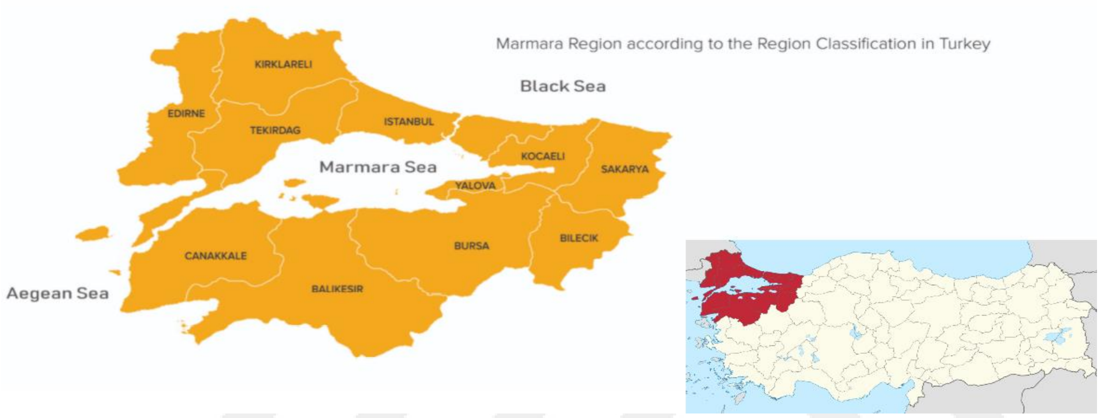

Figure 4.1 : Study area Turkey (right) and Marmara Region (left).

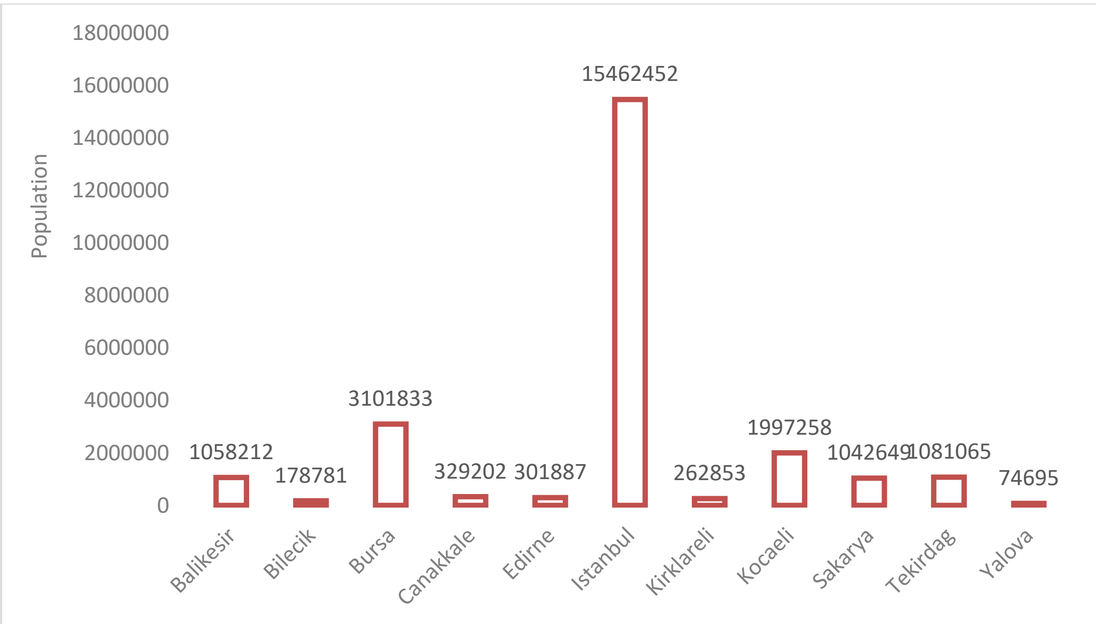

Figure 4.2 : Marmara Region’s provinces populations (TUIK, 2021)

4.2 Timeline

As it is known, 2020 was a difficult, sad, and tiring year when the COVID-19 virus captured the whole world. The virus, which started to spread from the Wuhan Region of China, quickly spread to the whole world through the international people infected with the virus. Although the virus-contaminated areas started to be closed to take urgent measures, especially in China, this measure could not prevent the global spread of the virus. After the COVID-19 virus, the first case of which was announced in Turkey on March 11, 2020, precautions were taken quickly. However, these precautions were insufficient, because it is difficult to implement mass social distancing in a country like Turkey with densely populated cities. Following the logarithmic and extraordinary increases in the number of people infected with the virus, Turkey started to restrict by following the warnings set by the WHO. The process, which first started by restricting the citizens over the age of 65 and under the age of 18 from going out, then continued with public transportation restrictions, remote home-office working in government institutions, remote education in schools, and finally curfews across the country. These restrictions, which were applied intermittently throughout the March-June 2020 period, were removed in mid-June due to the decrease in the cases and the provision of summer tourism. The only precaution taken during this period was the obligation to wear masks and social distance in social areas such as restaurants. However, after these measures being insufficient and the rapid increase in the number of cases (Figure 4.4), Turkey entered a period of intense restriction in the middle of November 2020. In Figure 4.3, the progress of the pandemic period for 2020 is given. The value “1” represents the days when there are no restrictions, the value "0.5" represents the days when only temporary measures are taken (reduction of the working hours in government buildings, restrictions on public transport, etc.) and the value “0” represents the days with a curfew.

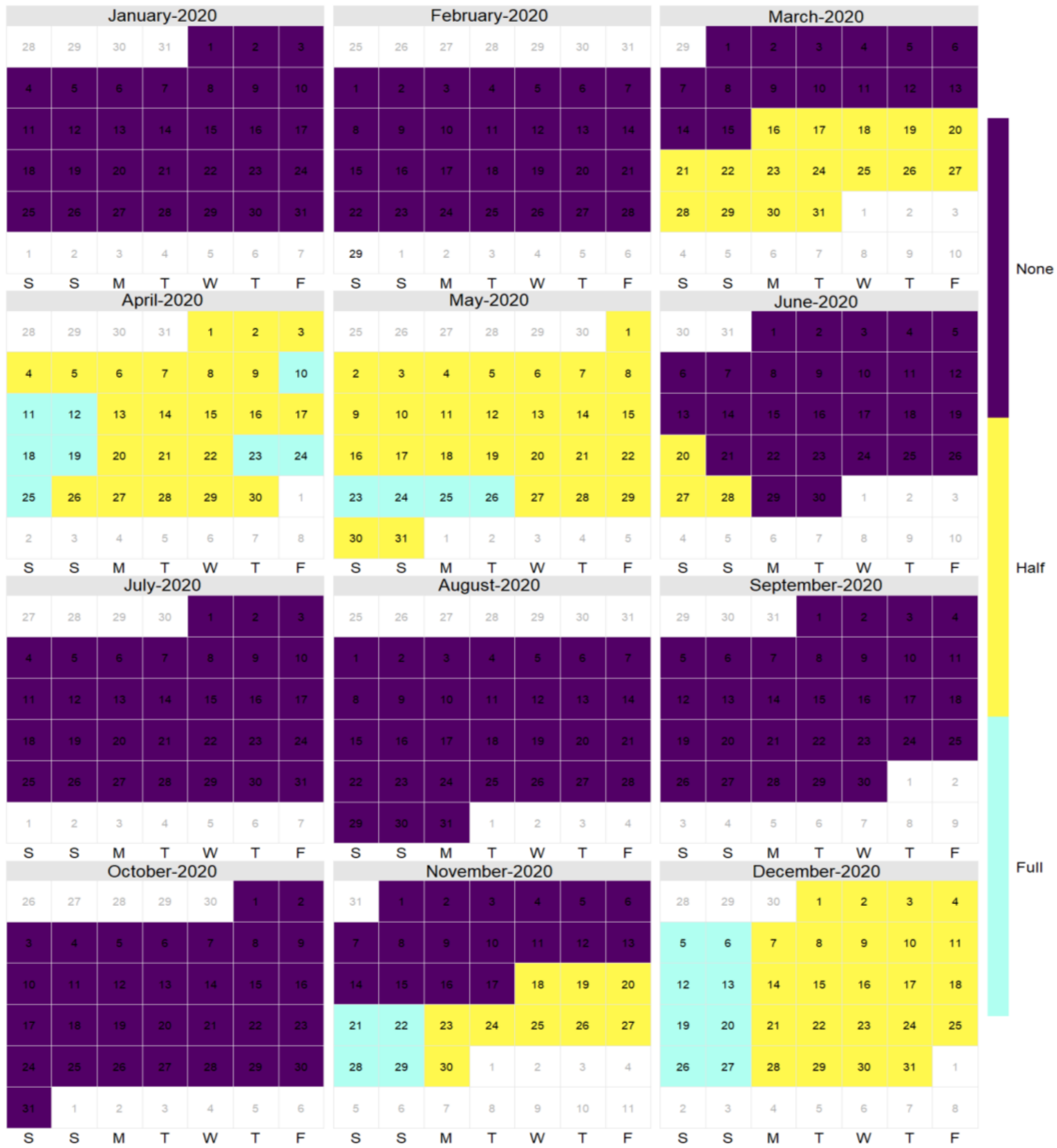

Figure 4.3 : Pandemic period timeline.

The time interval of the study consists of two parts; Before the pandemic (2019) and during the pandemic (2020). In 2020, curfews were made on various dates in Turkey, government buildings were closed, regular curfews were imposed for certain age ranges, and public transportation was limited. In addition, people spent more time at home due to the pandemic. In the study, a comparison was made considering the situations before and during the pandemic period.

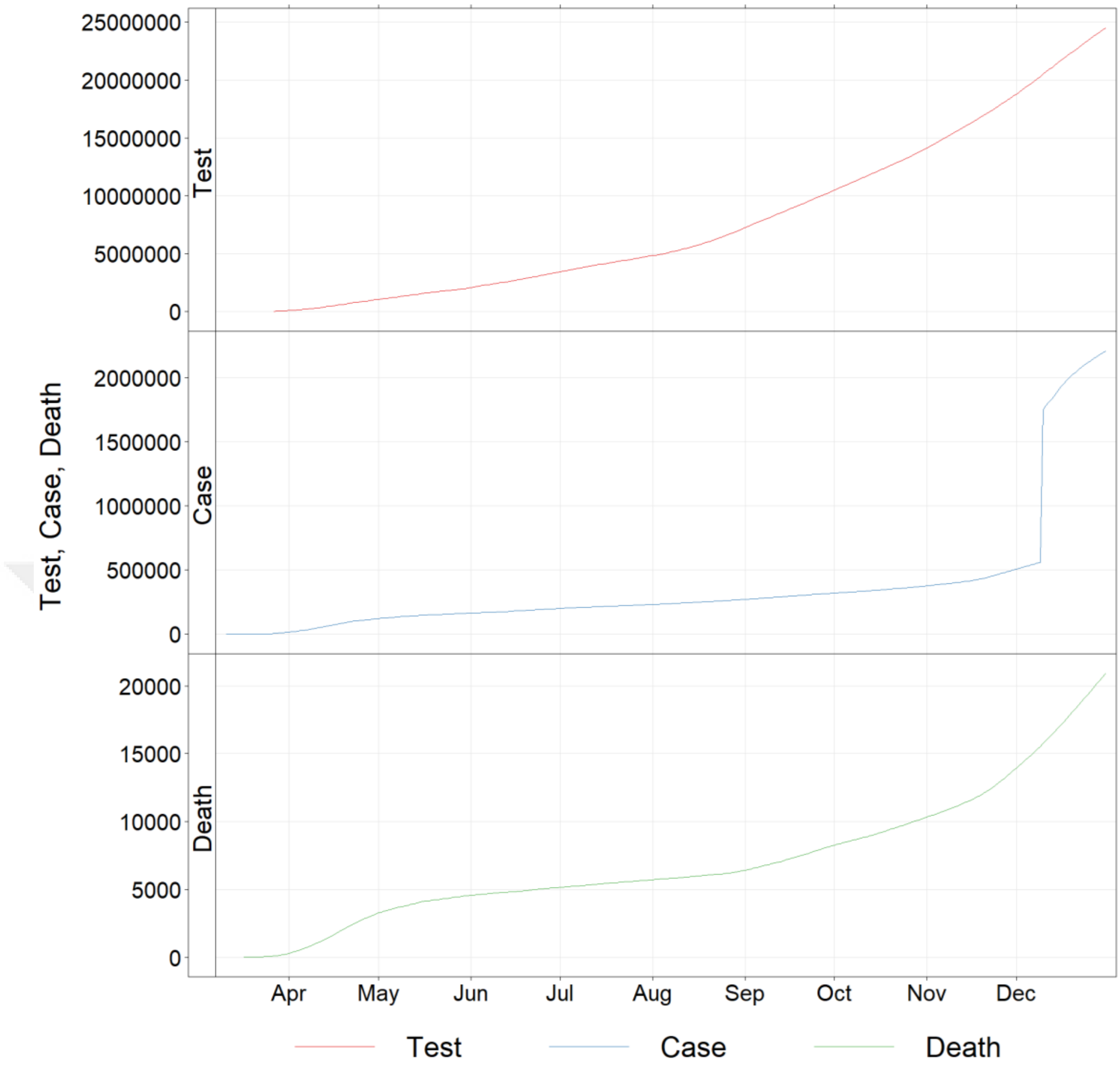

Figure 4.4 : COVID-19 timeline (WHO, 2021).

4.3 Satellite Retrievals

Sentinel-5P TROPOMI Level 2 (L2) NO_2 retrievals downloaded (NASA, 2021) over Turkey for two years (2019 and 2020) were processed. NO_2 data were filtered for QA value >0.5 (ESA, 2021). A domain covering Turkey with 1×1 km^2 grid resolution was used for spatial averaging. Gridded monthly NO_2 retrievals (molecules/cm^2) were calculated for the study domain with spatial matching. Monthly and annual pollution distribution NO_2 retrievals and statistics were calculated with the weighted mean, which is a kind of average. Instead of each grid contributing equally to the final mean, grids contribute to the averages according to the number of satellite retrievals in that grid as “weights”. If all the weights are equal, then the weighted mean equals the arithmetic mean (the regular “average” you were used to) because the weighted mean takes into account the relative importance or frequency of some factors like count in a dataset. When we used weighted mean for TROPOMI retrievals, annual means of NO_2 distribution on the sub-province level were calculated more accurately by using the counts of each grid cell. The programming languages R and Python were used for these analyses and ArcGIS for all GIS production (Url-3).

The collected and processed satellite retrievals allow regional analysis with the help of GIS programs. The satellite retrievals, whose coordinates are known, are then mapped with the regional grids, so it is possible to see the regional and time pollution of NO_2 pollution. This process occurs in three separate categories. The first part is about determining the pollution of each district using the weighted average as explained above. However, as it is known, NO_2 pollution is higher in large point sources such as urban areas, traffic areas, and thermal power plants. For the analysis of this in the study, the pollution data around the areas determined as the urban areas in the Marmara Region by using CORINE land use datasets (Copernicus, 2018) were used for the NO_2 pollution analysis of that county. In the third and last part, the satellite retrievals were also matched with the ground-based measurements whose coordinates are known and only the data of the ground measurement and the surrounding area were used. After this geographical analysis made in GIS, data of different types, sizes, and meanings are transferred to the R programming language. By coding with R, the three different data groups mentioned above were examined, visualized, and interpreted in terms of both clusterings, EDA, and correlation.

4.4 Ground-based Measurements

Hourly data of the surface-level NO_2 concentrations in Turkey are available on the website of the Turkish Ministry of Environment and Urbanization (Url-1). In this study, hourly ground-based NO_2 measurements from January 1 2019 to December 31, 2020, were collected for statistical analysis, such as correlation with TROPOMI datasets. The hourly measurements were averaged to obtain daily values and daily means with at least 75% of valid hourly data were retained.

5. NO_2 POLLUTION IN TURKEY FOR THE YEARS 2019 AND 2020

5.1 Introduction and Methodology

Turkey is a developing country that connects Europe and Asia. Turkey, where the majority of the population is in certain cities and regions, are exposed to intense pollution from time to time in terms of air pollution (TUIK, 2021). In Turkey, where the use of poor quality (with high sulfur content) coal was very high in the 90s, nowadays the rate of natural gas use is between 50-70%, but this rate is still around 20% in small cities that are developing (Alp et al, 2018). As is known, the most common sources of nitrogen dioxide are domestic heating and vehicle emissions. In addition, Turkey's mild climate makes the use of domestic heating unnecessary in summer and spring. Previously, there have been many studies that interpreted both general air pollution and NO_2 pollution in Turkey, both regionally and throughout the country. The methods used in these studies vary, it is possible to see studies made using remote sensing, model, or ground-based measurement (Oner, 2014; Kasparoglu et al, 2016; Butun et al, 2021). In this part of the thesis, Turkey's NO_2 pollution was investigated using the TROPOMI instrument. In the study, monthly average NO_2 for 2019 and 2020 were processed and visualized.

5.2 Results and Discussion

When the monthly average NO_2 values for the years 2019 and 2020 are investigated throughout Turkey, the first noticeable thing is the seasonal changes. In both years, the pollution values started to decrease in March and kept this low level until October. After October, until the end of February, regions with high NO_2 pollution stand out. It is seen that the regions with a high population have much higher pollution than the rest of the country. Especially in the Marmara Region, where both industry and population are most common (Northwest of Turkey), high populated Izmir (the westernmost part of Turkey), and Ankara (the capital and the middle of Turkey), the pollution values are 5 times higher than in other regions in several months. Intensive pollution rates in Istanbul (the most populous province in the Marmara Region) and the surrounding regions, where road and sea traffic are active, have risen to values far above the Turkey average. When looking at the difference between 2019 and

2020, certain months stand out. While it is seen that 2019 values are higher for February and October, in November 2020 is approximately 1.5 times higher than 2019, but the same is the opposite for December. This situation can be explained by the increase in the number of COVID-19 cases in November and the instantaneous changes in meteorology. In all months except November 2019 NO_2 pollution in Turkey is higher than in 2020. Average NO_2 pollution maps of all months can be found in the supplement section (the figures between Figure A.1 and Figure A.22 show the monthly average values starting with January 2019 to December 2020 for all Turkey, respectively.). Apart from these, the two months with the highest difference in the same month of 2019 and 2020 and the two months with the highest difference in 24 months are shown below (Figure 5.1 and 5.2).

While the biggest decreases were observed in March across Turkey, the month with the least change was December. Regional increases in November are more evident than in December and are generally around large point sources, as opposed to densely populated areas. Although the decrease rates are lower in April compared to March, but it is possible to observe a decrease of up to 50% in densely populated provinces (Figure 5.3, Figure 5.4, Figure 5.5, Figure 5.6).

The increase in cloudiness rates during the winter months and the decrease in the quality of the data obtained are should be noted.

Looking at the changes of the same months between two years is also important in terms of the working period. The NO_2 pollution differences between March and April, the first months of spring, and November, the last month of autumn, and December, 2019, and 2020, the first month of winter, were examined. These four months are also known as the starting months of the first and second pandemic restrictions in 2020.

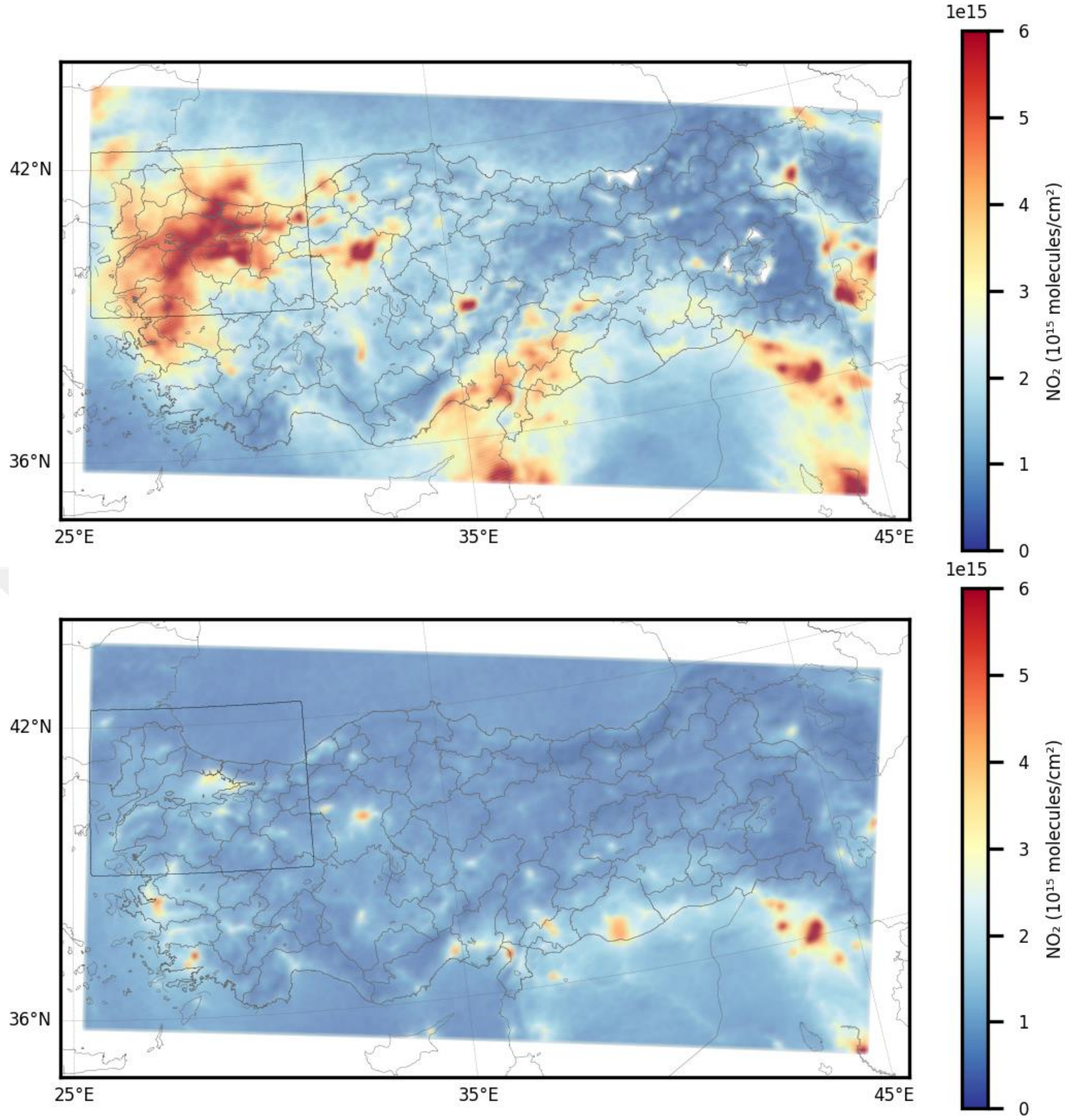

Figure 5.1 : NO_2 Turkey's most and less NO_2 polluted months in 2019 and 2020 (January 2019 and July 2020).

While there was no increase in 2020 in Istanbul, (which is the most populous province compared to others) but on other densely populated cities (Ankara and Izmir), significant decreases were observed only in March. Especially in provinces such as Mugla where there are thermal power plants (in the southwestern part of Turkey), high increases are noteworthy in the winter months of 2020. The increase in those provinces, which have energy production facilities and less population compared to other regions, may be related to meteorology, or it can be interpreted as the increase in the time spent at home during the pandemic period and the increase in electricity consumption due to this (Figure 5.5).

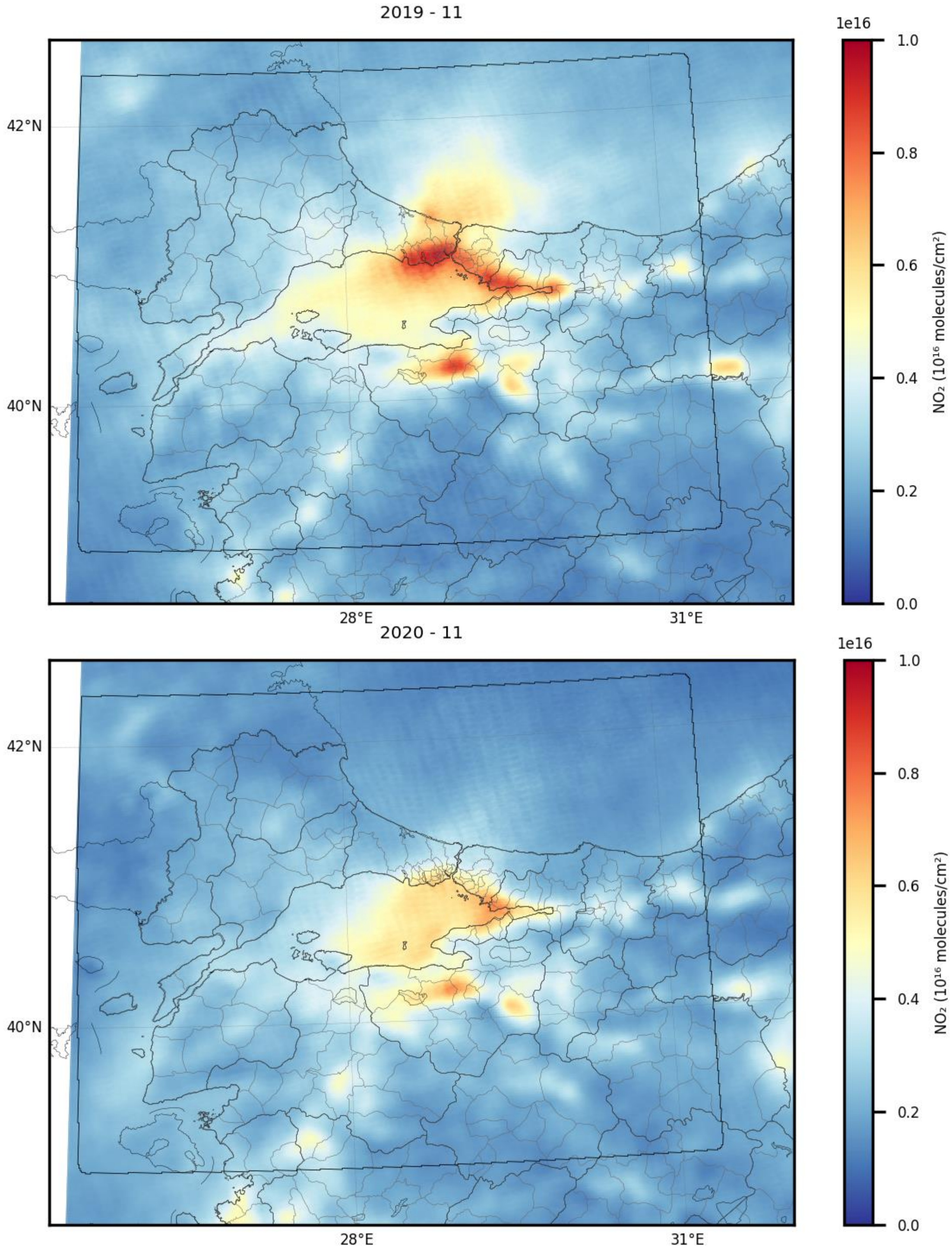

Figure 5.2 : NO_2 differences on Marmara Region for 2019 and 2020 November

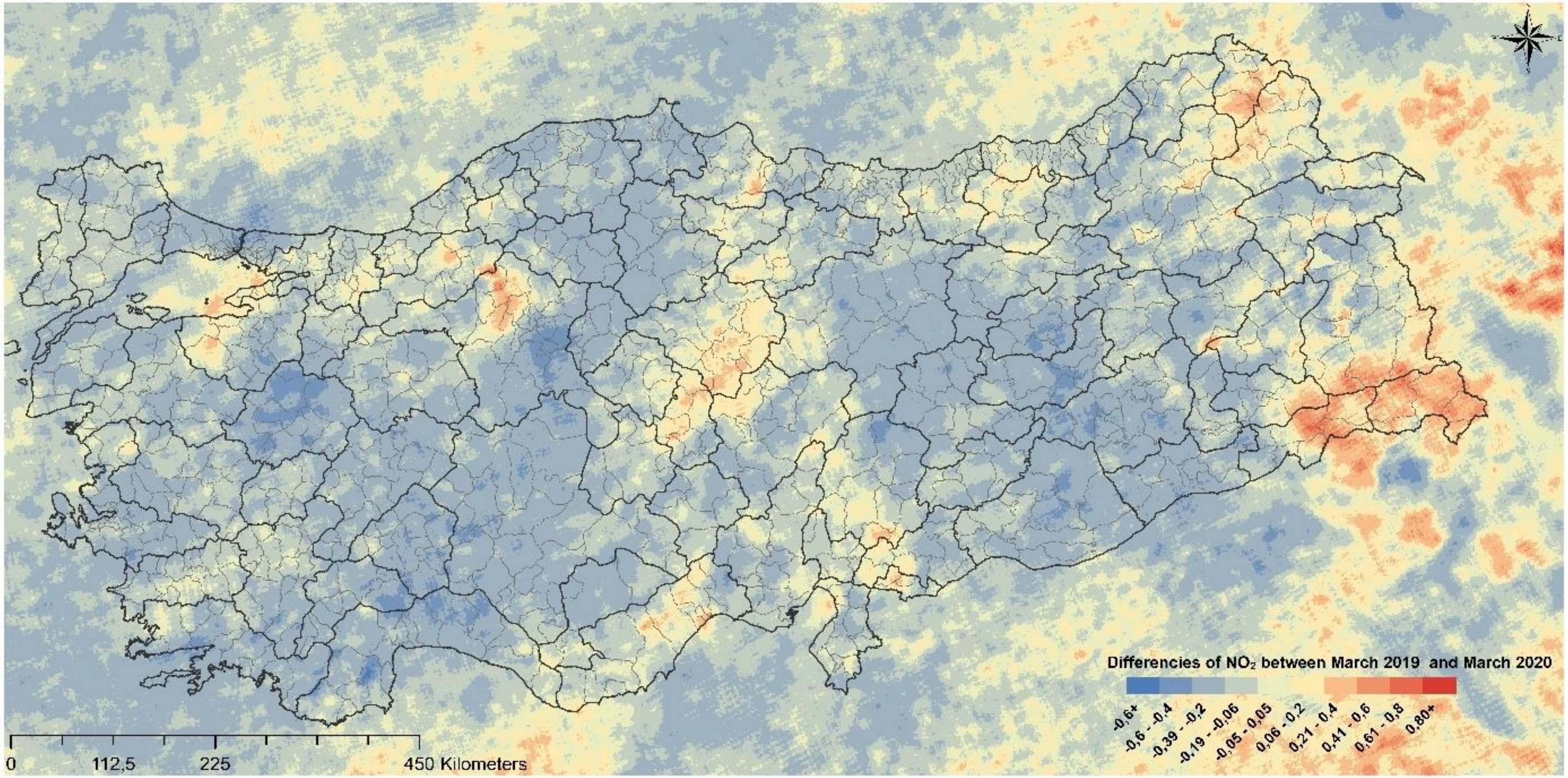

Figure 5.3 : Differences of NO_2 between 2019 and 2020 for the month of March

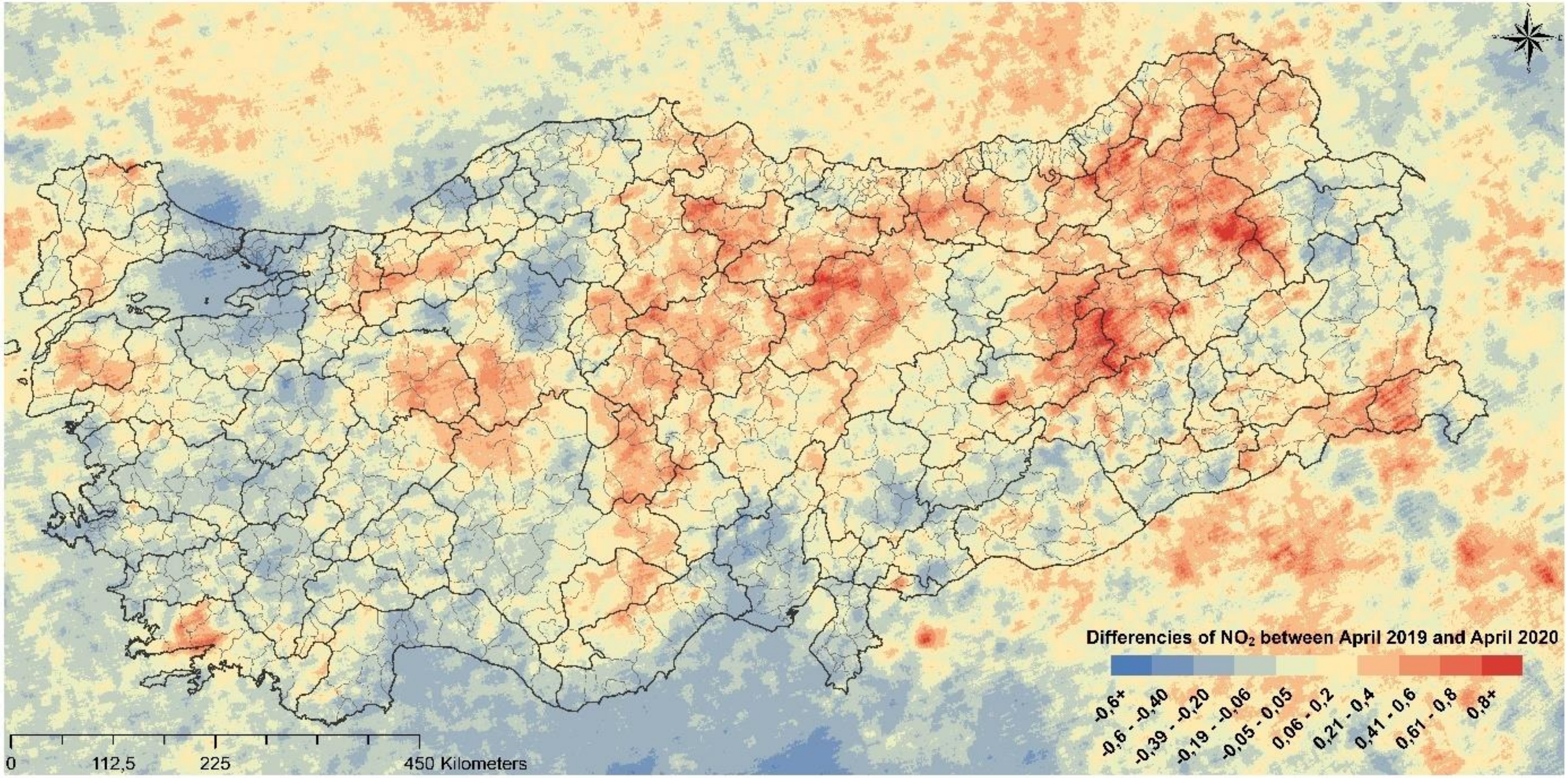

Figure 5.4 : Differences of NO_2 between 2019 and 2020 for the month of April

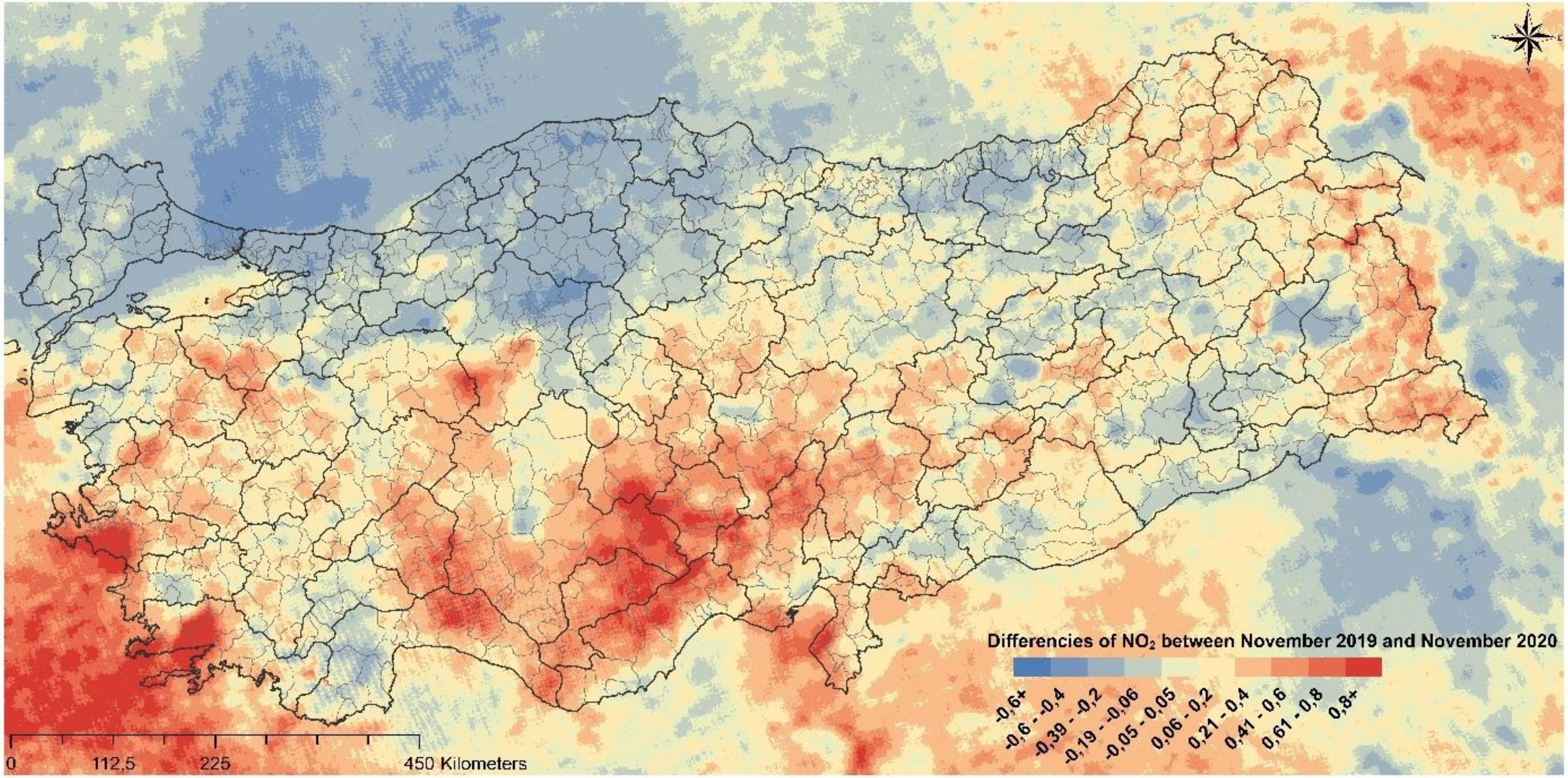

Figure 5.5 : Differences of NO_2 between 2019 and 2020 for the month of November

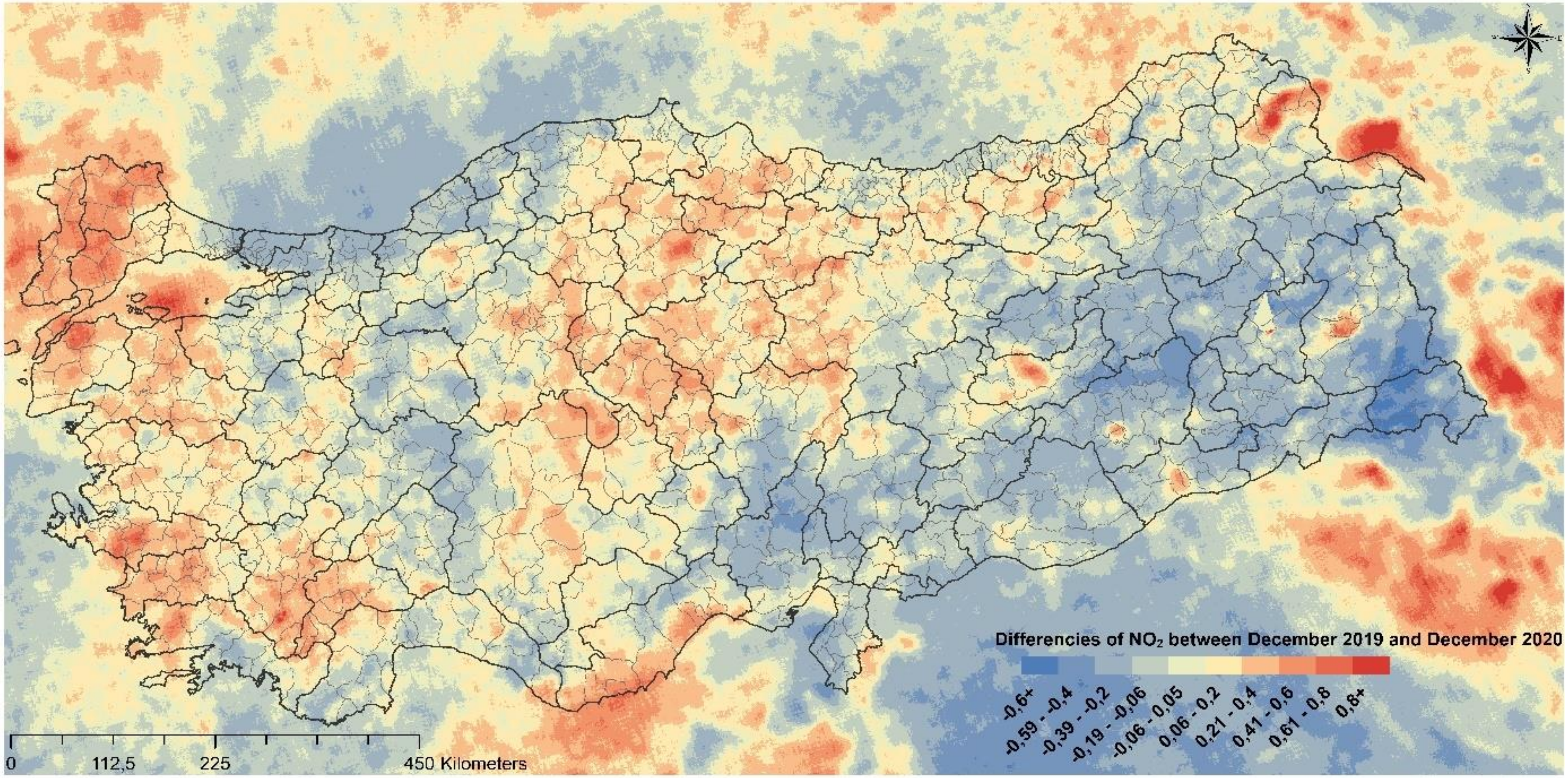

Figure 5.6 : Differences of NO_2 between 2019 and 2020 for the month of December

6. THE CHANGE OF NO_2 POLLUTION DURING THE PANDEMIC PERIOD IN THE MARMARA REGION

6.1 Introduction and Methodology

The COVID-19 pandemic has affected human society on several issues, including of course the most important ones are health care, economic structures, and social structure of our society. WHO made global announcements including closures of businesses and social lockdowns, and most of the countries started to lockdowns and social distances for months. But this lockdown period has wrought unprecedented regional consequences. It is still unknown how the pandemic may impact other factors like the hazard of air pollution. Air pollution exposure is an important and persistent risk factor for cardiovascular and respiratory health outcomes (Burnett et al, 2018).

The pandemic process has created a chance to observe the air pollution trends of the urban areas where people have to stay at home and whose social life is restricted and public transportation usage have been decreased. Although studies in many regions showed that levels of many pollutants decrease in this process, it was possible to see the opposite in some studies as well. Studies which showed that some pollutants increase during the pandemic period focus on two possibilities. The first is the effect of the increase in domestic heating, especially in areas where coal use is intense, and the second is that people start to use their private vehicles instead of public transportation (Berman et al, 2020; Bechle et al, 2013). Considering that the main source of NO_2 is both domestic heating and vehicle traffic, it was concluded that it was one of the most important pollutants to be investigated during the pandemic period.

Turkey has been fighting against COVID-19 since March 11, 2020. In this process, especially in 2020, working hours were stretched, curfews were imposed on certain age groups, and even the whole country was prohibited from going out in certain periods. Especially in the Marmara Region, which stands out with the traffic density, population, and the number of industrial enterprises, these restrictions caused life to come to a standstill.

In this part of the study, NO_2 pollution in 2019 and 2020 were analyzed using both satellite and ground-based measurements, and how the pollution was affected in urban areas during the pandemic and non-pandemic time intervals was statistically analyzed for all districts in the Marmara Region.

In this chapter, three basic time intervals were used, and besides these, the correlation of all ground-based measurements with satellite retrievals were examined. The first timeline will be the general comparison of 2019 and 2020, the main reason for this is that the desire of the people towards social life has decreased, although the whole of 2020 has not passed with restrictions. In the second part, the same months will be used in 2019 and 2020, and this part will focus on the months with restrictions. In the last part of the study, daily constraint trends will also be analyzed.

6.2 Results and Discussion

As can be seen in Figure 6.1, all districts in the Marmara Region have been clustered by the clustering method according to their pollution values in 2019-2020. While selecting satellite retrievals for clustering, only continuous or intermittent urban areas around 2 km were taken as a basis for NO_2 pollution. It is seen in the clustering results that the same months between 2019 and 2020 received similar values and were grouped. Especially February, December 2019, and October, January 2020 seem to be the most polluted months in almost all district averages. The month with the lowest values in the cluster is May 2019, while the month with the highest pollution is November 2019. It is possible to see seasonality in pollution from the dirtiest district to the cleanest district. Although the districts of cities with dense population and vehicle traffic such as Istanbul are generally clustered together, some districts of cities with an industrial density such as Kocaeli and Bursa have districts where they are clustered together with Istanbul. These clusters provide us with important results that NO_2 pollution is a serious problem not only in Turkey and Europe's largest province, Istanbul but also in the entire Marmara Region. Although the districts of cities with lower populations such as Canakkale are clustered among themselves, the pollution values of districts with thermal power plants such as Can sometimes exceed the pollution values of cities with a higher population. Especially in the districts between Kocaeli Darıca and Istanbul Bakırkoy, the fact that some districts have higher values even in summer months compared to winter months summarizes the intense exposure of these Regions to NO_2 pollution.

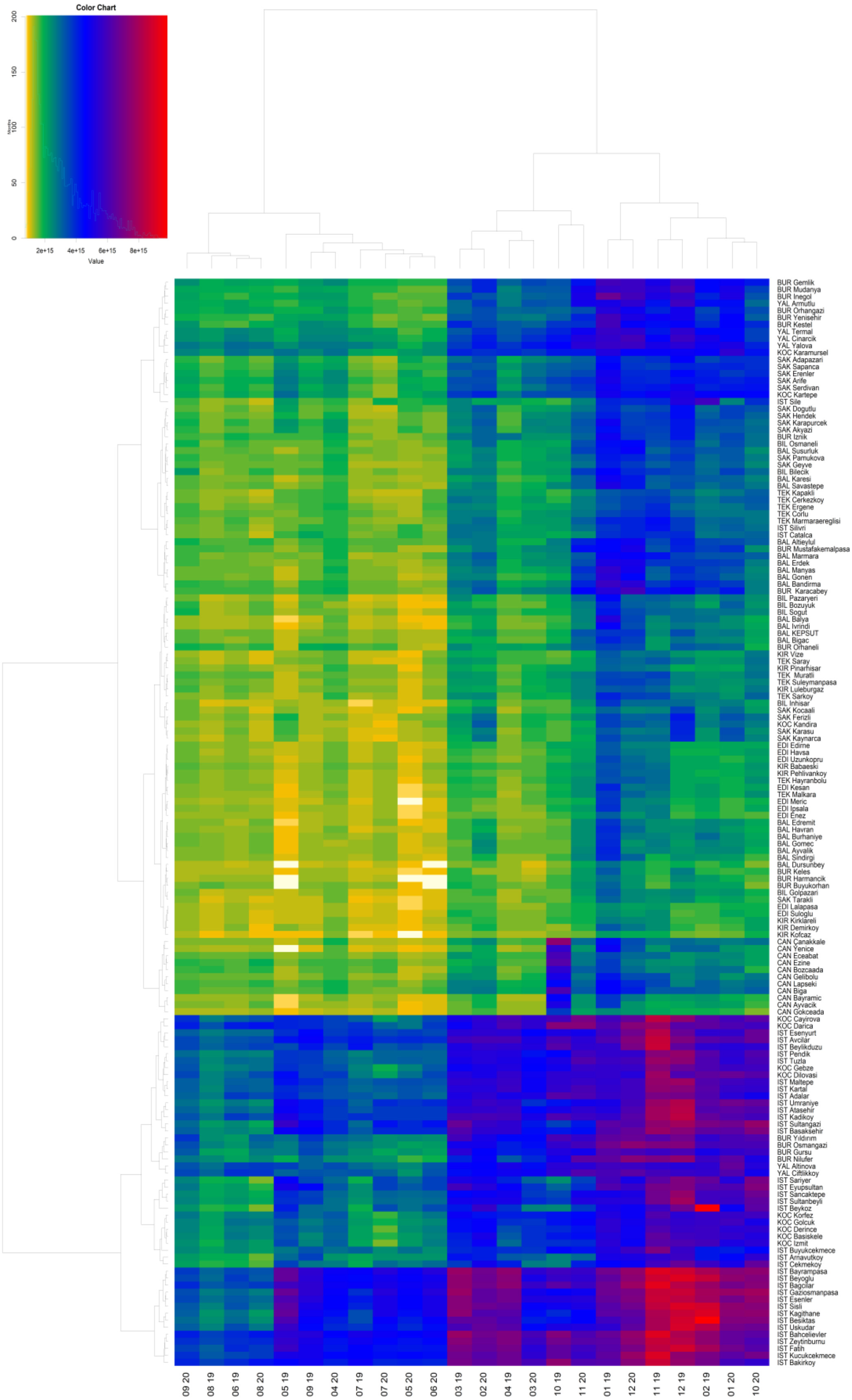

Figure 6.1 : Comparison of NO_2 pollution of the Marmara Region's urban areas on district level with using satellite retrievals for 2019 and 2020 (molec/cm^2)

Also in the study, NO_2 pollution was measured using both ground-based measurements and TROPOMI retrievals in the measurement area (Figure 6.2). When we look at the satellite retrievals, seasonality predominates for both 2019 and 2020, similar to the clustering of urban regions. The distribution of stations is similar to the distribution of the cities they are located in. Most stations in crowded cities such as Istanbul are clustered together, while cities such as Edirne and Tekirdag are mixed. In addition to these, some stations distort the linear distribution mentioned. For example, districts in Istanbul such as Sile and Silivri, where the settlement and population are low, and the population increases in summer, are clustered with the measurement stations of low-population cities such as Edirne. It is possible to see very low pollution values around some stations, especially in May 2020, and in February and November 2019, almost all stations have the highest values according to satellite retrievals. In particular, February 2019 contains two anomalies. One of them is that the station, which is located in the Kandilli district of Istanbul and has pollution between 5-7×10^{15} molec/cm^2 increased to 2.5×10^{15} molec/cm^2 in February 2019. The Kandilli district is generally exposed to both sea and land traffic due to its proximity to the Bosphorus. Another anomaly was seen in the Kocaeli Kandira district. The region with the lowest pollution value in July 2019 and 2020 has the highest values among all stations in February 2019, according to satellite retrievals. This coastal districts like Kandilli is located in the north of Kocaeli and has a coast close to which ships coming from the east via the Black Sea which is to enter the Bosphorus pass. Although the biggest source of these high values seems to be maritime traffic, these values should be examined in more detail for a district such as Kandira where the population and NO_2 pollution are low. In general, the whole of February 2019 has abnormal pollution values compared to both the months before or after it and the year 2020, and it is clustered separately from all months.

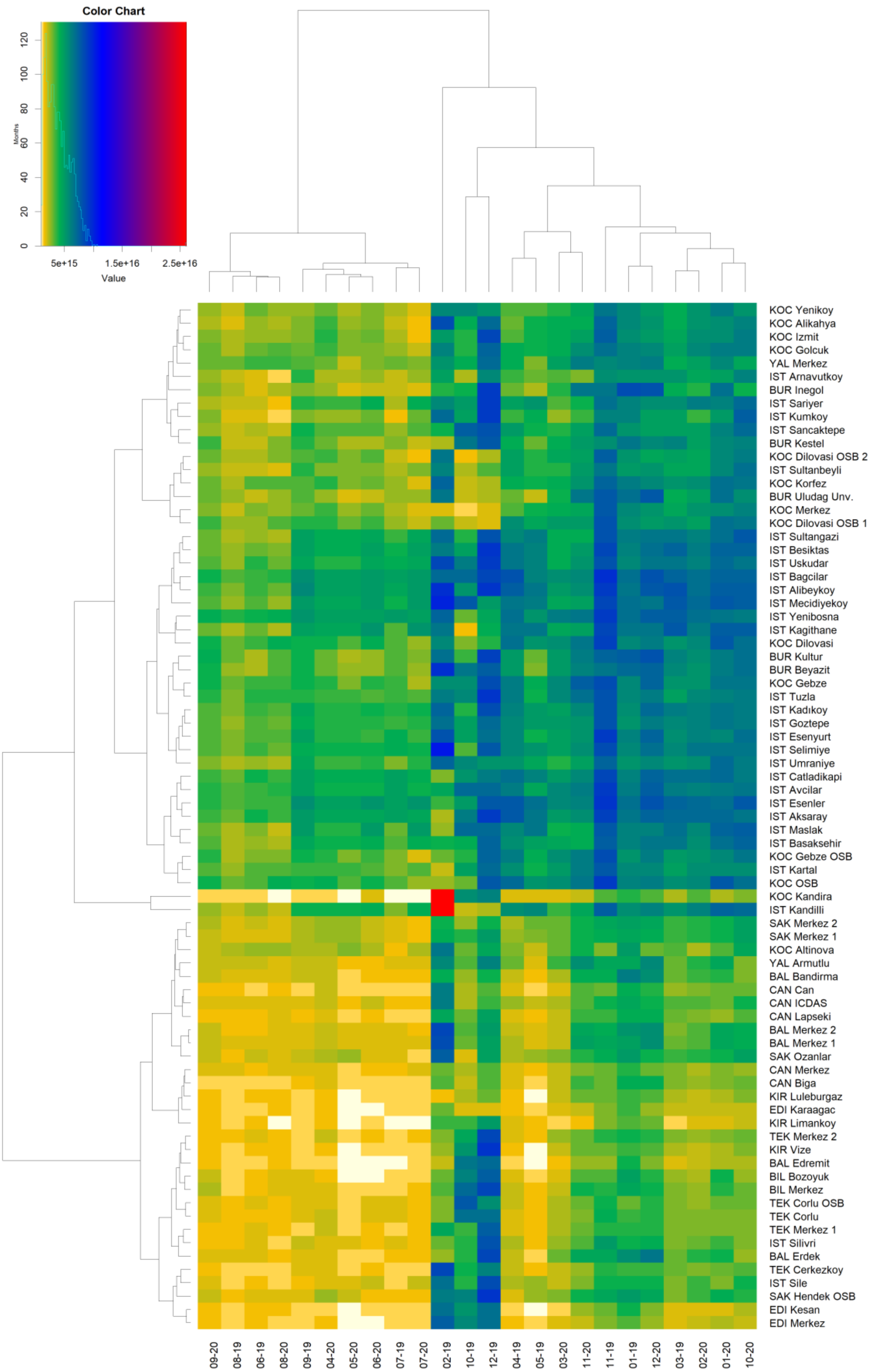

Figure 6.2 : Comparison of NO_2 pollution on the ground-based measurement of the Marmara Region with using satellite retrievals for 2019 and 2020 (molec/cm^2)

In Figure 6.3, where NO_2 pollution is analyzed according to the ground-based measurement data of the same stations, the clusters formed and the pollution values are very different. First of all, it is possible to see missing values or values very close to zero in many stations, and besides, the clusters of the districts themselves are more scattered, except for the most polluted areas of Istanbul. At stations such as Limankoy and Sariyer, the average values are below 40 $\mu g/m^3$ in the 20-22 months of the 24 months. In monthly clusters, on the other hand, the consecutive months of the same year generally formed a common cluster. The seasonality effect is not seen in the whole districts, as in satellite retrievals, and is only noticeable at some stations when viewed individually. Although August and September 2020 are the most polluted months for many stations, it is explained by the increasing pollution error or the heavy vehicle traffic of people after pandemic restrictions in these months, when domestic pollution is seen less than the winter months and the effects of pandemics are seen. Although Istanbul Kadıkoy, Aksaray, and Selimiye seem to be the most polluted districts, some stations such as Bursa Beyazit stand out in 24-month averages due to their low values in October, November, and December 2020.

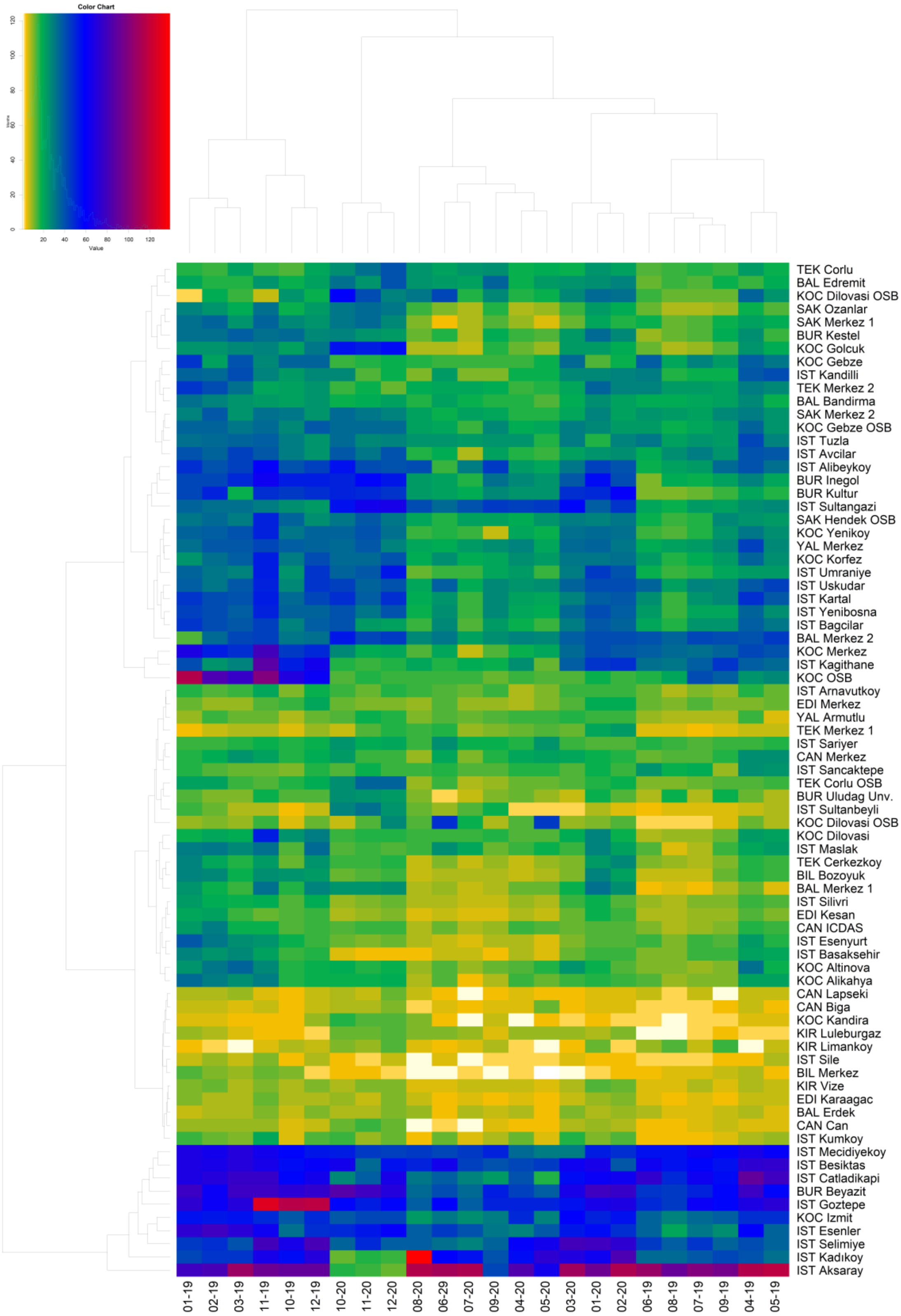

Figure 6.3 : Comparison of NO_2 pollution on the ground-based measurements of the Marmara Region for 2019 and 2020 (μg/m^3)

On these differences in results, the correlations of ground-based measurements and satellite retrievals based on stations were examined. Correlation coefficients show that in many stations the correlation values I are below 0.7. It is possible to see negative correlation values in some densely populated and polluted stations. In the correlations, only Bilecik Merkez Station was inconclusive due to the missing months. Inegol and Kestel for Bursa, ICDAS for Canakkale, Bagcilar, Kartal, Sile, Umraniye, Yenibosna for Istanbul, Gebze OSB, Yenikoy for Kocaeli Ozanlar for Sakarya and finally Yalova Merkez stations have correlation values between 0.7-1 and are grouped as highly correlated. The fact that most of these stations have medium or low pollution values shows that the districts with high NO_2 pollution cannot be analyzed well by ground-based measurements and should be examined. The stations with low, zero or negative correlation are Edremit and Merkez for Balıkesir, Aksaray, Kadıkoy, Kagithane, Sancaktepe, Selimiye and Sultangazi for Istanbul, Limankoy for Kırklareli, Dilovasi OSB 2 for Kocaeli, Hendek OSB for Gebze, Kandira Sakarya, and finally for Tekirdag, there were Corlu, Corlu OSB and Merkez 2 stations. The fact that most of the stations with low or negative correlations have negative or zero correlations with the ground-based measurement data of other stations proves that the stations need a general analysis and development.

When the monthly pollution values of 2019 and 2020 are examined in the pandemic time frame, it is seen that the 2020 period is decreasing in almost all districts of the Marmara Region. The main reasons for this are the decrease in vehicle traffic and public transportation, the inability of people to leave their homes, and the remote working period. In addition to these, the fact that people spend more time in their homes and consume more resources for heating is the main reason why the difference between the two years remains at a value of 10-15%. While it is possible to see this decrease especially in cities with crowded districts such as Istanbul, Kocaeli, and Bursa, the rate of decrease is less for other Marmara cities. Although in different periods in the study, it is seen that the pollution of some months is similar, but these months do not include the months with restrictions. Especially when the periods between March-July and November-December are examined, the year 2020 showed lower values. Correlation studies between satellite retrievals and ground-based measurement show that they are insufficient for this study or future studies without development.

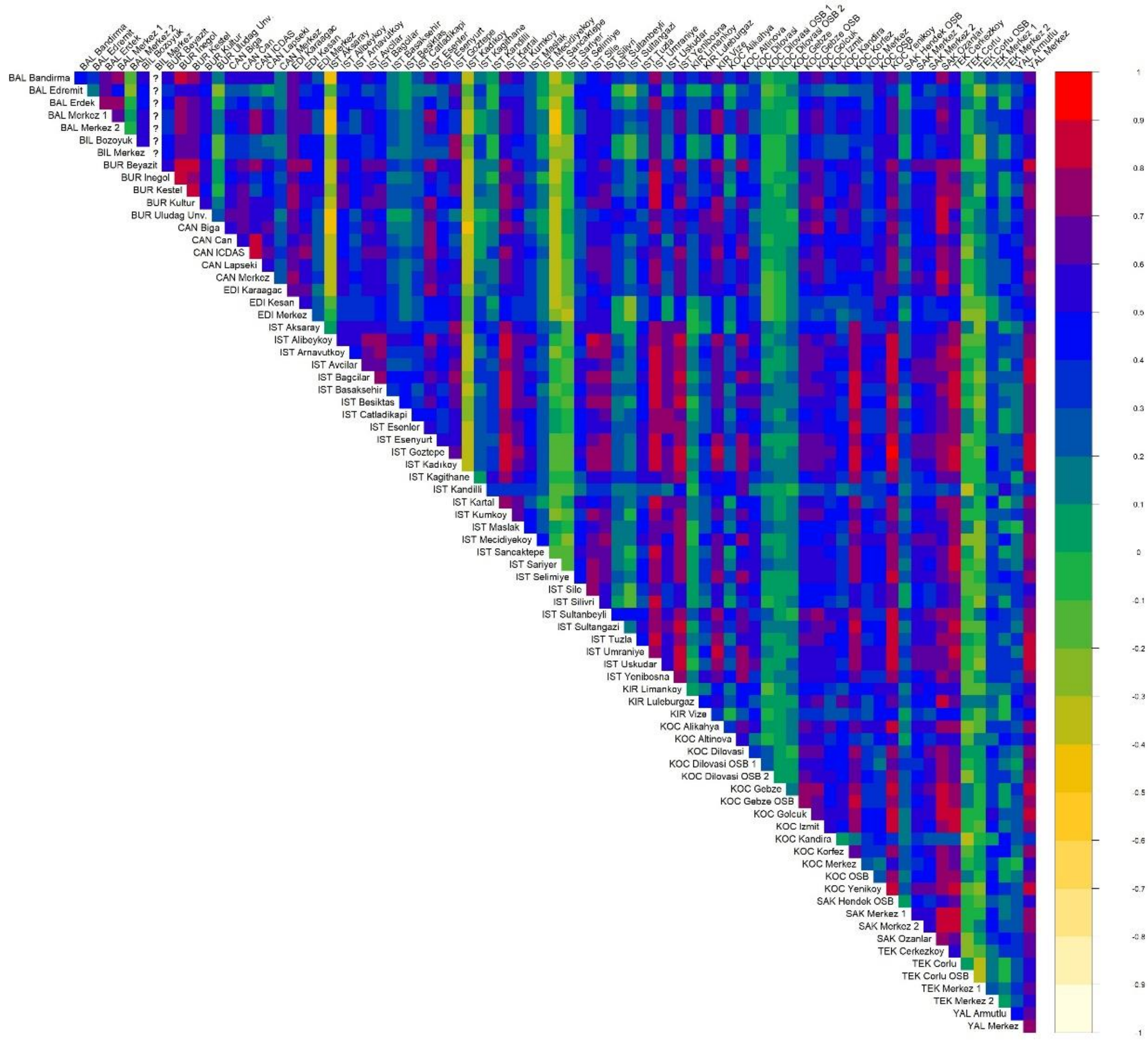

Figure 6.4 : Correlation of ground-based measurements and TROPOMI data of the Marmara Region (R)

The years 2019 and 2020 were created for the most polluted districts of each province as separate time series. Two districts (Kadikoy and Avcilar) for the Istanbul provinces were visualized separately for the two sides of the province. Istanbul Avcılar district shows seasonality with satellite retrievals and ground-based measurements in parallel with each other in 2019, pollution was low in the summer months and reached its highest values in April 2019, contrary to what is expected from winter months. Although the same situation is similar in 2020 when there is a pandemic restriction, it has lower values compared to 2019 in the April-June and November-December periods when the restrictions were increased. It is possible to see values below 40% of the monthly average on weekends, especially in November 2020, during weekend restrictions. For the Kadikoy station, the ground-based measurements for 2020 are insufficient or inaccurate, but when the satellite retrievals were examined, the highest value in 2019 was March and November, while in 2020 these months were October and November. According to satellite retrievals, pollution rates decreased by 50% between January and May compared to 2019, the biggest reason for this is that Kadikoy district is a central district both as a social and business terms (Figure B.1 and Figure B.2 for Kadikoy and Figure B.3 and Figure B.4 for Avcilar stations)

Uludag Univ. Station was selected for Bursa province. When the NO_2 pollution around the station is examined for 2019 and 2020, the highest months for both satellite and ground-based measurements in both years are seen as January and November. However, no significant change was observed for the province of Bursa in the months with the effect of the pandemic. The ground-based measurement average in November and December 2020 is higher than in 2019. Uludag Unv. is a station located near Uludag, one of the largest mountains in Turkey, and it is possible that this district was affected by strong winds. In Kocaeli, another industrial city of the Marmara Region, like Bursa, it is possible to see the effects of the pandemic. Measurements taken from the Dilovasi station for Kocaeli, which has the most intense industrial pollution in the Marmara Region and maybe even in all of Turkey, showed a decrease by %20 with satellite retrievals. Although according to ground-based measurements, 2020 is more polluted than 2019 on an average of almost every month. There is a possibility of inaccuracy on ground-based measurements, where low pollution values are measured only between May and June (Figure B.5 and Figure B.6 for Uludag Unv. and Figure B.7 and Figure B.8 for Dilovasi OSB stations).

When Sakarya Central station is examined, all months of 2020 are lower than 2019 (except November for satellite retrievals). Daily decreases observed in November 2020 weekend restrictions and monthly average decreases for April-June 2020 in both satellite and ground-based measurements in the district, where a decrease of 30-40% was observed compared to 2019, especially during the periods when pandemic restrictions. The situation is the opposite in the Yalova Central district, which has similar meteorological and geographical features. In the district, where even seasonality is not seen on the ground-based measurements, Difference between the pandemic period or 2019-2020 were not observed, even if NO_2 seasonal pollution is observed only with the satellite retrievals (Figure B.9 and Figure B.10 for Sakarya Central, Figure B.11 and Figure B.12 for Yalova Merkez stations).

Tekirdag Corlu is another industrial district of the Marmara Region and is especially known for its car and leather industry, so it is occasionally the subject of air pollution. During the pandemic period, the reduction of the working hours and therefore the production of many factories showed a decrease in the NO_2 pollution of the Corlu district. Especially in April-June, 2020 has 40% less NO_2 pollution compared to 2019.

The same situation is seen in the satellite retrievals for November. Especially the weekend restrictions affect daily measurements (Figure B.13 and Figure B.14 for Corlu station).

When the NO_2 pollution is analyzed in Canakkale (Can), Edirne (Kesan), Balikesir (Edremit), and Kirklareli (Luleburgz), where the population is low and agricultural production is equivalent to or higher than industrial production in some provinces, seasonality is the first thing that noticed, in these provinces' summers are hotter than other Marmara provinces., Seasonal changes observed in both measurements and years. When it comes to the pandemic period changes, although there are decreases in ground-based measurements, this decrease does not mean much because it has NO_2 pollution below the limit values even in the pre-pandemic period. In satellite retrievals, the decrease rates are between 1-5% and even Edirne Kesan s'ation's 2020 November is more polluted than 2019 November, the same is true for Luleburgaz station satellite retrievals (Figure B.15 and Figure B.16 for Can, Figure B.17, and Figure B.18 for Kesan, Figure B.19 and Figure B.20 for Edremit and Figure B.21 and Figure B.22 for Luleburgaz stations).

No significant results could be obtained from the ground-based measurement data of Bilecik Central station, and when the satellite retrievals were examined, no seasonal decrease was observed except seasonality (Figure B.23 and Figure B.24 for Bilecik Merkez stations).

To examine the effect of NO_2 pollution more closely during the pandemic period, three stations (Istanbul Mecidiyekoy, Alibeykoy, and Bagcilar) in the same cluster, which are the most polluted in ground-based measurement and satellite retrievals, were visualized as separate time series for both 2019 and 2020, years (Figure 6.5 and 6.6). The relationship with the pandemic restriction dates was also examined. In particular, the year November 2020, which belongs to the period when the restrictions started again after the summer period and continued with weekend curfews for a long time, is shown as a separate graphic (Figure 6.7).

In the three stations as mentioned, the pollution changes for both 2019 and 2020 are seasonally similar. In particular, the peak days when the values correspond to almost the same days. This similarity by the fact that the regions where the three stations are located are close to each other and have similar pollution parameters.

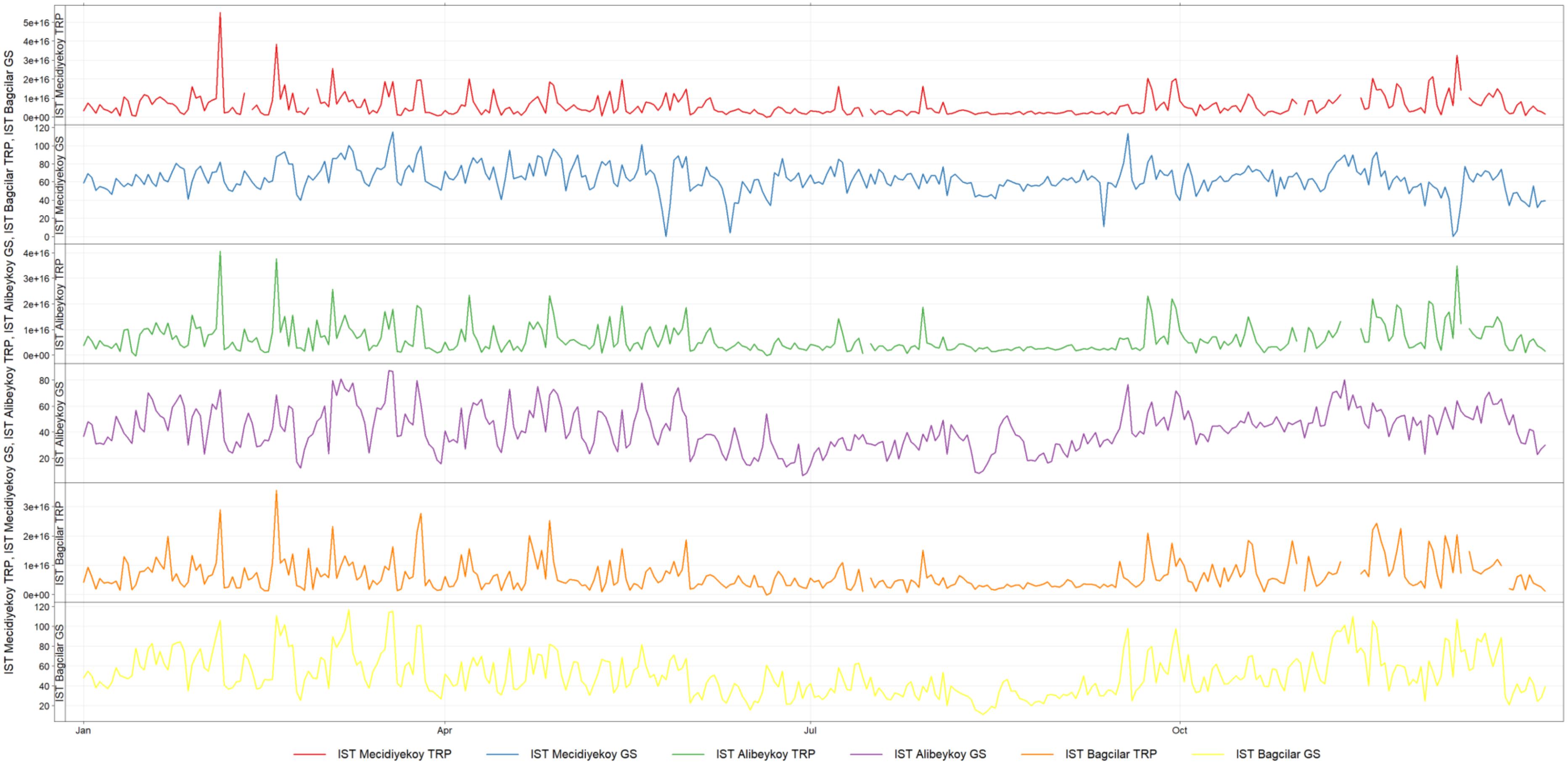

Figure 6.5 : Evaluation of three stations selected in clustering for NO_2 pollution with ground-based measurements and satellite retrievals for 2019.

Figure 6.6 : Evaluation of three stations selected in clustering for NO_2 pollution with ground-based measurements and satellite retrievals for 2020 with pandemic period timeline.

For satellite retrievals, the months of February and March in 2019 have high NO_2 values, but for 2020 these values increase in January and have a downward trend until April but with the effect of the pandemic restrictions between March and June, it is possible to see low NO_2 values in 2020, while these values are 10-15% higher in 2019. When looking at the period of June-August, it is seen that the values are low in both years, but the increasing trends seen in 2019 are not seen for the summer of 2020. The reason for this is that people have avoided activities that require high social contact, such as holidays, even if the restrictions are canceled. There are some missing data for November and December 2020, when the restrictions started again, but when the weekend days are examined in Figure 6.7, the NO_2 pollution of each station is 20-50% lower than the weekdays according to satellite retrievals, especially in November, only the last weekend of November, (28-29 November) the pollution values of Alibeykoy and Mecidiyekoy stations were at the highest values of the whole month. The main reason for this high inclease is thought to be the seasonal cold that comes with December.

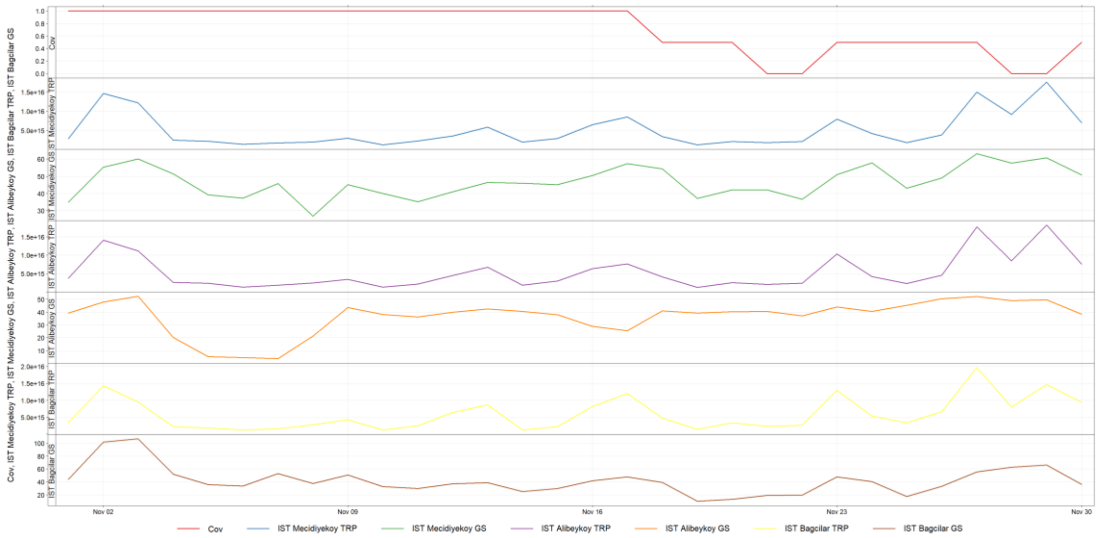

Figure 6.7 : Evaluation of three stations selected in clustering for NO_2 pollution with ground-based measurements and satellite retrievals or 2020 November with the pandemic period timeline.

When the ground-based measurements data are examined for 2019 and 2020, it is seen that 2019 has higher values compared to 2020, but the values in the periods with pandemic restrictions are almost the same for the same months. Although the Mecidiyekoy station increases in correlation with the satellite retrievals, there is no connection between the Alibeykoy and Bagcilar stations and the satellite retrievals, and it is observed that it has higher values especially during the weekend restrictions of November compared to weekdays. However, in parallel with the satellite retrievals, it can be said that the first days of November have lower values for all three stations compared to the days with restrictions.

This decrease can be seen more clearly in the box-plot images made using satellite retrievals of December and April for Kocaeli Dilovasi, Bursa Uludag Unv., Istanbul Kadikoy, and Istanbul Avcilar stations. When the NO_2 pollution is taken from the column top of the stations, it is seen that all four stations have lower values in April 2020 compared to 2019. As mentioned before, April 2020 is considered to be the month of restriction, but an important NO_2 source such as domestic heating is not seen much in this period. In addition, when the December measurements are examined, it is seen that the Avcilar station gives higher values in 2020. It was thought that the biggest reason for this was that Avcıilar was exposed to heavy land traffic even during the restrictions and people resorted to domestic heating more because they stayed at home during curfews. Uludag Univ. It has been concluded that the station should be examined in detail, especially with the wide range of values it received in December. Similar changes to Avcilar station are also observed at other stations, this analysis also showed different trends of pollution in different districts of the province depending on the effects of the pandemic.

When the results of the study are examined in detail, the effects of the pandemic period on NO_2 pollution in the districts of the Marmara Region were analyzed and discussed with both satellite retrievals and ground-based measurements. The results show that while the reduction of NO_2 pollution in regions with low population, industry, and traffic is generally directly proportional to the pandemic, pollution in high population and more socioeconomically active districts depends on many parameters. In the analyzes to be made for the continuation and future of the study, it was discussed that it would be better to carry out box plot analyses in all Marmara Region districts in wider time intervals and with satellite retrievals that cover urban regions. In addition, it has been shown by both clustering and correlation analyses that very low or missing data at ground-based measurement stations do not represent NO_2 pollution in the Marmara Region.

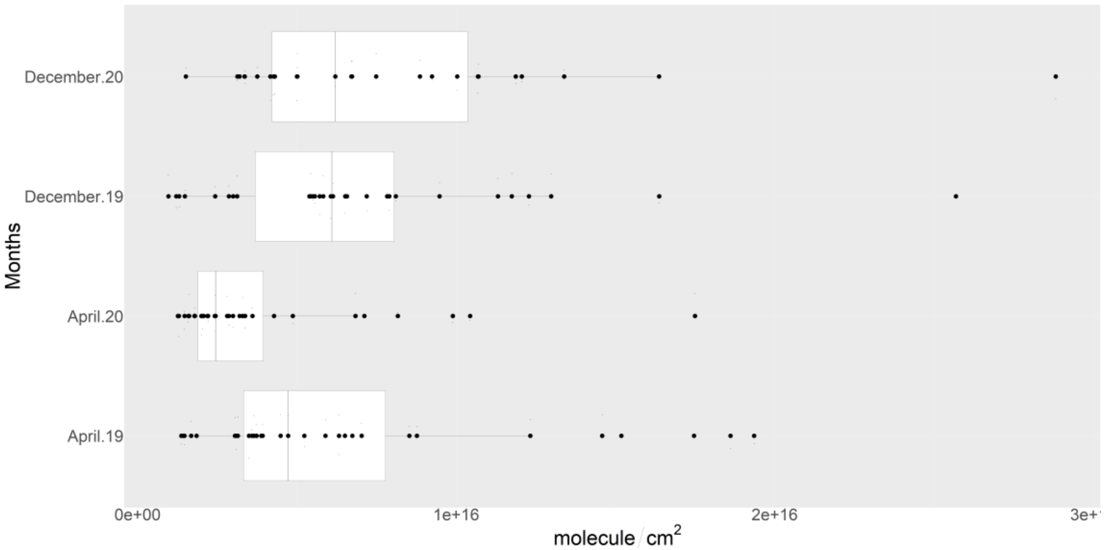

Figure 6.8 : NO_2 measurements for April and December 2019-2020 using satellite retrievals for Kocaeli Dilovasi station.

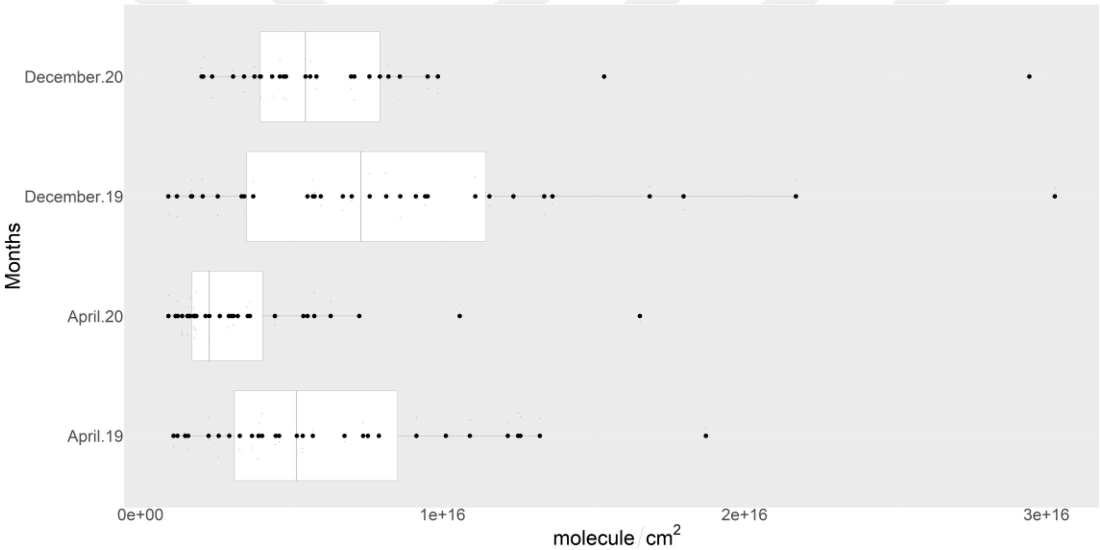

Figure 6.9 : NO_2 pollution measurements for April and December 2019-2020 using satellite retrievals for Istanbul Kadikoy station.

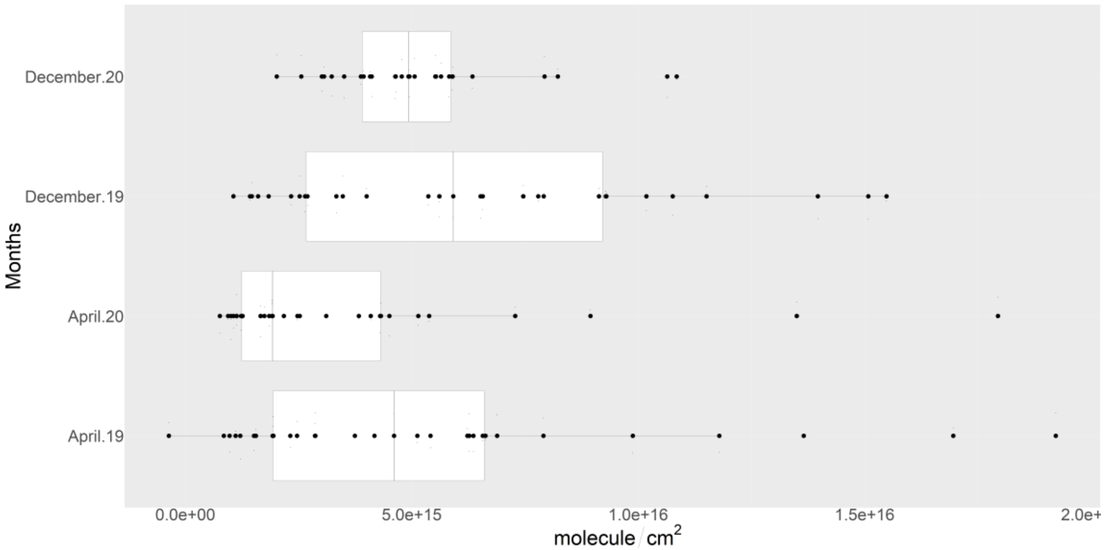

Figure 6.10 : NO_2 pollution measurements for April and December 2019-2020 using satellite retrievals for Istanbul Avcilar station.

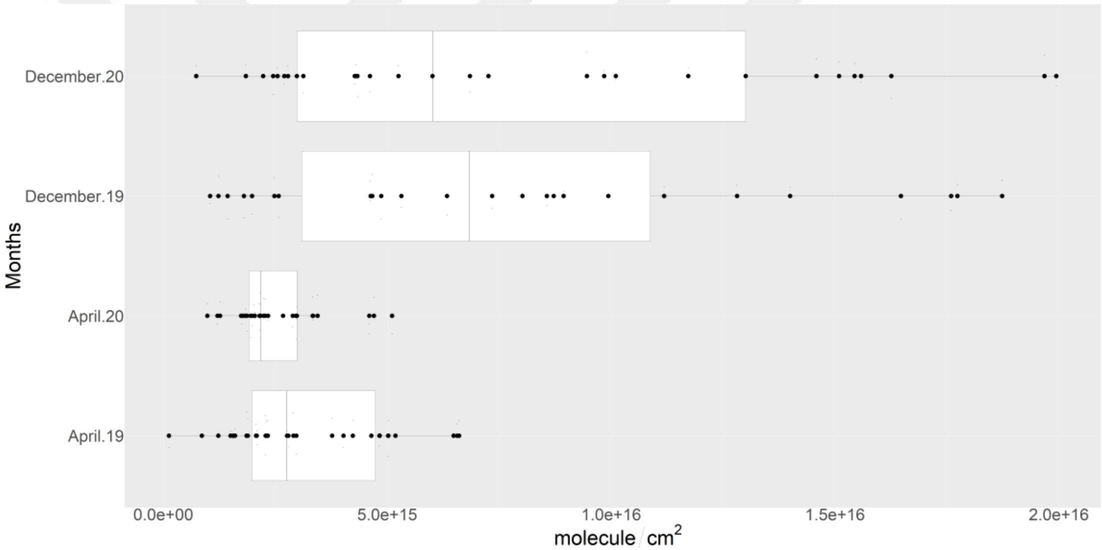

Figure 6.11 : NO_2 pollution measurements for April and December 2019-2020 using satellite retrievals for Bursa Uludag Univ. station.

7. THE RELATIONSHIP BETWEEN URBAN DEVELOPMENT AND AIR POLLUTION FOR THE MEGA-CITY OF ISTANBUL

7.1 Introduction and Methodology

The term “urban” is widely used to define areas with a high-density population or with people who have social and economic interaction with each other. The term “urban indicators” explain ways to measure the conditions and status of an urban area with a variety of factors. They differ from most types of indicators because they are connected, with aspects of economic, environmental, and equity dimensions impacting and connecting. In other words, it means the connection and interaction of the population and environment. But are larger and more densely populated cities better or worse places to live? Over the past centuries, the world has become increasingly urban as the benefits of metropolitan areas have drawn humans to large cities. The urbanization about economic circumstances on these benefits is vast, to predict the optimal balance and size of cities, robust evidence of the costs and benefits of agglomeration is required, and it appears that much less is known about the costs (Kahn, 2010).

Ambient air pollution causes up to 10 million deaths per year and approximately 90% of the world's population lives in urban environments where air pollution exceeds the WHO guidelines (WHO, 2021). In regions where air pollutant concentrations are higher than the safety limit values for people who breathe polluted air than for groups living in a clean atmosphere. Anthropogenic sources of pollution from industrial and urban development lead to an accelerated deterioration of air quality and reduce the quality of life of its residents (Boubel, 1999). Awareness of the effects of air pollution on public health is increasing rapidly, especially in urban areas where legal air quality limits (QA) are frequently exceeded. This awareness has led lawmakers to minimize citizen exposure, not only through direct legal control of emissions but also through the use of mobility restrictions to change traffic patterns and through the use of timed alerts to alert citizens about air pollution episodes.

The ambient levels of nitrogen oxides ($NO_x = NO_2 + NO$) are a good indicator of air quality in urban and industrialized areas. For nitrogen dioxide (NO_2) pollution, the most contributing indicators in urban areas are the number of working people, incomes of the people or population these indicators are as important, as large point resources and number of vehicles in the region. Atmospheric NO_x levels in urban areas are directly related to human activities (fuel combustion of road traffic, residential and tertiary sectors, and industrial activities) (EPA, 2008). NO_x species are produced during combustion processes, therefore can act as a substitute for fossil fuel-based energy use, as well as emitted greenhouse gases, and other pollutants (Duncan et al, 2016). NO_x emissions are regulated in many countries (UNECE, 2007; Vestreng et al, 2009) because they are precursors for the formation of surface ozone, which also has harmful effects on human health and vegetation. NOx is measured at ground level using dispersed measurement networks. Measurements are sensitive to distance to sources such as main traffic routes. Pollutant distributions can be obtained through land-use models that interpolate between measurement stations, and this is achieved through the use of additional data (altitude, meteorology, inventories of pollution sources, etc.), whose reliability is uneven. Measurements of NO_2 columns from space are suitable for following NO_x emissions, since the lifetime of NO_2 is relatively short (from several hours to 1 day) (Beirle et al, 2006; Leue et al, 2001). This ensures that measurements of relatively high levels of NO_2 in the boundary layer are close to the emissions, and therefore clearly indicate the sources.

The population of Istanbul in 2019 was 15,519,267 (TUİK, 2020). At this point, it should be noted that some cities and districts of the province of Istanbul have been divided or merged with one or more districts over the years for planning reasons. Therefore, the population dynamics could not be compared in pairs between 2007 and 2017. The five most populous districts were Umraniye (897,260), Kadikoy (744,670), Uskuudar (582,666), Kartal (541.209), and Esenler (517,235) in 2007 and Esenyurt (846,492), Umraniye (699.901), Uskuudar (533,570), Sultangazi (528,514) and Kartal (463,433) in 2019 (TUİK, 2020).

We used the technologies that provide high-resolution data due to the crowdedness of the cities and the pollutant sources to better understand the effective indicators of NO_2 pollution at the sub-province level. Remote sensing of atmospheric gases provides wide spatial coverage with reasonable temporal resolution. Satellite retrievals are very useful for spatially capturing urban areas, whereas ground-based measurements may have limitations due to meteorological and topographical factors.

Table 7.1 : SES Scores of Istanbul Districts (Istanbul Development Agency, 2016).

Districts	***Average SES Score (0 to 100)***
Adalar	60.00
Arnavutkooy	16.77
Atassehir	50.73
Avcilar	43.75
Baggcilar	28.40
Bahcelievler	45.45
Bakirkoy	79.16
Basaksehir	38.75
Bayrampasa	32.95
Besiktas	91.30
Beykoz	36.11
Beylikduzu	50.00
Beyoglu	45.27
Buyukcekmece	42.70
Catalca	13.78
Cekmekoy	39.28
Esenler	23.43
Esenyurt	31.10
Eyup	35.26
Gaziosmanpasa	33.59
Gungoren	40.90
Kadikoy	82.14
Kagithane	40.13
Kartal	45.62
Kucukcekmece	35.71
Maltepe	54.16
Pendik	32.29
Sancaktepe	26.97
Sariyer	57.56
Silivri	17.50
Sultanbeyli	18.33
Sultangazi	23.33
Sile	15.72
Sisli	68.50
Tuzla	38.97
Umraniye	42.50
Uskudar	64.01
Zeytinburnu	43.26

7.2 Results and Discussion

The relationship between the seasons and the NO_2 pollutant, which is known to be formed from all combustion processes, is especially can be measured in big cities like Istanbul. The overall pollution over Turkey and the spatio-temporal distribution of the NO_2 were identified for 2019 and Istanbul was examined closely. Figure 7.1 shows

NO_2 pollution in two different months (the months with cleanest signals for both summer and winter seasons) in 2019 and the seasonal changes were observed. Due to the high spatial resolution of TROPOMI while we can see the districts in more detail for Istanbul, also interpret the whole of Turkey's NO_2 pollution. When looking at July (upper), it is possible to say that the pollution values for the whole of Turkey and Istanbul are low, besides, Istanbul is still the most polluted province in Turkey. In November (lower), pollution values increased in all cities with high populations, especially in Istanbul.

As can be seen in Figure 7.1, Istanbul's NO_2 pollution is quite high (around 6×10^{15} molecules/cm^2) but when combined with other similar polluted cities in Marmara (like Kocaeli which is adjacent to Istanbul from the east, have two major industrial zones in the Marmara Region) exposes the entire Marmara Sea and the Bosphorus with NO_2 pollution. Although there is no significant change in the population of the region or the number of vehicles between July and November, the reason for the increase in pollution is that there is a direct relationship between domestic heating and NO_2. In addition, it is possible to say that the entire Marmara Sea is exposed to NO_2 in winter months when the dense traffic in Istanbul is combined with high natural gas and another source of heating used due to cold winters and high population and also with the dense maritime traffic in the Marmara Sea.

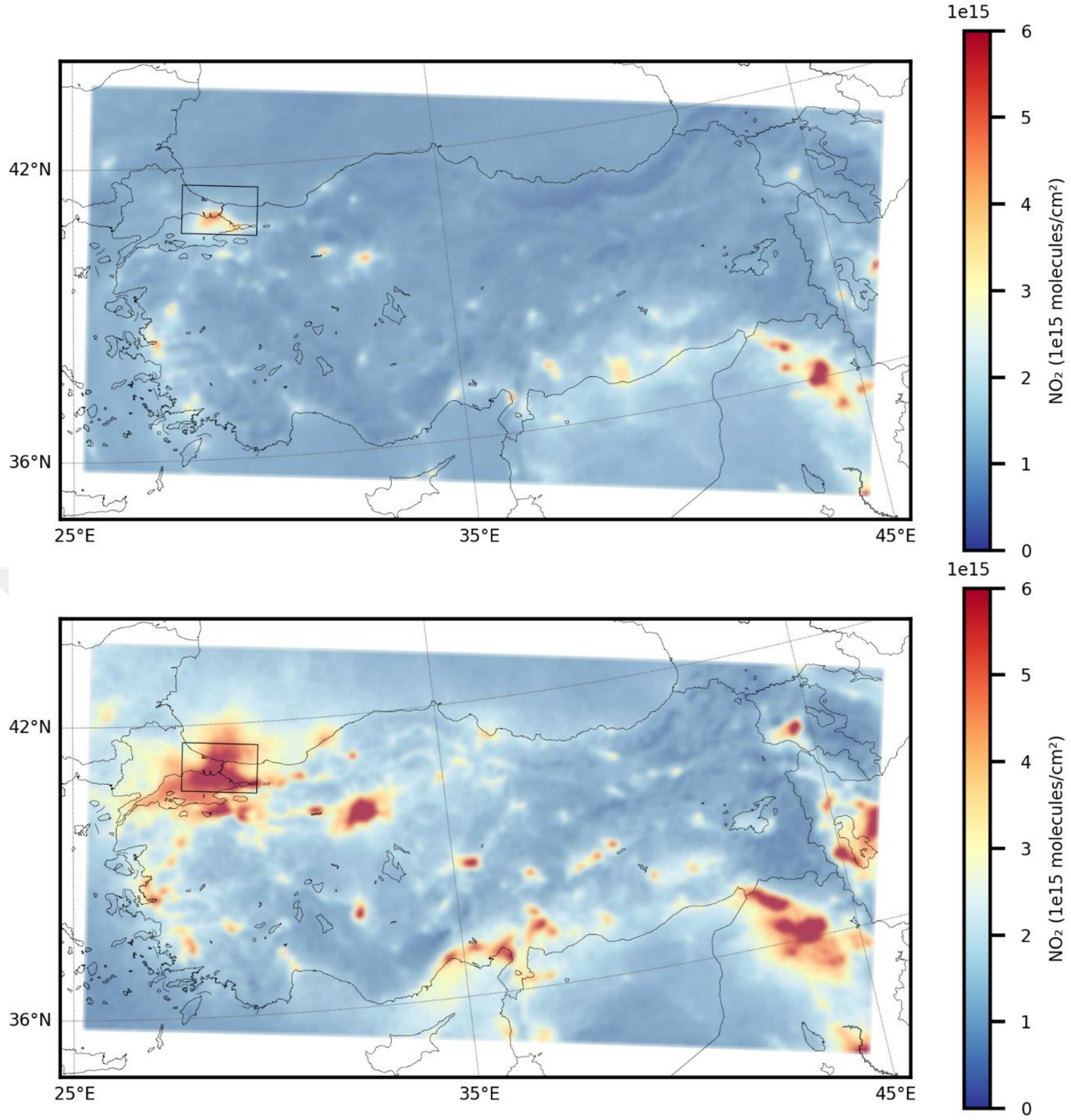

Figure 7.1 : The monthly average of NO_2 (2019) July (upper) and November (lower) with 1×1 km^2 resolution of the TROPOMI dataset. The black rectangle from the left corner represents the study area

In the case of NO_2 pollution in Istanbul in 2019, we use a heatmap to observe two different datasets with two different clustering methods (Figure 7.2 and Figure 7.3). Both TROPOMI and the ground-based measurements were clustered with months of 2019 and districts (or ground-based measurements) and colored for their NO_2 pollution the understand their relationship with each other. For TROPOMI retrievals, the clustering of months is very seasonal, summer months (June, July, and August) separated from others because of their low NO_2 profile all district's lowest values are seen in one of these three months. High NO_2 profile months like February, November, and December and all district's highest values are seen in one of these three months for other six months of year May and September are medium-high and others are medium-low. Pollutions of NO_2 with TROPOMI generally clustered with their neighbor districts like Gaziosmanpasa, Esenler, Beyoglu and Bayrampasa or Bahcelievler, Bagcılar, Zeytinburnu and Fatih. Catalca, Silivri, and Sile generally have a low profile in all months which we mentioned before they have high surface area and are highly populated in summer. Also, some clustered districts which are not related in terms of population or location but have similar NO_2 pollution like Cekmekoy, Arnavutkoy, and Buyukcekmece. Additionally, Beykoz district is not clustered with any districts because of their pollution while it is one of the highest in February but averages in November.

When analyzed ground-based measurements heatmap, clustering of months almost similar with TROPOMI’s heatmap but for March, April, and May some stations have very high values, and those months clustered separately. Sancaktepe station has two NA months in 2019 (January and December) and Aksaray station (in Fatih district) values are extremely high especially in Spring season which we mentioned before not cold months that may be because of stations location (if near some main-roads) also Sirinevler MTHM station (in Bahcelievler district) have high values in spring. Sirinevler, Esenler, Mecidiyekoy (in Sisli district) and Besiktas (near districts with near road connection and population) have similar pollution levels almost every month with high profile and Sile, Sultanbeyli and Kumkoy (in Sarıyer district) have similar pollution levels with low profile but there is no connection each other even Sultanbeyli much more polluted in TROPOMI retrievals.

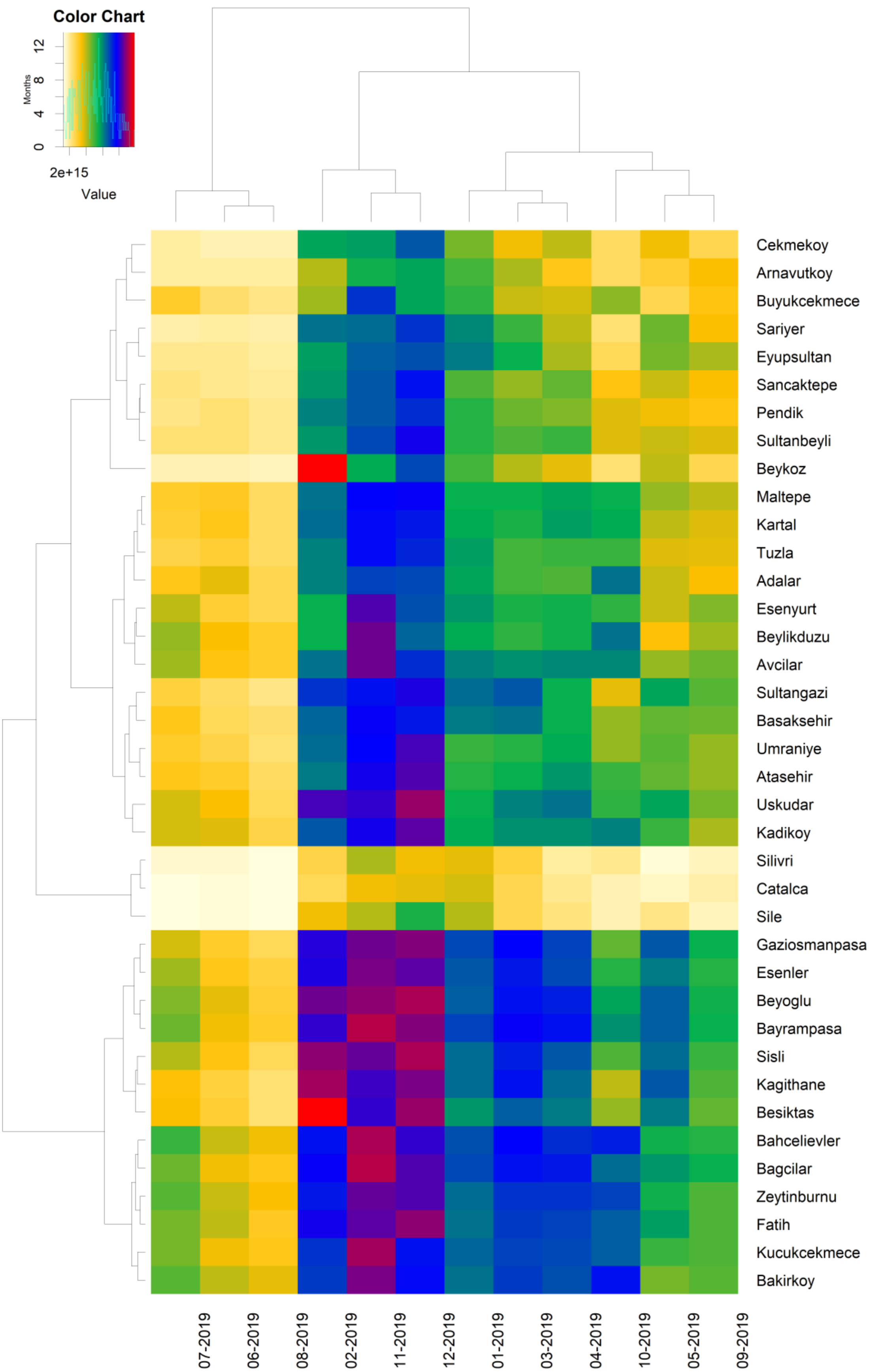

Figure 7.2 : The monthly average of NO_2 for 2019 using TROPOMI retrievals with heatmap

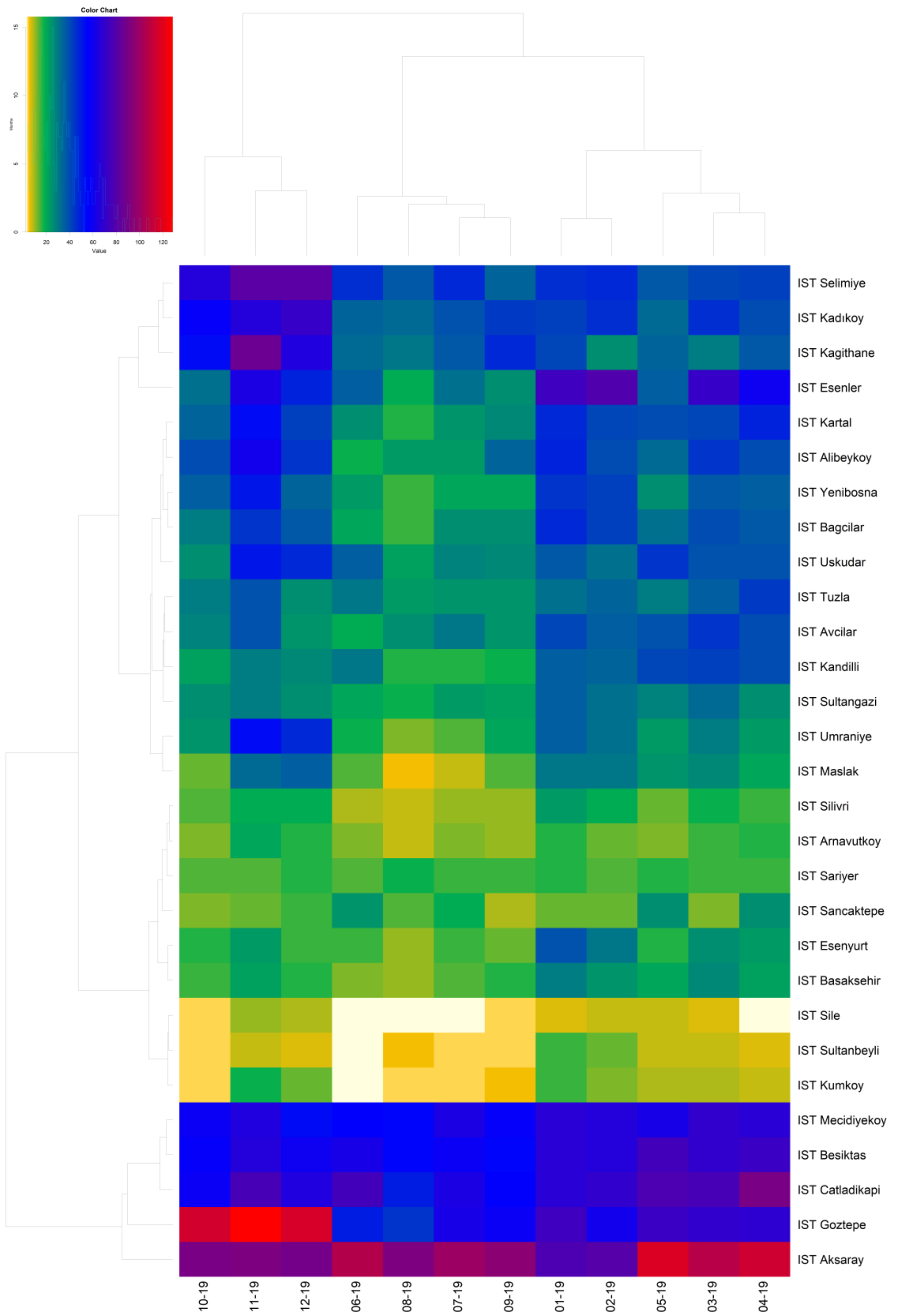

Figure 7.3 : The monthly average of NO_2 for 2019 for ground-based measurements with heatmap

The main difference between the two heatmaps is that, while seasonal changes can be easily distinguished on the TROPOMI heatmap (most districts behave in similar ways). It is difficult to say the same for ground stations heatmap, even though the months are clustered in the almost same way with TROPOMI heatmap nearly every station has a unique pattern.

Figure 7.4 shows the yearly average of NO_2 pollution in Istanbul with both TROPOMI retrievals and ground-based measurements, and results showed the pollution spreads in a layered manner. While the Bosphorus and the surrounding districts (especially Bahcelievler, Zeytinburnu, and Bakırkoy in the west) are exposed to intense pollution (5.6 – 6.5×10^{15} molecules/cm^2) pollution of NO_2 decreases to the west side of Istanbul. The main reason for this is the residence and traffic decrease as you move away from the center of the province. However, for the east side of Istanbul, the pollution does not decrease and even increases again in the Kocaeli province. It was seen that the pollution increases towards the Marmara Sea and decreases towards the Black Sea with the effect of sea vehicles. Except for Esenler and Zeytinburnu districts, all districts with higher-than-average NO_2 pollution (~3.8×10^{15} molecules/cm^2) also have higher than average natural gas usage and population (~180,000,000 m^3/year and ~450,000 people respectively). While the Bahcelievler district has the highest value, the Catalca district has the lowest value (1.61 and 6.44 × 10^{15} molecules/cm^2 respectively).

When the annual averages of the ground-based measurements are examined most of the measurements are consistent with the TROPOMI data. While Aksaray station has the highest value, Sile station has the lowest value (94.12 and 8.51 µg/m^3, respectively).

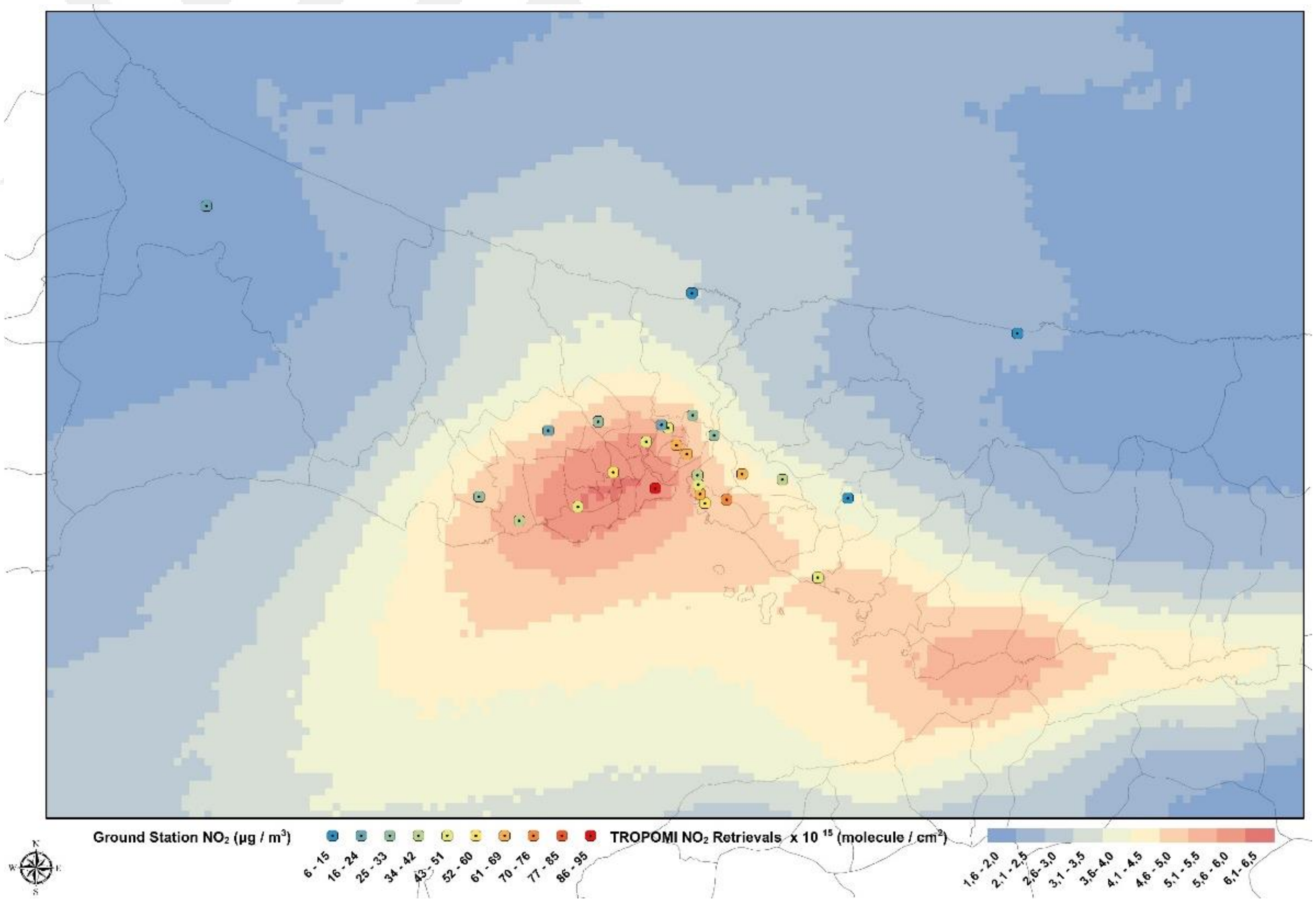

Figure 7.4 : The yearly average of NO_2 pollution in Istanbul with both TROPOMI retrievals and ground-based measurements.

Only one of the two stations in the Sisli district (Mecidiyekoy MTHM) shows lower values than expected. It is important to compare the newly released TROPOMI data with the data of ground-based NO_2 concentrations for understanding their relationship and missing parts. In Figure 7.5, measurements of all ground-based measurements which can be measured NO_2 (except Sancaktepe station because of missing values) and their TROPOMI data of the 10 km^2 area were correlated to compared ground stations and TROPOMI retrievals performance with each other. Only the first square of each row on the left to down represents ground-based measurements (bottom) and TROPOMI dataset (upper) correlation.

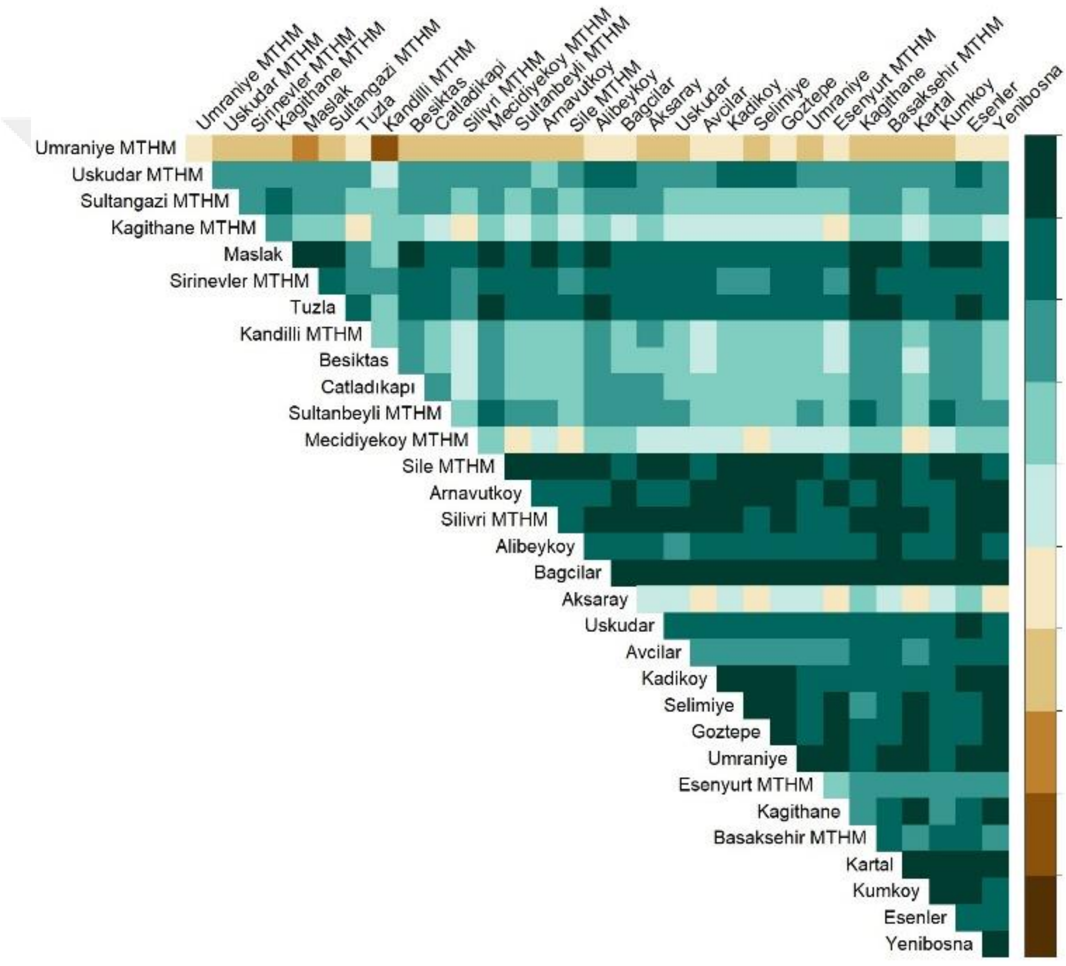

Figure 7.5 : The correlation between ground-based measurements and TROPOMI retrievals which cover 10 km^2 area of ground-based measurements

Maslak, Kartal, Kadıkoy, Bagcılar, Kadıkoy, Selimiye, Goztepe and Umraniye stations which have high values (>45.5 μg/m^3) and Sile, Kumkoy and Yenibosna which have low values (<45.5 μg/m^3) are highly correlated with TROPOMI dataset (R >0.8). Some extremely high (Aksaray, Mecidiyekoy) or extremely low (Umraniye, Mecidiyekoy) stations have no or zero correlation with TROPOMI datasets and some stations like

Uskudar, Tuzla or Silivri are moderate or low correlated with TROPOMI datasets (0.6 < R < 0.3). NO_2 pollution is highly related to human activities and habits.

In Figure 7.6, TROPOMI retrievals for each district and their urban indicators data are correlated with each other to show the relationship between them. TROPOMI retrievals are moderate-high correlated (0.8 > R > 0.6) with population, natural gas usage, and the number of residences that have a natural gas subscription and low correlation with SES score (0.4 > R > 0.2) it is mainly cause some district like Eyupsultan has a low population and natural gas usage but the high surface area and SES score and that cause low NO_2 pollution, on the other hand, some districts like Kadıkoy and Beyoglu have high NO_2 pollution, natural gas usage and SES score but low population because of low surface area. One should note that most of the districts which have low SES score than average have dense land and sea traffic because of marines and highways (Maltepe, Buyukcekmece, Sarıyer, Zeytinburnu).

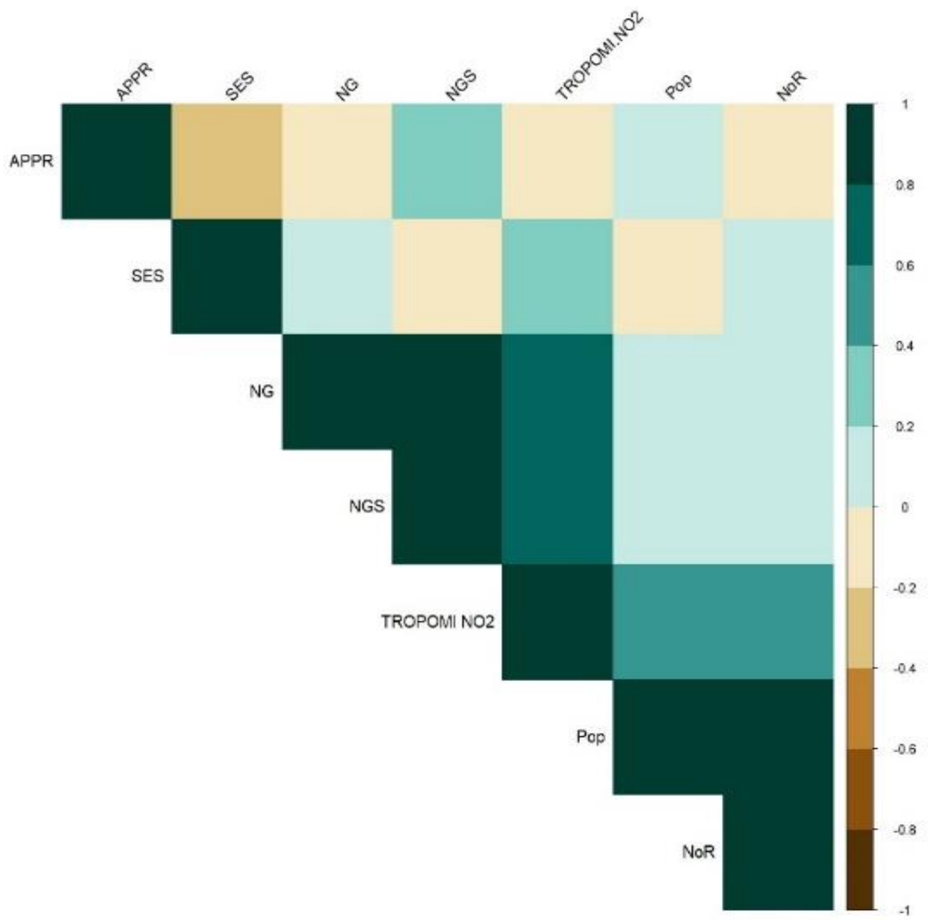

Figure 7.6 : The correlation between TROPOMI retrievals and urban indicators (APPR: Average person in per residence, SES : SES score, NG: Natural gas usage, NGS: Number of residences which have natural gas subscription, Pop: Population of districts, NoR: Number of residences.

Daily NO_2 concentration is highly related to human activities and adversely affects the life of all living things. It causes irreversible damage to people living in dense and unplanned urbanization by air and causes millions of people to die every year. The first and most important step in analyzing this pollution and creating prevention strategies is to know what to look for. It is seen that urban indicators are an effective way to analyze the daily activities of people living in megacities and are an important parameter to avoid a pollutant directly related to human activity such as NO_2.

8. CONCLUSIONS

NO_2 pollution was analyzed in this thesis covering Turkey, and the Marmara Region, which is the most important region of Turkey. The study also found important results with many sides analyses as well as showing the high values of NO_2 pollution found in densely populated areas today.

The induction method used in the study was made by processing high resolution (7×3.5 km^2) TROPOMI data with programming languages and then mapping it to the grids covering Turkey (1×1 km^2). The study outputs were analyzed and interpreted with statistical analysis, thus revealing the relationship between Turkey's current NO_2 pollution, pandemics and effects such as urban indicators. The study is the first study made in this region for NO_2, and it was aimed to be a source for NO_2 pollution prevention strategies to be made in terms of prevention.

While there are high increases in NO_2 values especially in the winter months in densely populated areas, NO_2 pollution caused by traffic and large point sources has been observed in the periods when there are no domestic heating sources such as summer and spring months. Based on two-year measurements, for regions with high NO_2 pollution in both winter and summer, the levels were lower in 2020 than in 2019, but the results showed that NO_2 pollution still has high values, especially in the urban areas.

In addition to the TROPOMI retrievals, ground-based measurements were also used in the study, and the correlation between two different datasets and their representation of pollution in the region were examined. The limited measurement area of the ground stations makes them insufficient for large-scale studies. Besides the advantage of a large measurement area in satellite retrievals, they have the disadvantage of not being able to represent all the pollution of the whole day because of the crossing time, and giving low-quality or incomplete data due to factors such as cloud cover.

These two datasets used in the study and the relationship between them showed that satellite retrievals is more efficient in representing the NO_2 pollution of the Marmara region. There are multiple reasons for this situation. The primary reason is that the ground measurement stations have incomplete or erroneous data in many months and regions (mostly in the winter months with heavy pollution and at densely populated areas). It was possible to see differences even between stations located very close to each other and within the same district borders (for example IST Goztepe and IST Kadikoy, KOC Gebze and KOC Gebze OSB stations). As a result of the two-year measurement analysis, IST Kadikoy station is the most polluted district with 155 μg/m^3 on a monthly average (August 2020), while IST Aksaray station is the most polluted district with 102 μg/m^3 in the two-year average. The fact that these two districts have very low values in October, November and December 2020 is a good example of the above-mentioned and considered erroneous data.

The correlation analysis between stations and satellite retrievals showed that Marmara Region stations do not reflect the pollution of this region very well, and some stations have values that have zero or negative correlations with both satellite retrievals and the ground-based measurements of other measurement stations. The satellite retrievals used in this analysis were selected to belong only to the measurement area of the ground measurement station.

When the ground-based measurements and satellite retrievals time series in all districts were examined, it was seen that many stations were insufficient to represent the NO_2 decreases during the curfew period, but satellite retrievals could show these reductions in those time intervals. Cluster analyses made similar to this, while the seasonality of satellite retrievals can showed cluster between districts located in nearby districts or having similar characteristics (population, number of vehicles, industry), but it can’t be observed for the ground measurement stations.

In addition to being the focus of the study, the analysis of the effects of the pandemic was tried to be understood in this analysis, the effect of changing daily routines as a result of restrictions on pollution was investigated. The results showed that while the NO_2 decreases are high as a result of the pandemic restrictions in the districts with population or industrial density, decreases were observed at a lower rate and even increases in some regions in low population or partially rural areas were found.

Pandemic restrictions, which are considered as two separate periods, the decreases in the time interval that started in March 2020, which is the first restriction period, are higher than the period after November 2020, which is the second period, according to the NO_2 satellite retrievals. While the biggest decrease in the March period was observed in Kocaeli Dilovası District, where NO_2 pollution decreased by 38.5% compared to 2019, for the November period, and for Istanbul Kadıkoy District with

25%. Satellite retrievals used in this part of the study were selected to cover only urban settlements and their surroundings, using CORINE land use dataset.

The study also analyzed urban indicators and their effects on air pollution, in the analyzes that included the comparison of the ground-based measurements and the TROPOMI data, it was concluded that the data of the ground-based measurements were insufficient and needed to be improved. In the study, during the pandemic period (March-December 2020), a decrease in NO_2 pollution was observed in the Marmara Region compared to the pre-pandemic period. In addition, as a result of the analyzes made for the province of Istanbul, including satellite retrievals, ground-based measurement, and urban indicators, it was concluded that NO_2 pollution was directly related to the region where the people living in the province live, their income level and natural gas consumption.

Satellite retrievals obtained on the basis of all districts showed that especially the districts located on the shores of the Bosphorus and the Marmara Sea are exposed to much more intense pollution than the districts on the Black Sea coast. However, the fact that the pollution levels of districts with intensive industry are close or even less than districts with dense population and traffic, reveals the dimensions and risk of NO_2 pollution originating from urban areas.

In conclusion, this thesis showed that the TROPOMI retrievals can detect NO_2 pollution of Turkey, revealed the deficiencies with the comparisons made with the ground-based measurements and examined the pollution changes in the districts of the Marmara Region during the pandemic period. Also, the study revealed the relationship between urban indicators and NO_2 pollution on a district basis for Istanbul.

9. DISCUSSION AND FUTURE WORKS

In this thesis national NO_2 pollution levels for Turkey were investigated with TROPOMI, the newest and most advanced remote air pollution measurement instrument along with ground-based measurements. In the study, using the deductive method, examinations were made for Turkey, Marmara Region, and Istanbul for the years 2019 and 2020. The results of the study found that the Marmara Region has the highest NO_2 pollution in winter and the most important reason is domestic heating. In addition, the decreasing air pollution with the effect of the pandemic restrictions in the Marmara Region was discussed in detail and the results were evaluated with statistical methods.

Satellite retrievals are one of the most effective methods used for air pollution analysis on a global scale, and its use with many different data increases the accuracy of the researches. Satellite retrievals are often used in conjunction with ground-based measurements and emissions inventories. In this study, satellite retrievals were used together with ground-based measurements for both verification and comparison purposes. When Turkey's NO_2 pollution was examined, it was seen that the pollution has spread to all the surrounding provinces, not only known for its high population and industry. According to the results of the study, Turkey should implement NO_2 pollution prevention practices, especially in densely populated regions such as Marmara Region.

The most important problem encountered in the thesis was that the ground-based measurements have quite low signals or are insufficient. As a result of this evaluation made specifically for the Marmara Region, it was clear that ground-based measurements should be improved to developed and expanded for future studies. In addition, the results of the study showed that the NO_2 pollution of the Marmara Region at high levels for all Turkey, even during the time intervals that affect the whole world, such as the COVID-19 pandemic, and when life stoped. Future studies would include broader and more detailed analyses of this period and more important information about the impact of the population and its habits on air pollution.

Urban indicators and NO_2 analysis specific to Istanbul proved the direct impact of the lives of people who will continue to live in urban areas on air pollution. In addition, many other urban indicators were not used in the study, but should be added for future work. It can reach more important and broader results by using indicators such as working time interval traffic density, number of working people.

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APPENDICES

APPENDIX A. Monthly Pollution Distribution Maps

APPENDIX B. Time Series of NO_2 Satellite and Ground-Based Measurements for Selected Districts

APPENDIX A. Monthly Pollution Distribution Maps

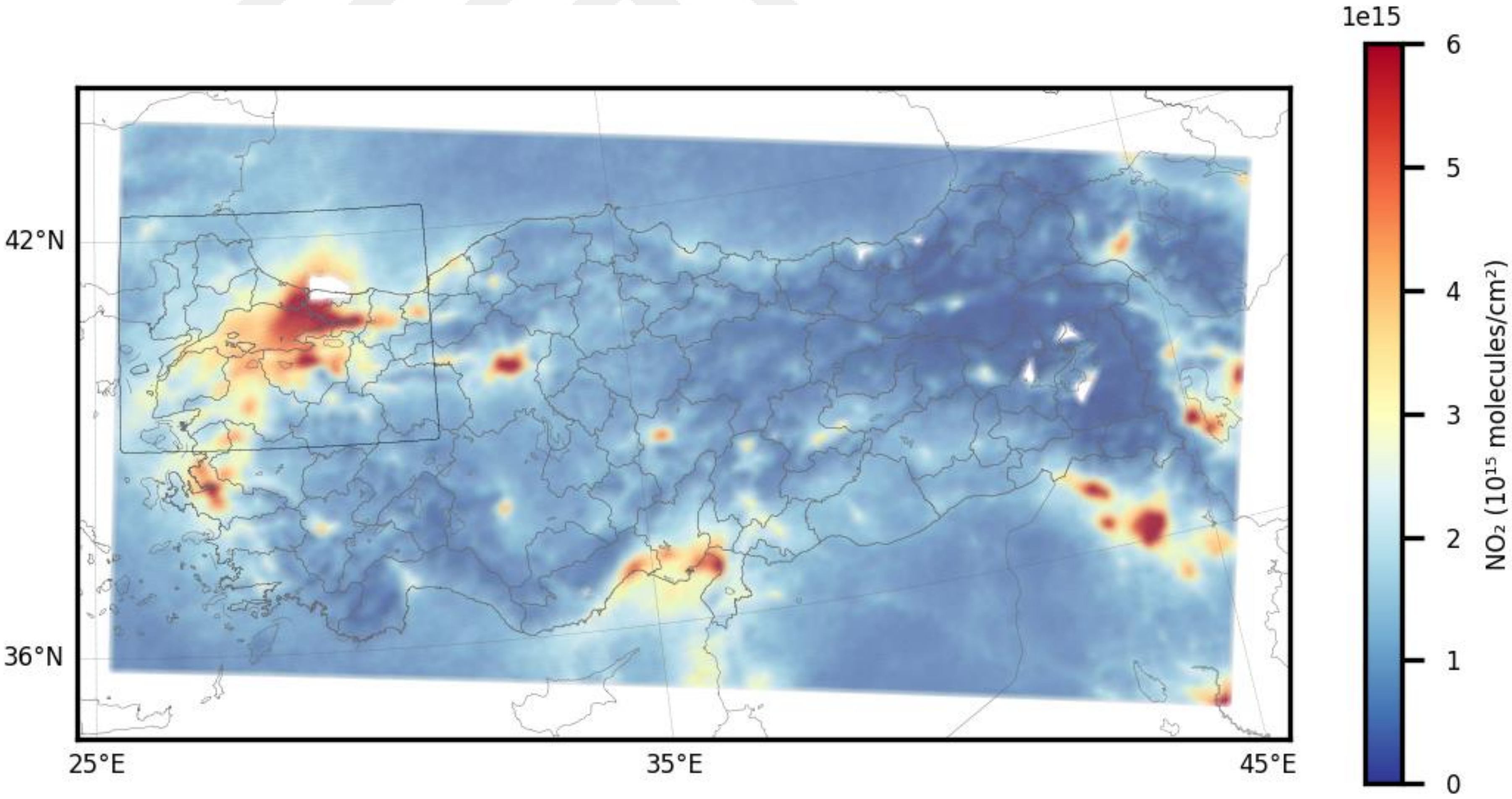

Figure A.1 : NO_2 distribution of Turkey for February 2019

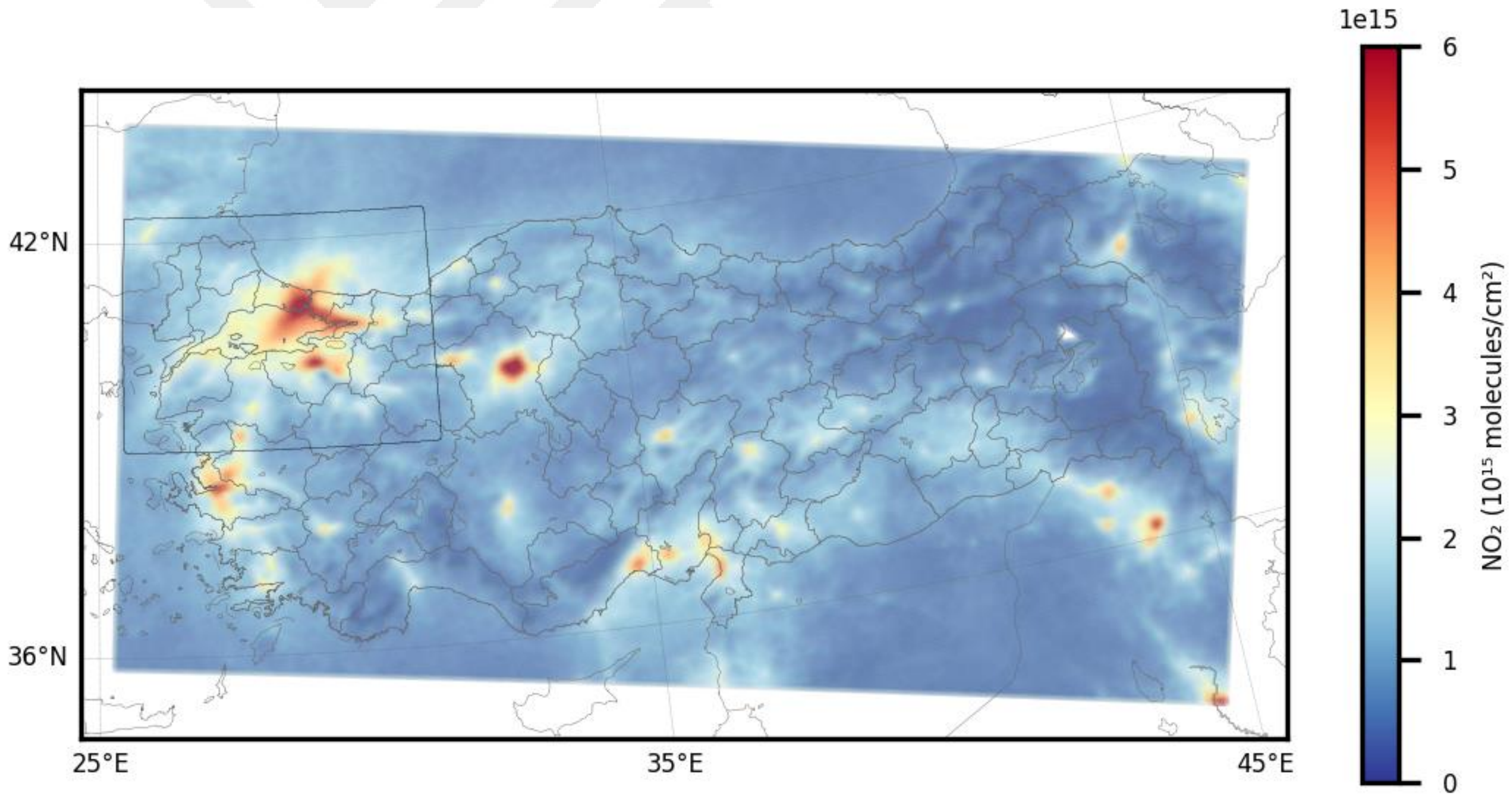

Figure A.2 : NO_2 distribution of Turkey for March 2019

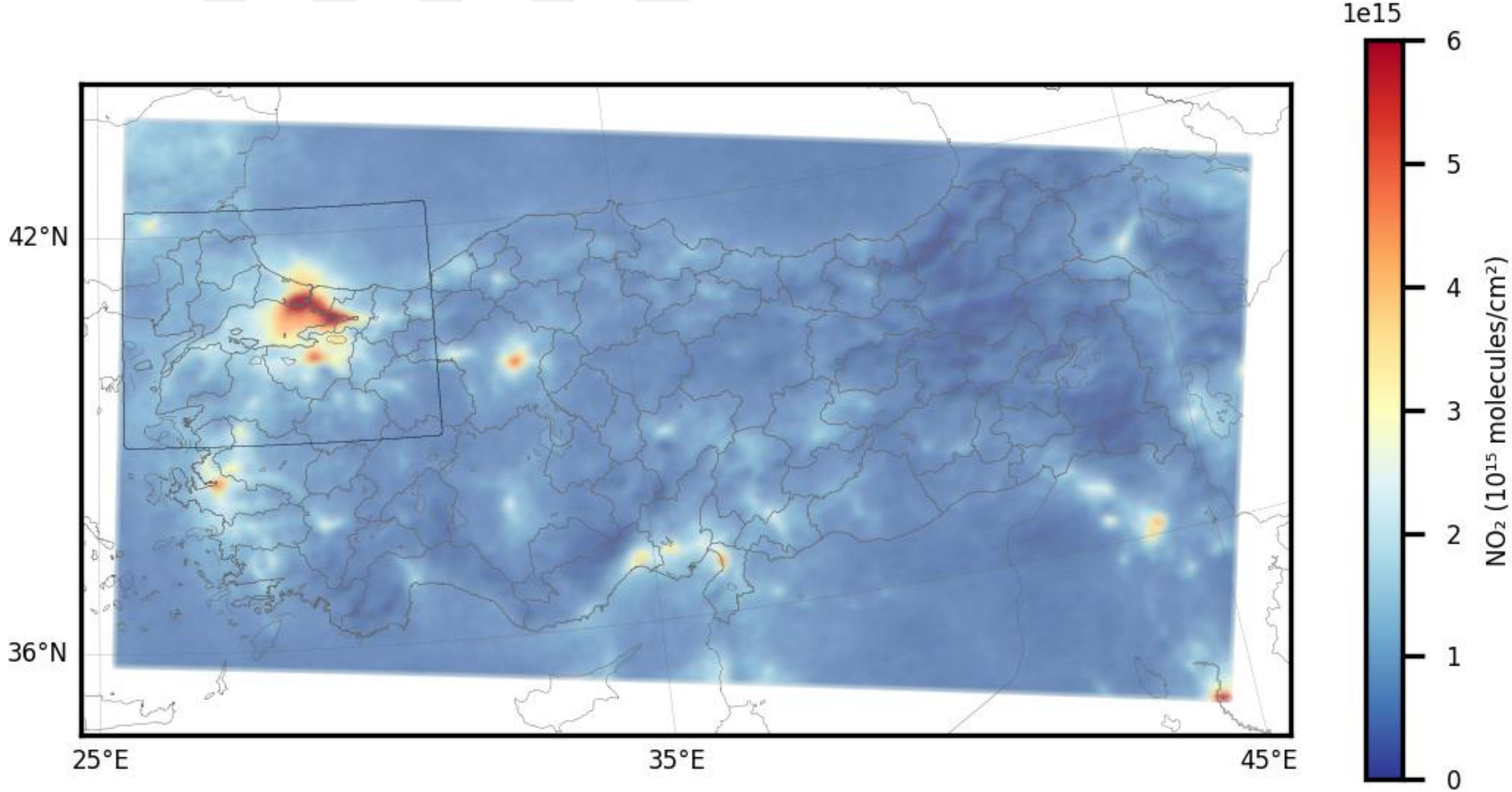

Figure A.3 : NO_2 distribution of Turkey for April 2019

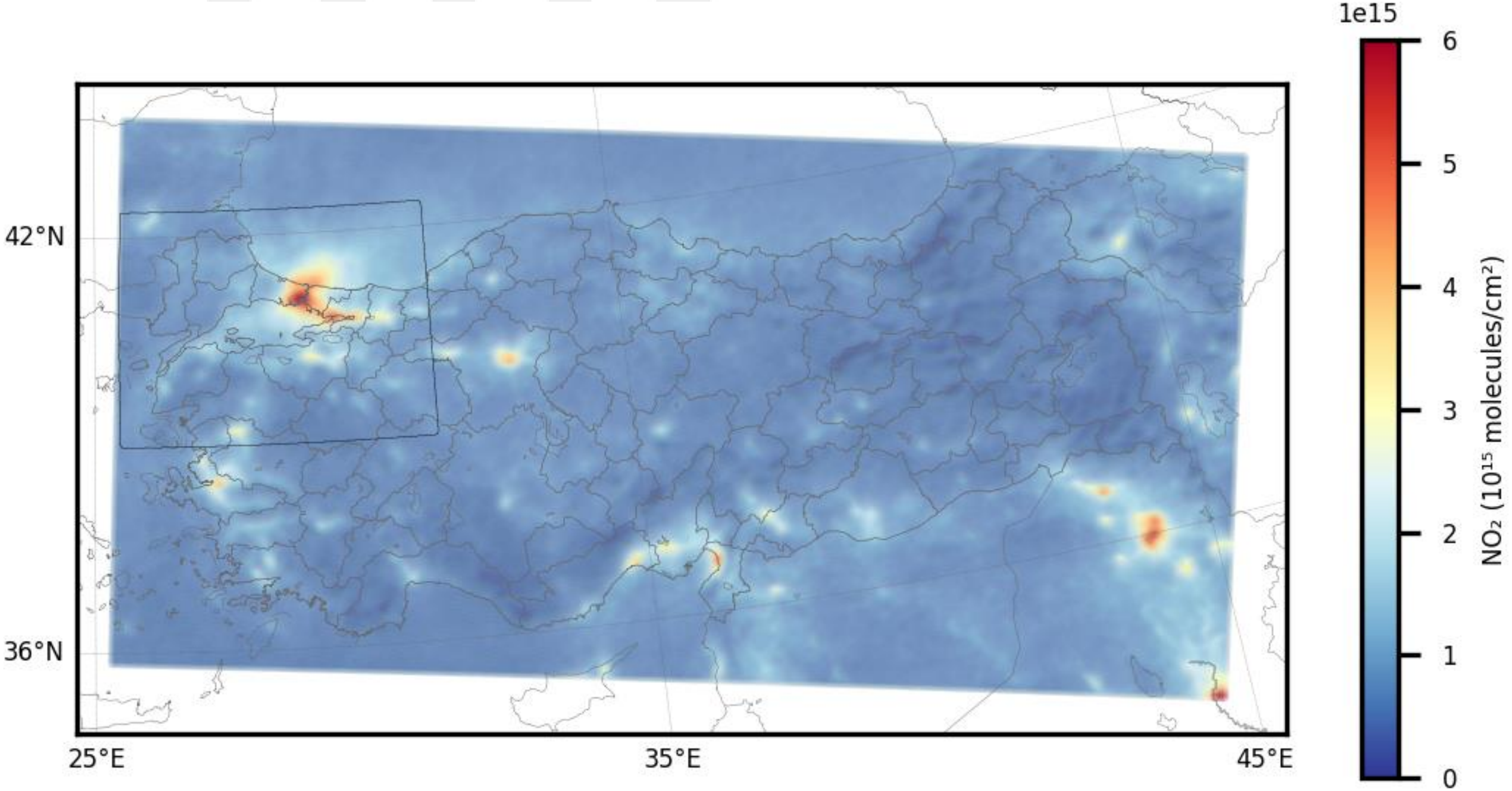

Figure A.4 : NO_2 distribution of Turkey for May 2019

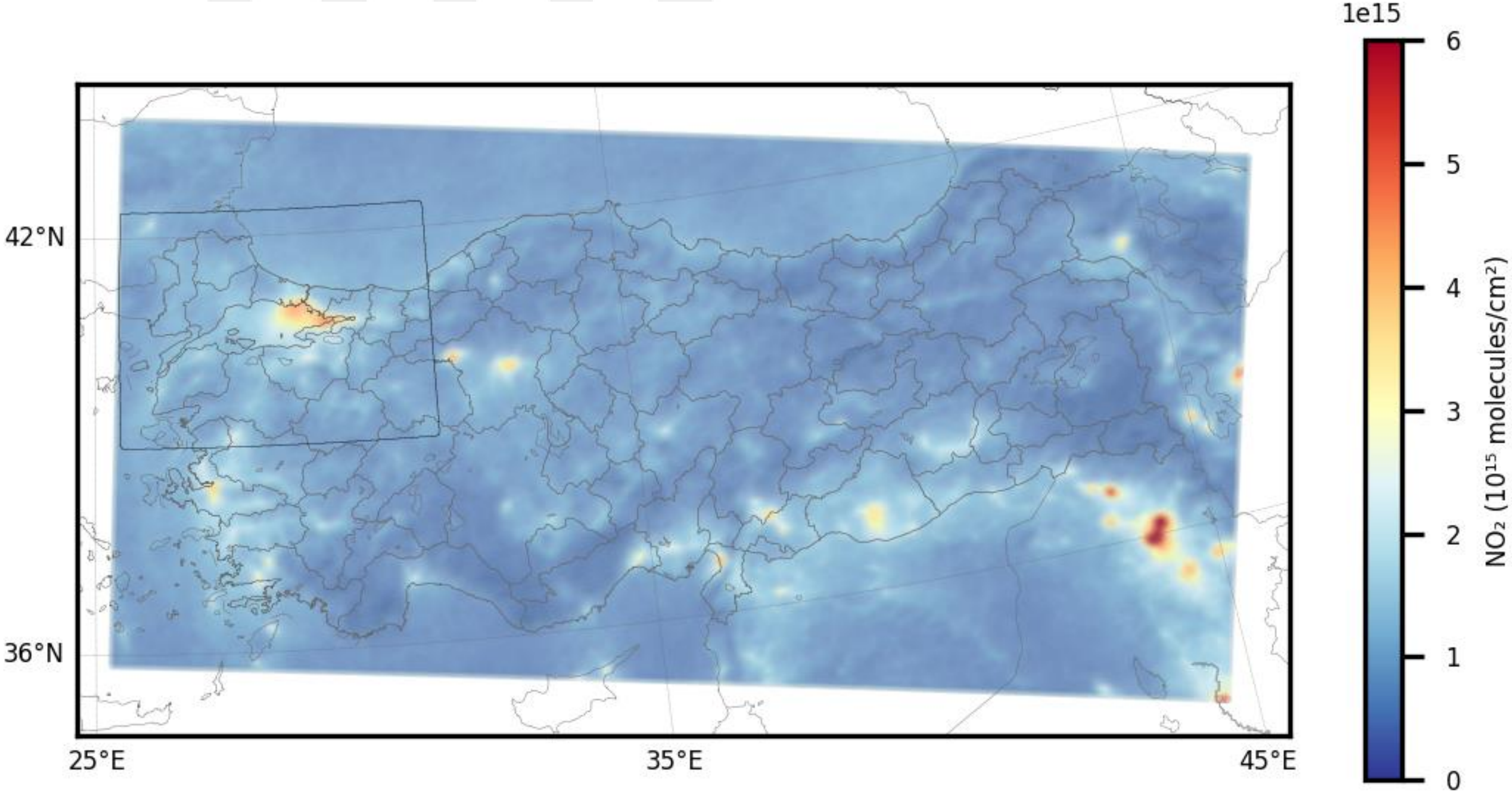

Figure A.5 : NO_2 distribution of Turkey for June 2019

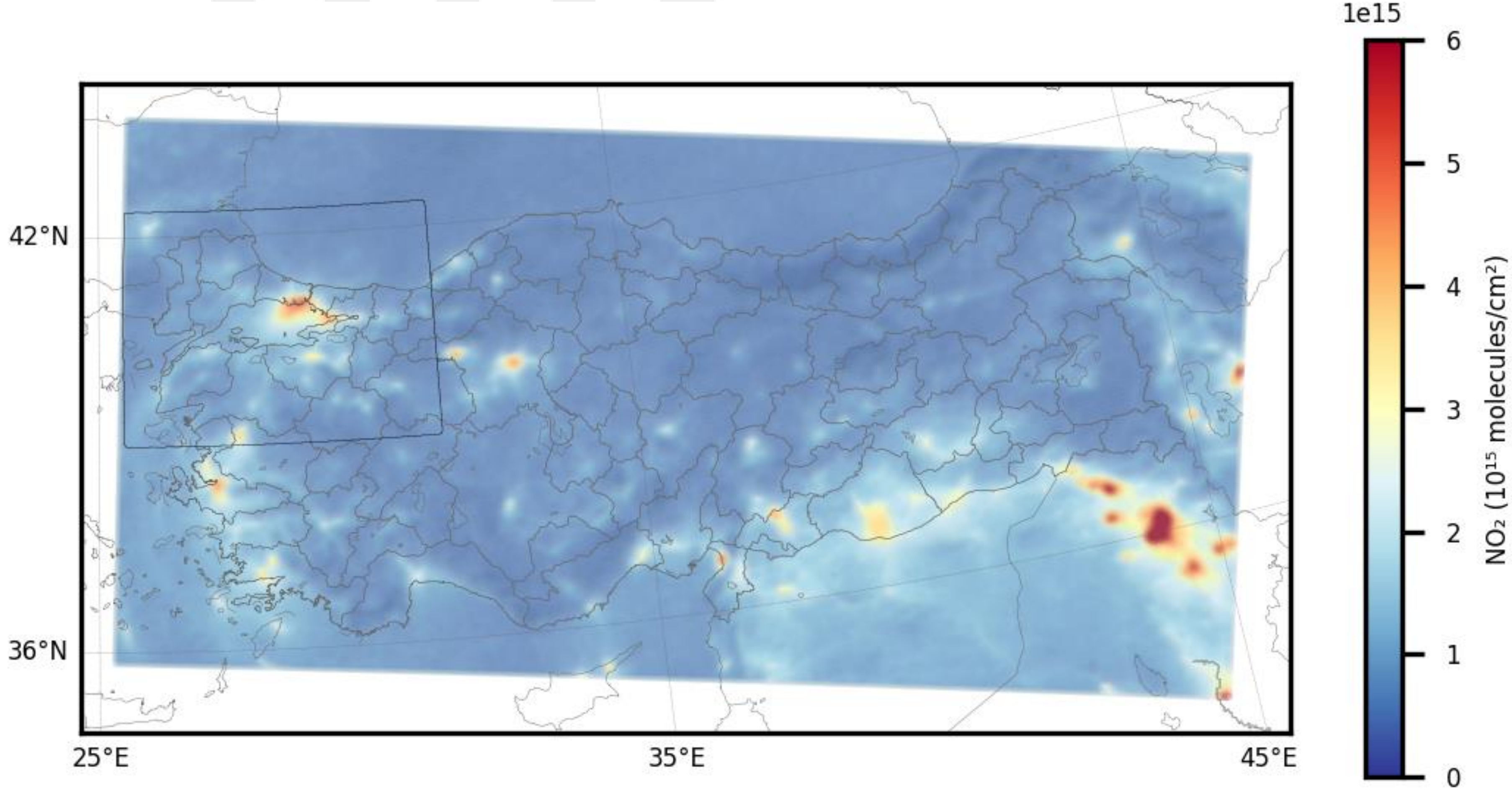

Figure A.6 : NO_2 distribution of Turkey for July 2019

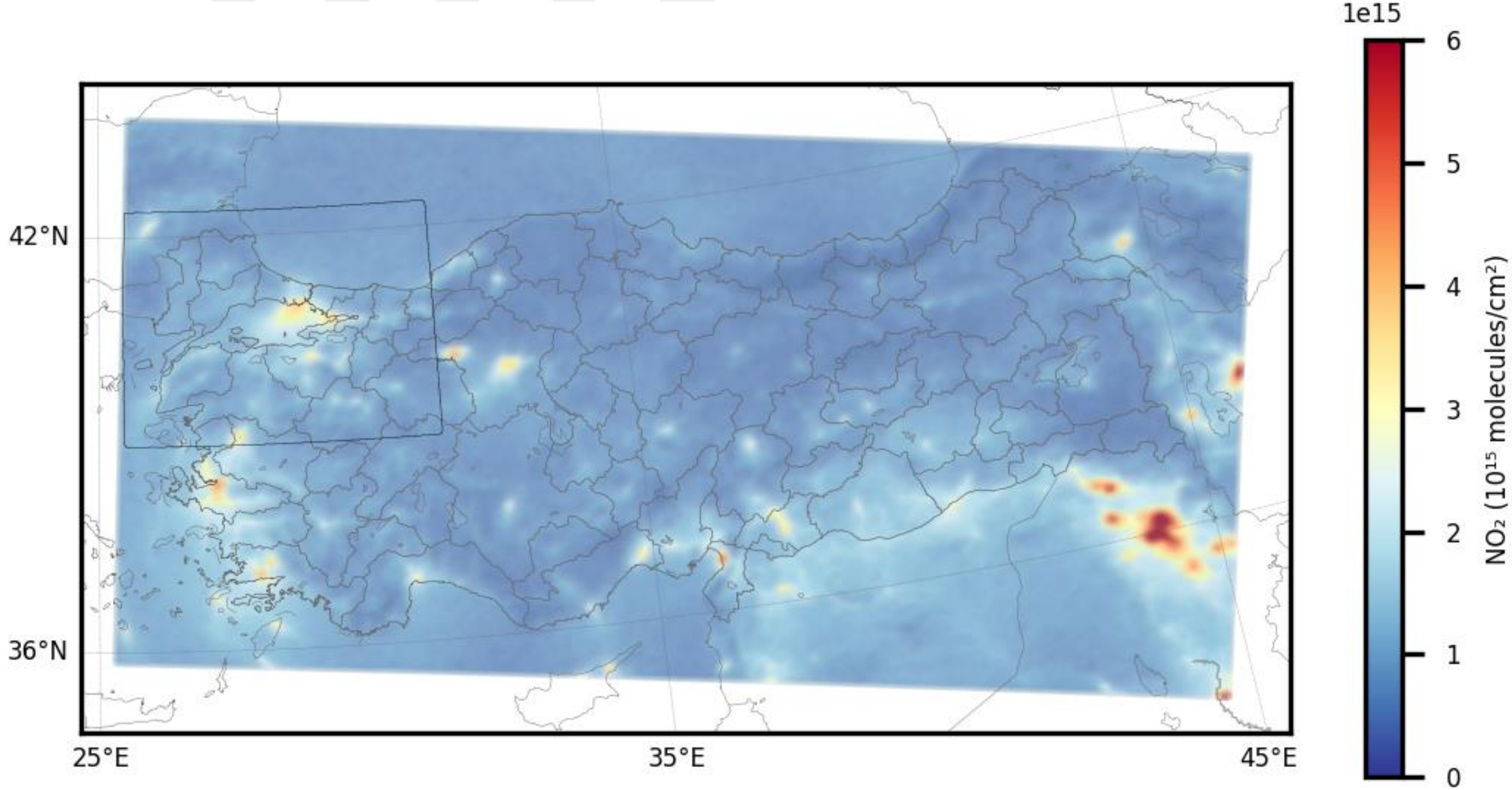

Figure A.7 : NO_2 distribution of Turkey for August 2019

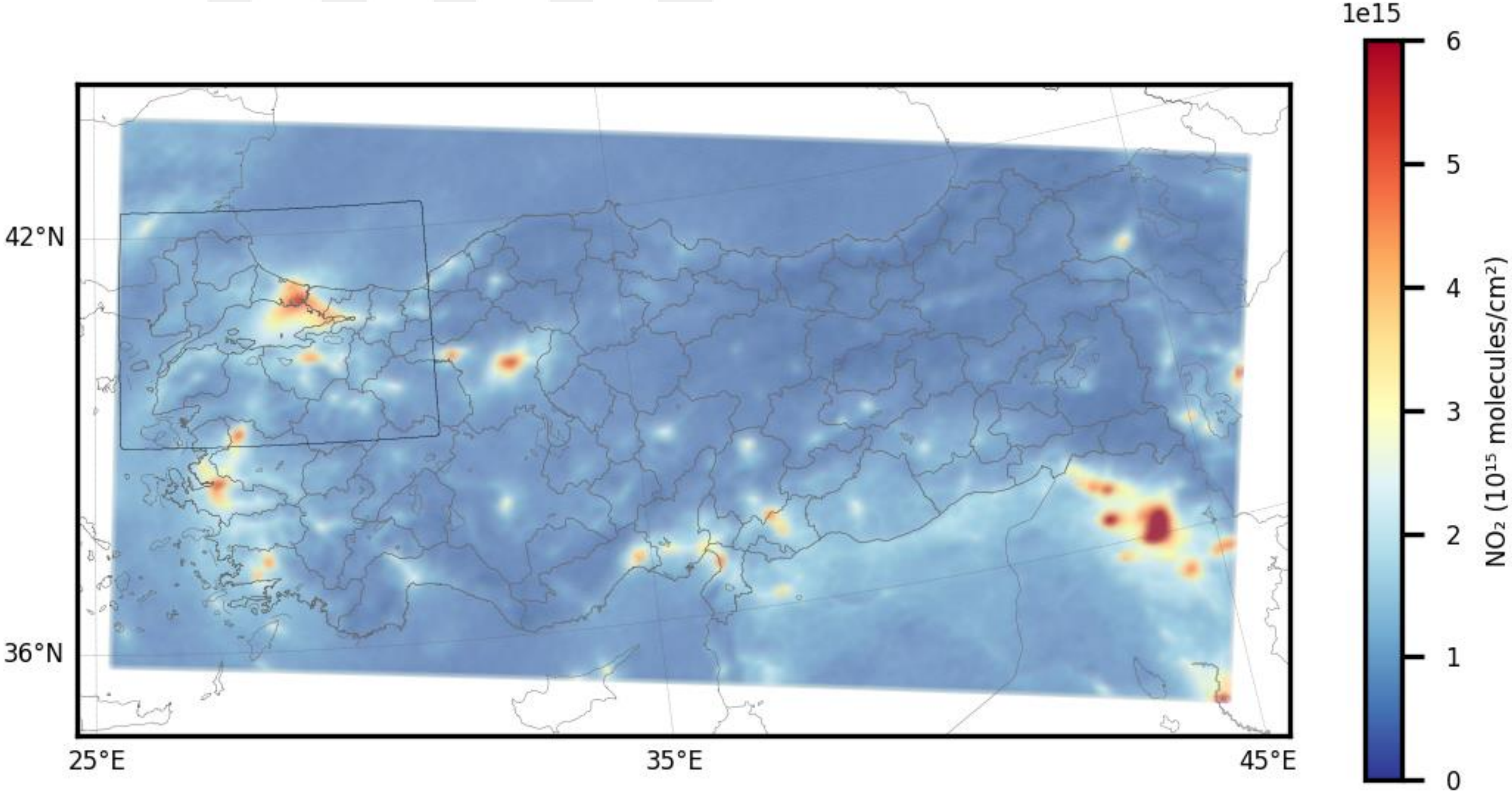

Figure A.8 : NO_2 distribution of Turkey for September 2019

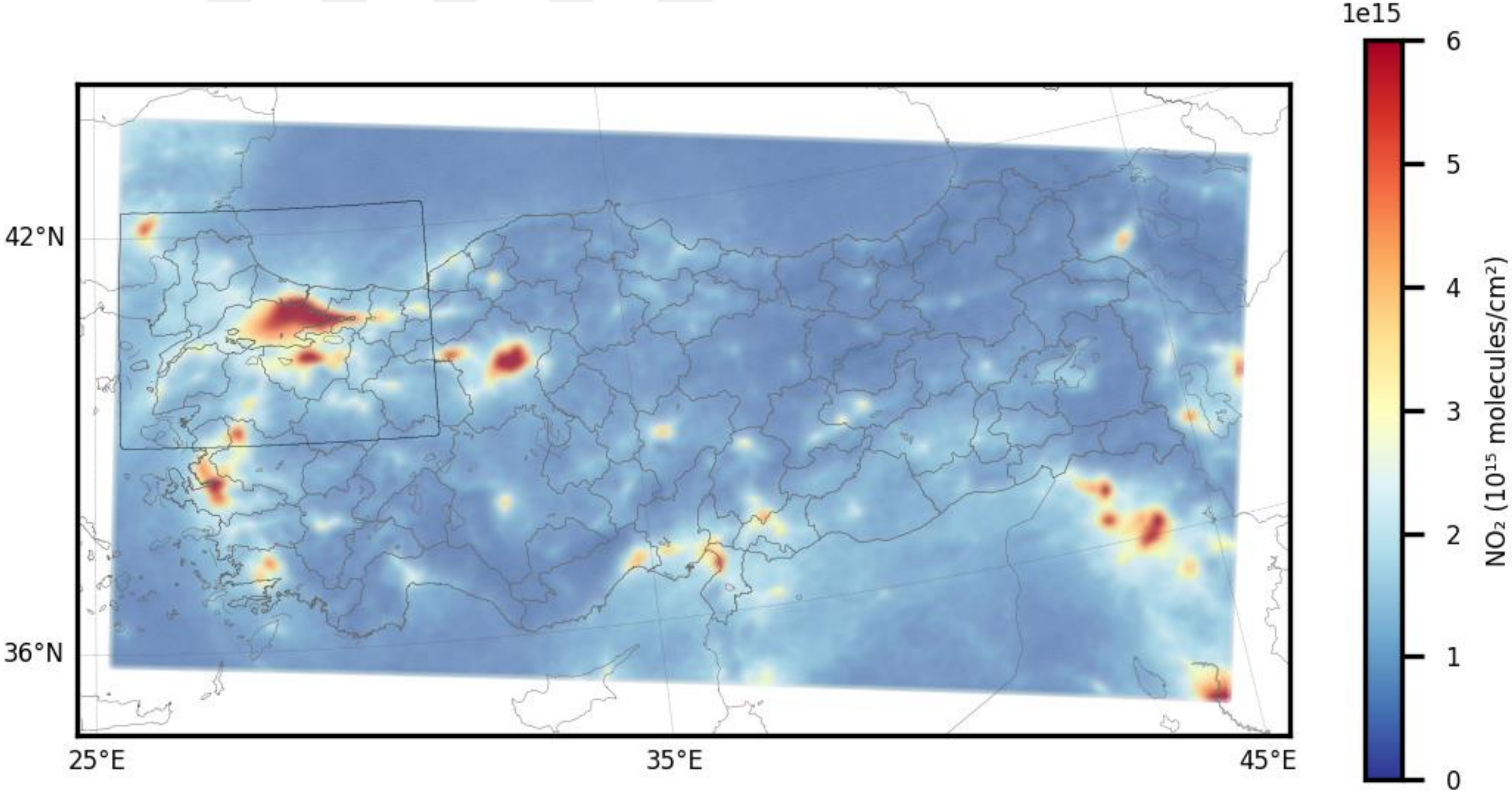

Figure A.9 : NO_2 distribution of Turkey for October 2019

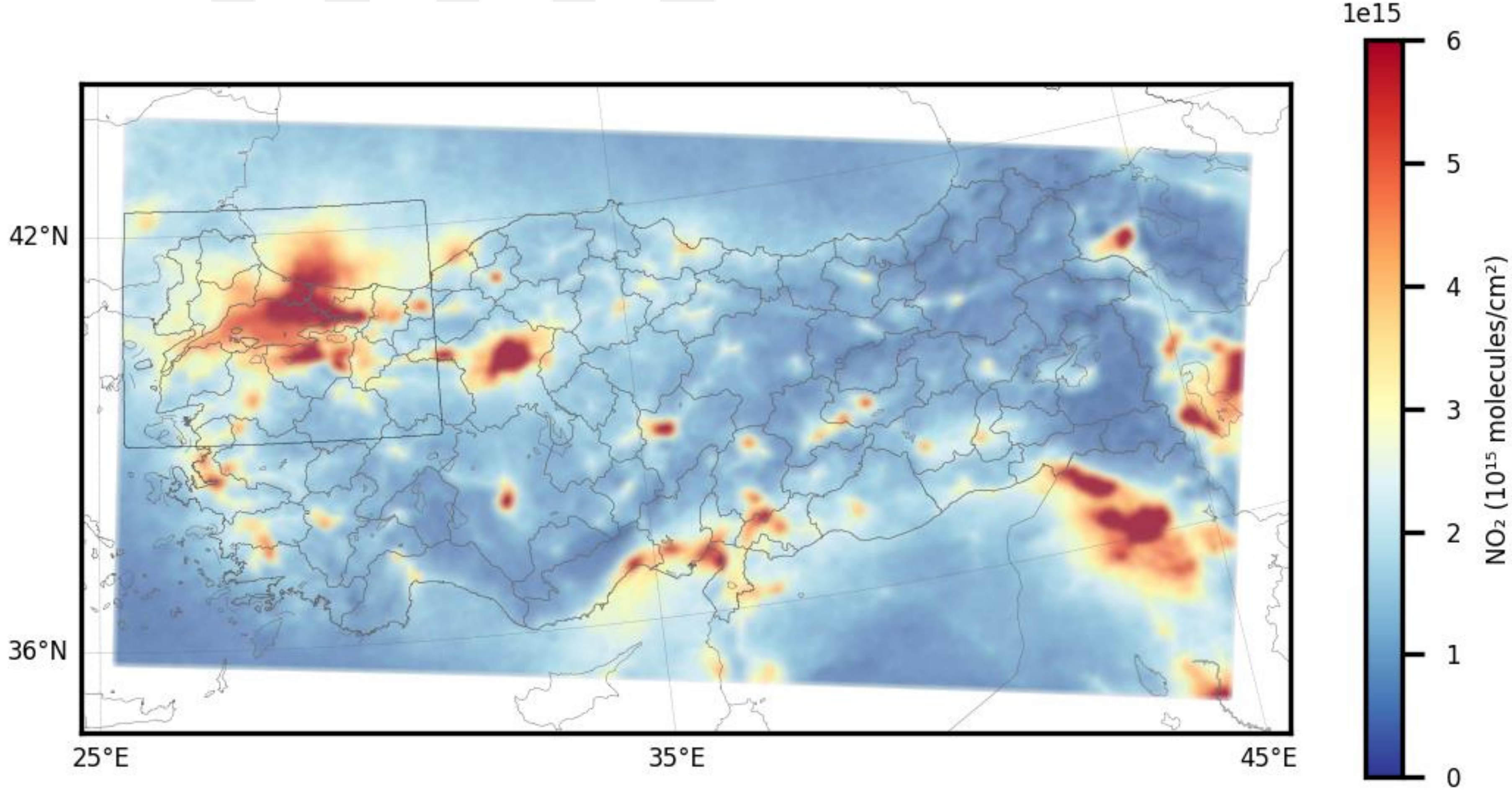

Figure A.10 : NO_2 distribution of Turkey for November 2019

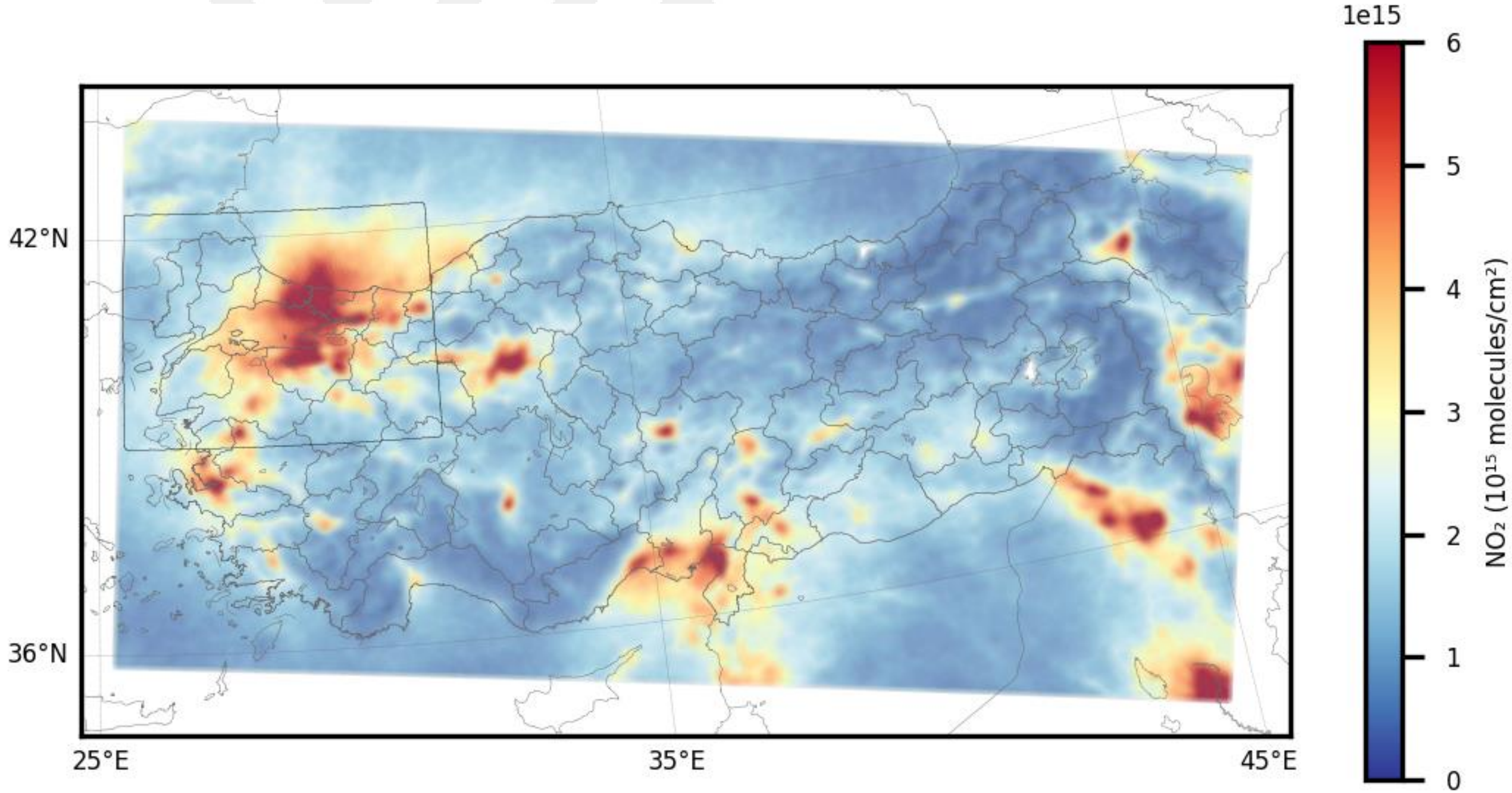

Figure A.11 : NO_2 distribution of Turkey for December 2019

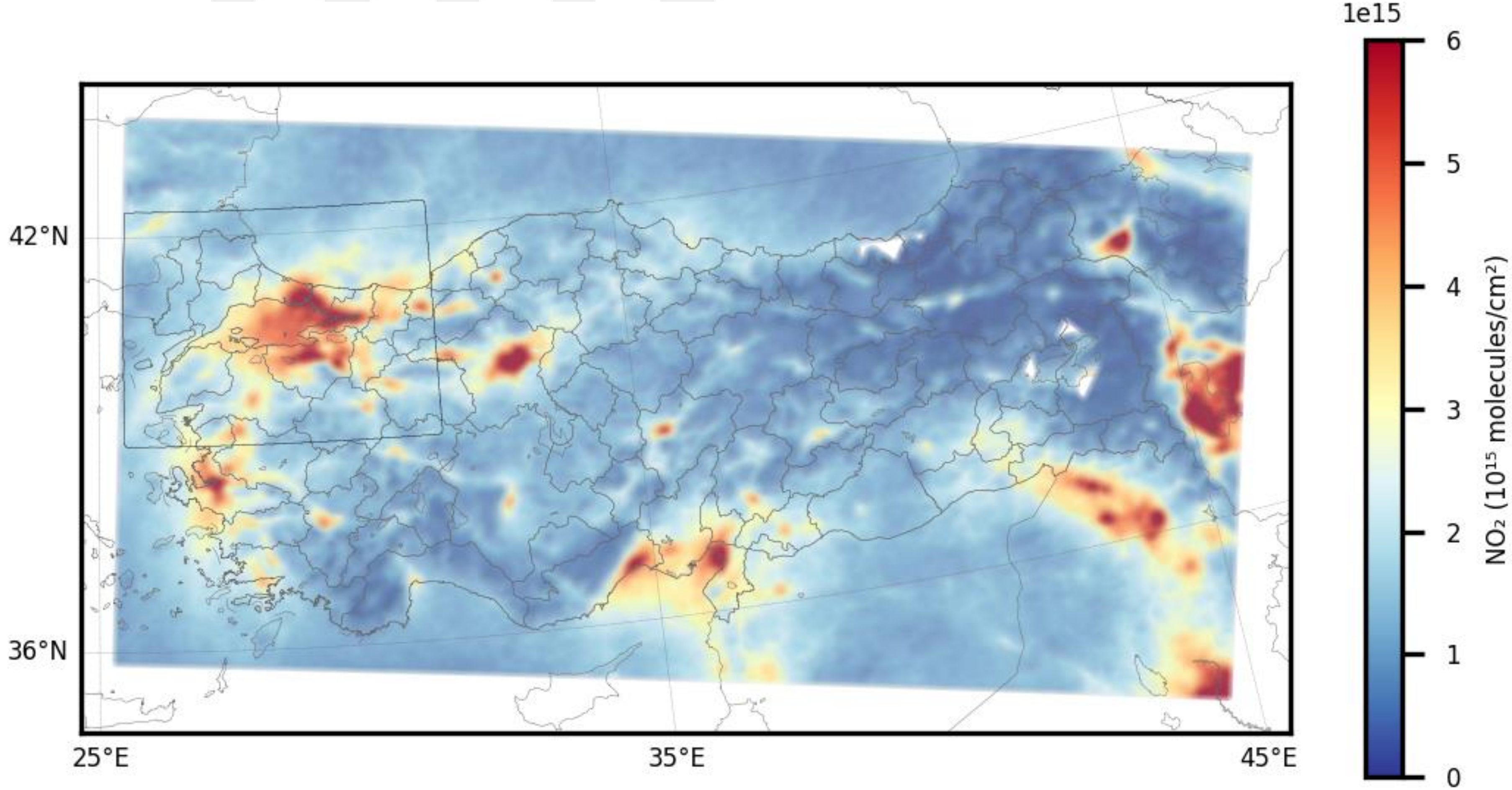

Figure A.12 : NO_2 distribution of Turkey for January 2020

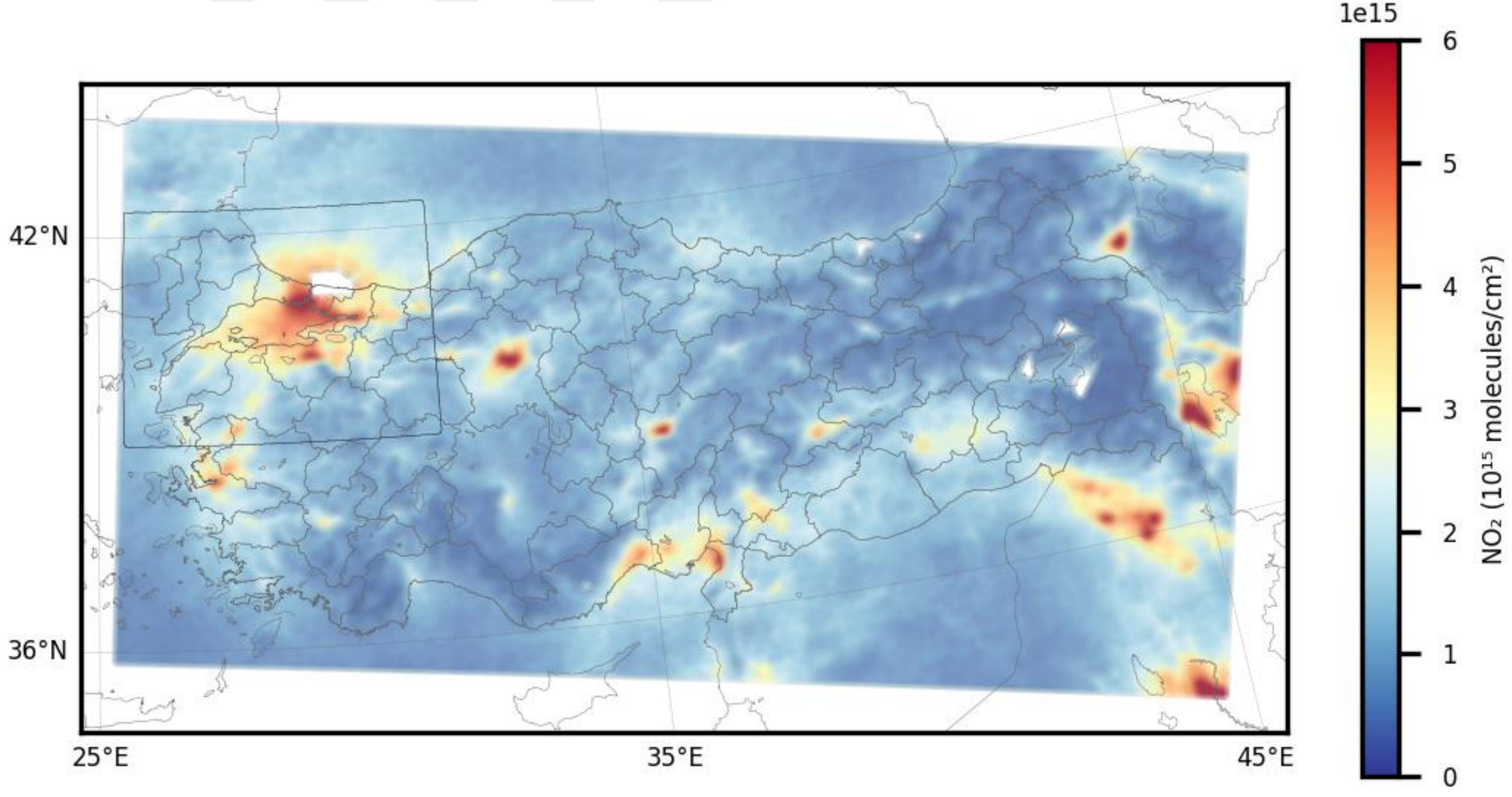

Figure A.13 : NO_2 distribution of Turkey for February 2020

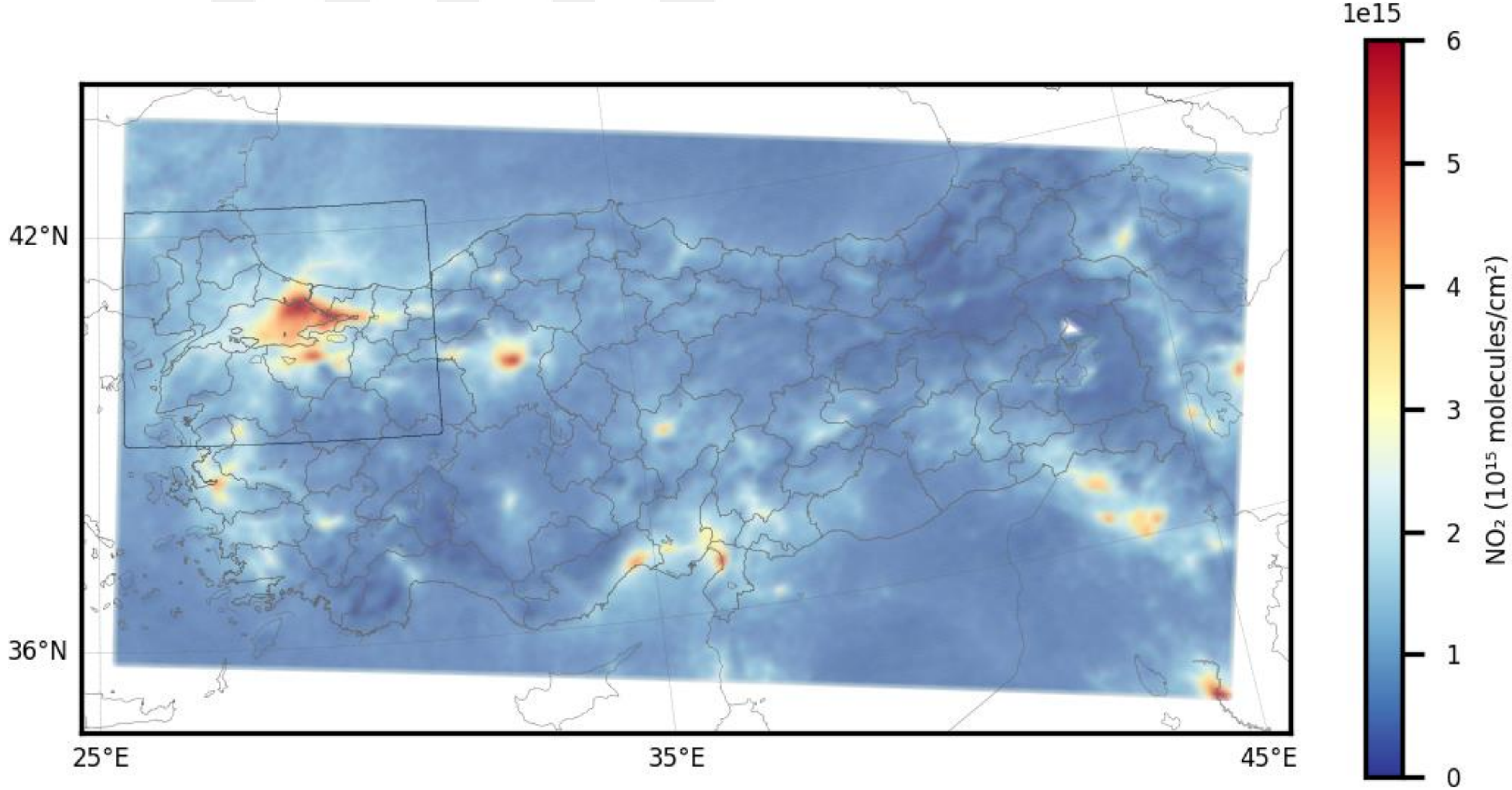

Figure A.14 : NO_2 distribution of Turkey for March 2020

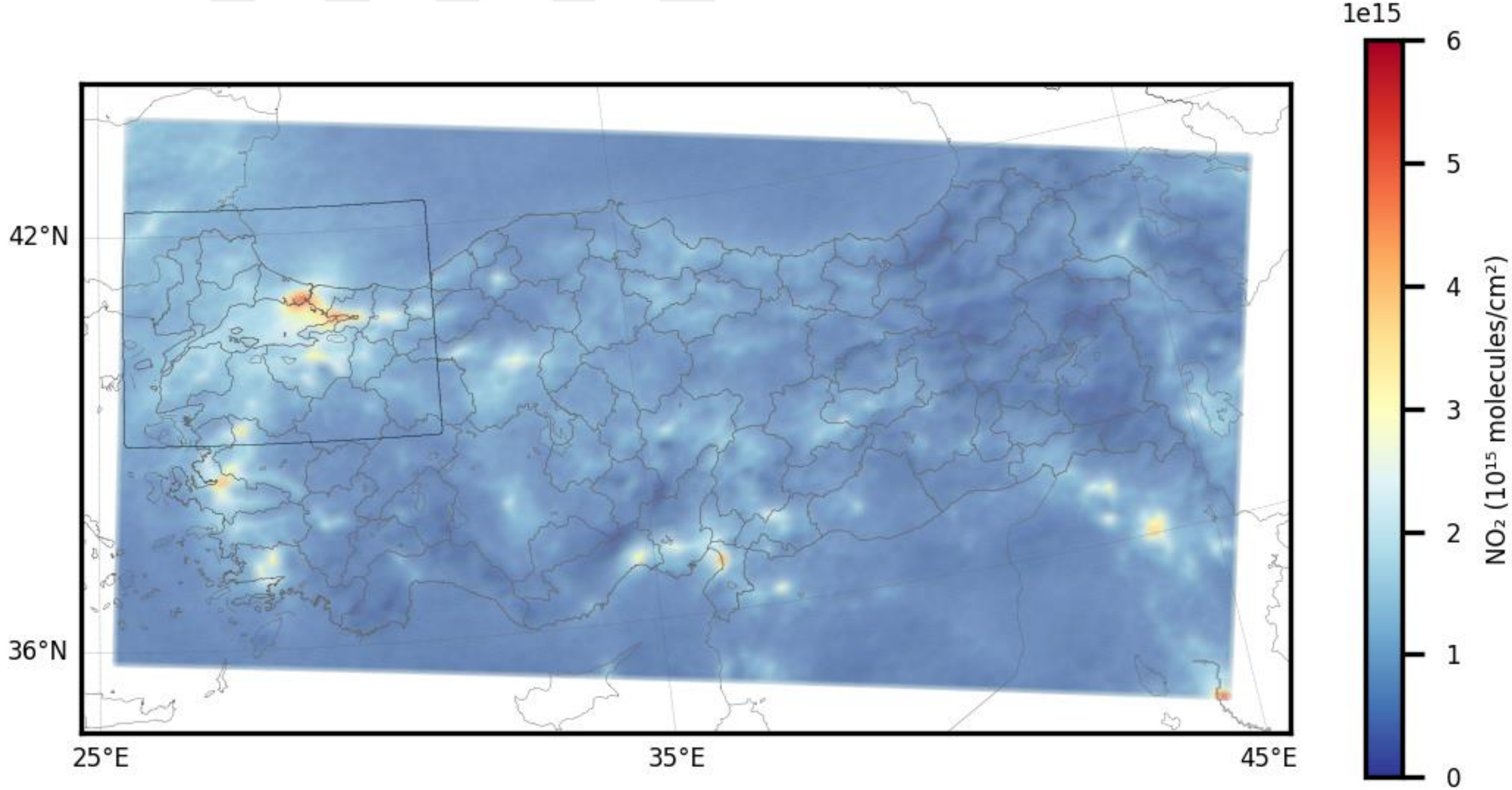

Figure A.15 : NO_2 distribution of Turkey for April 2020

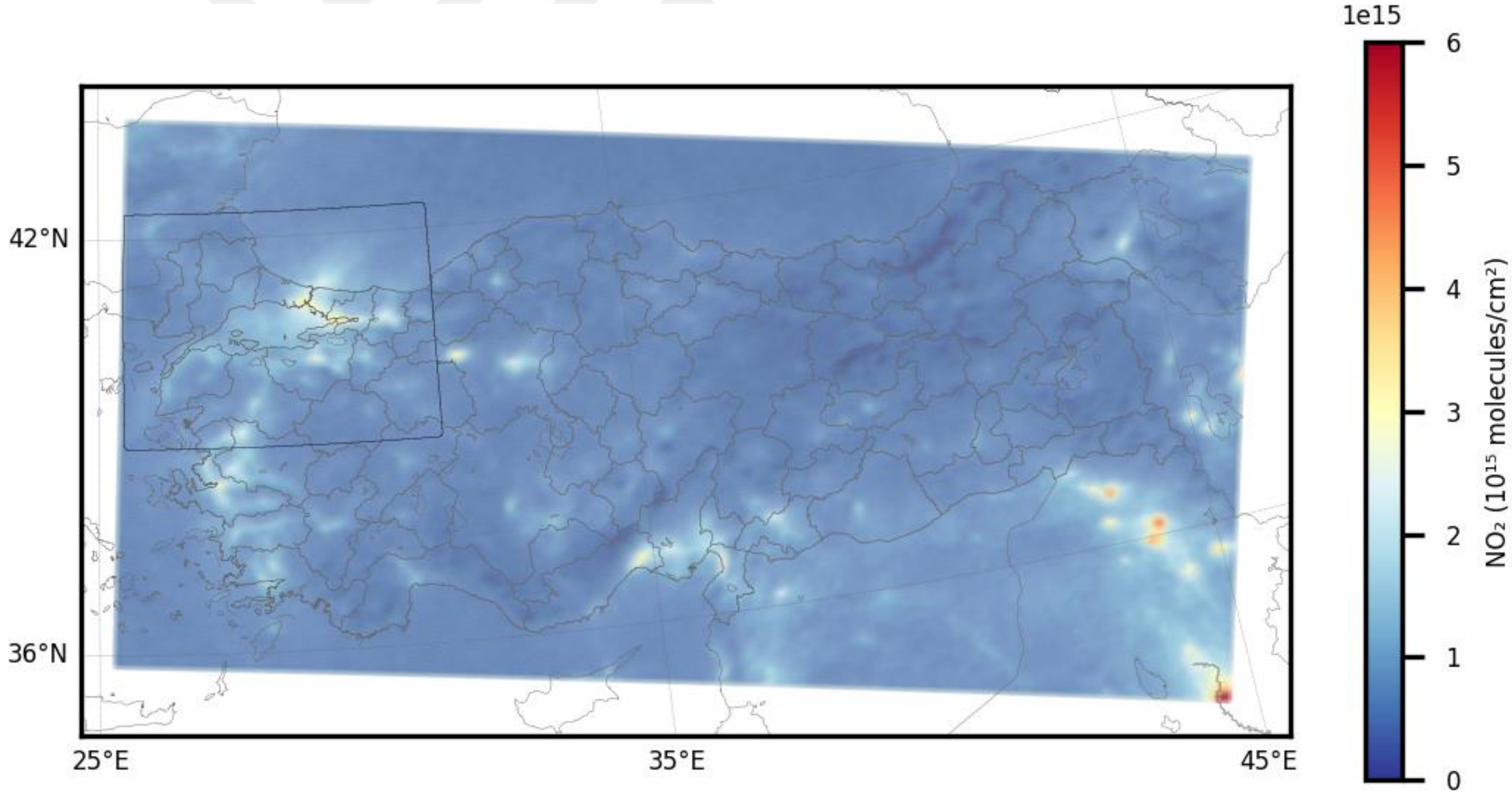

Figure A.16 : NO_2 distribution of Turkey for May 2020

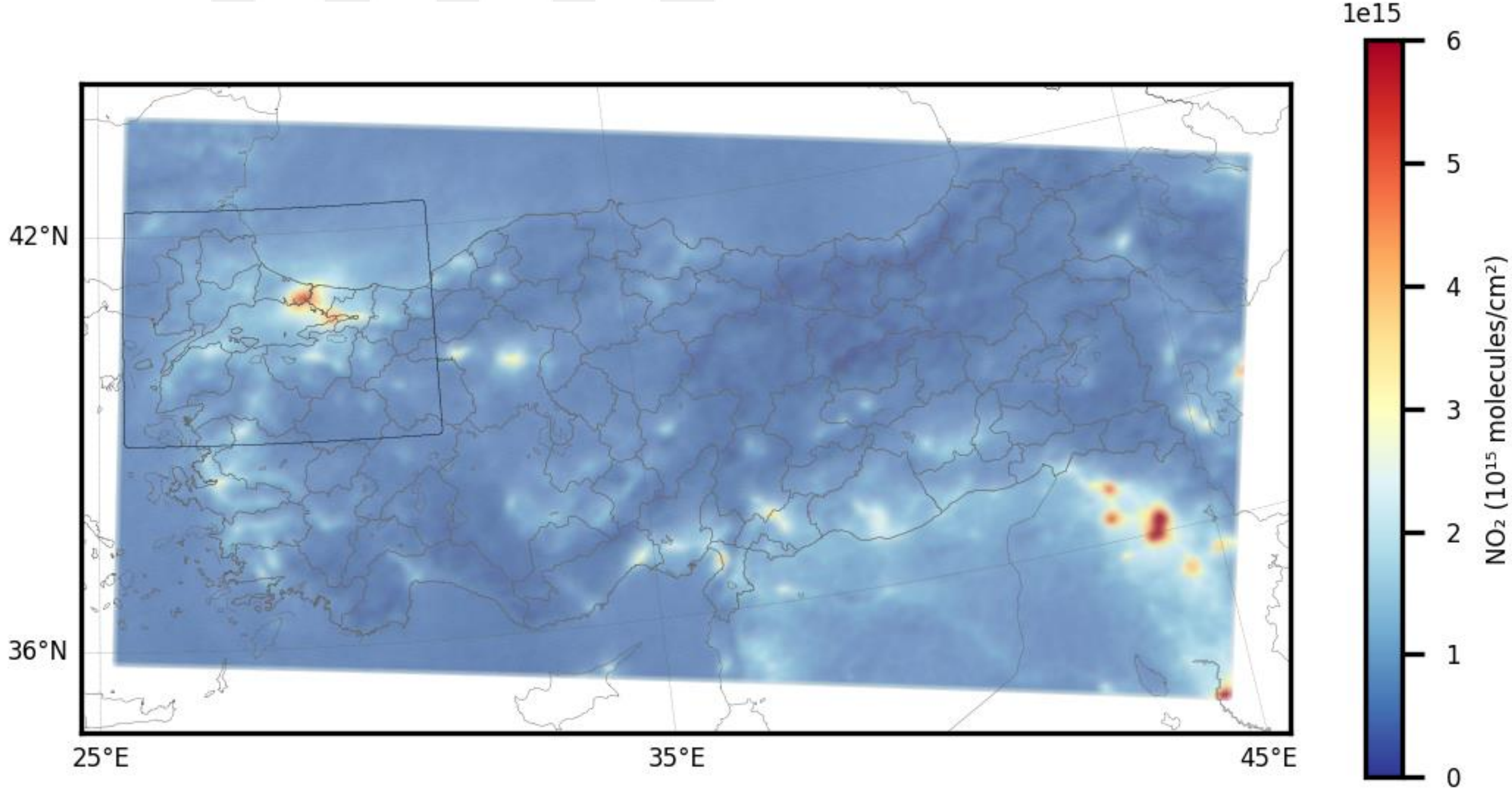

Figure A.17 : NO_2 distribution of Turkey for June 2020

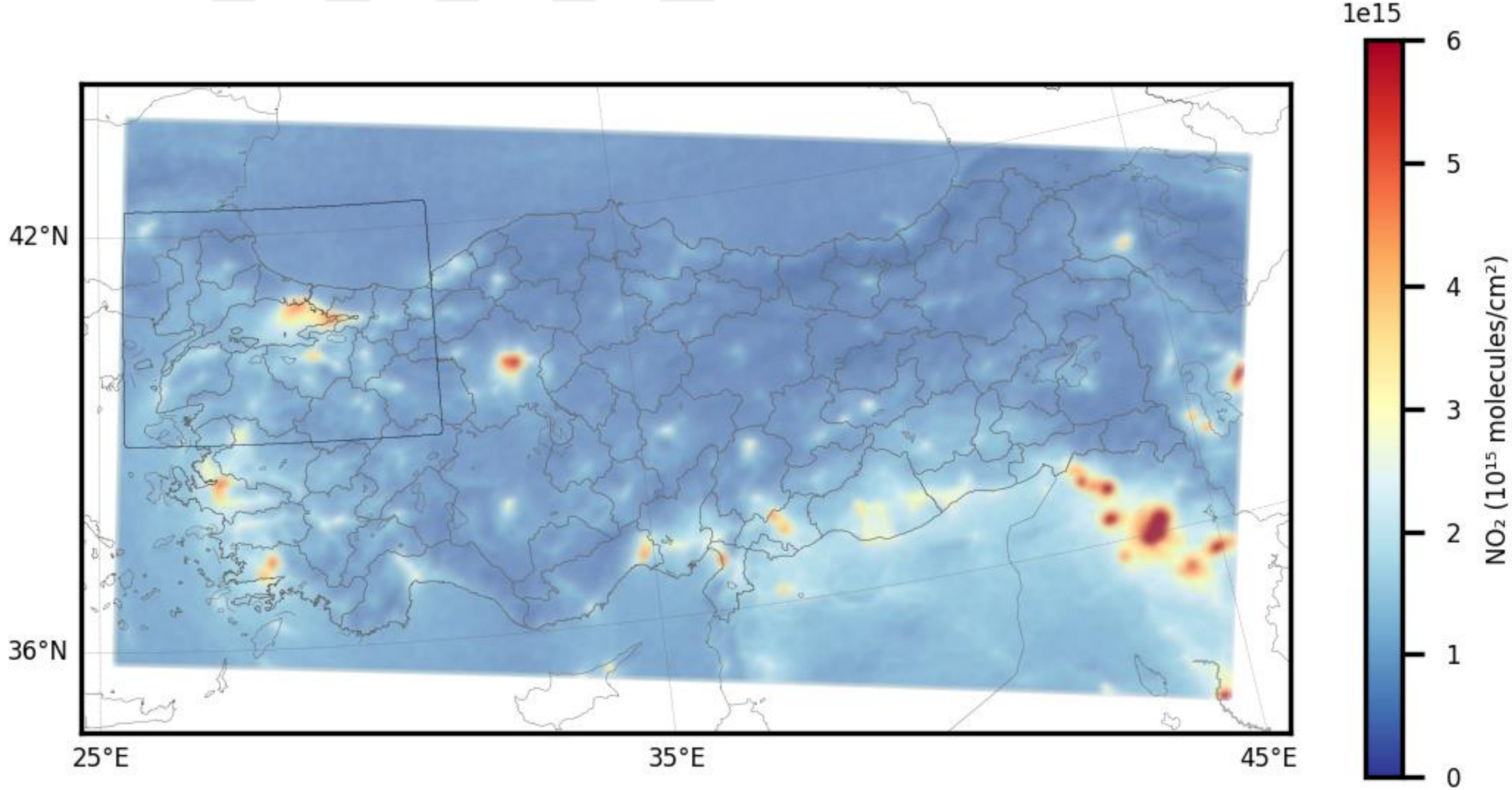

Figure A.18 : NO_2 distribution of Turkey for August 2020

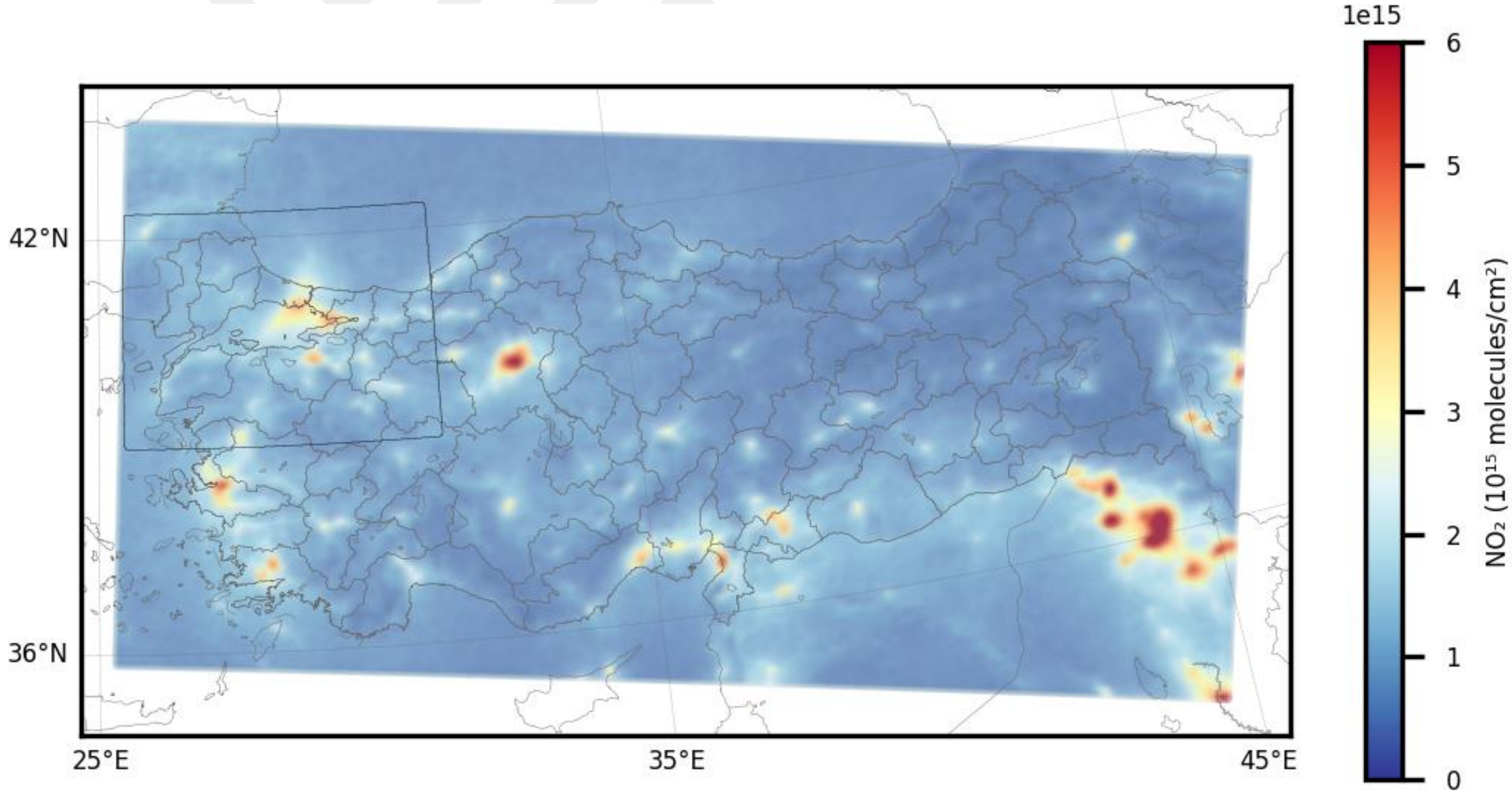

Figure A.19 : NO_2 distribution of Turkey for September 2020

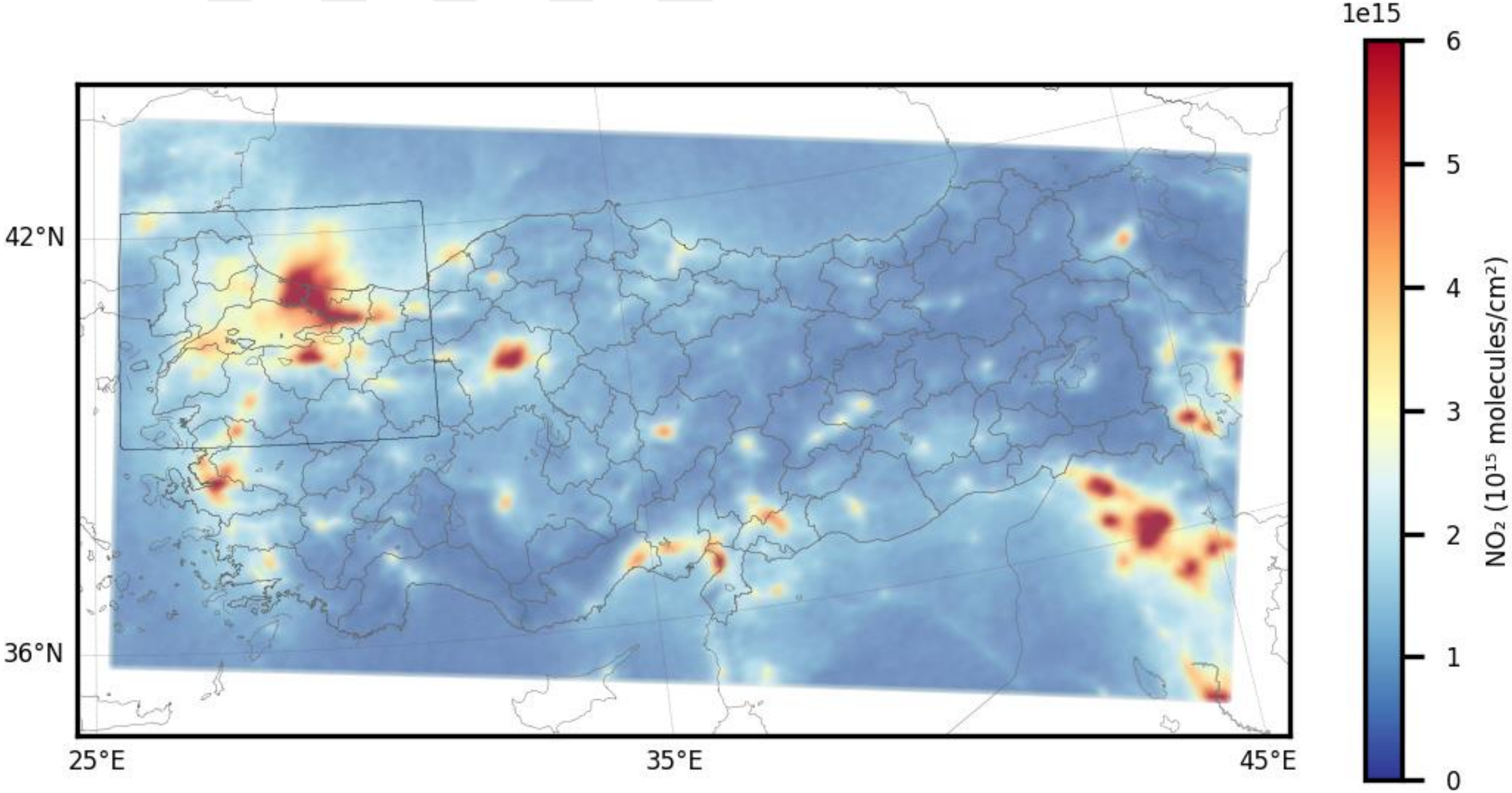

Figure A.20 : NO_2 distribution of Turkey for October 2020

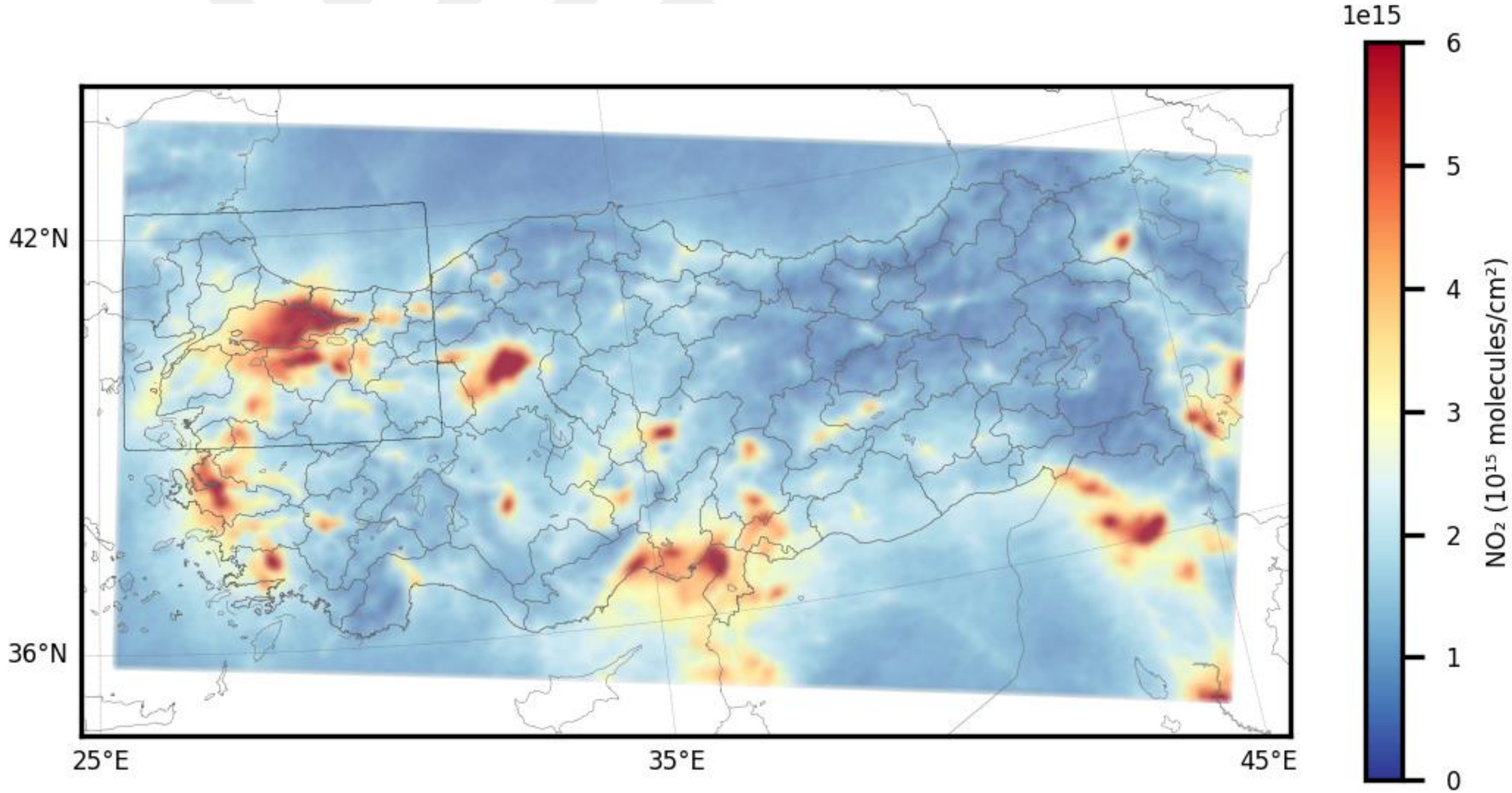

Figure A.21 : NO_2 distribution of Turkey for November 2020

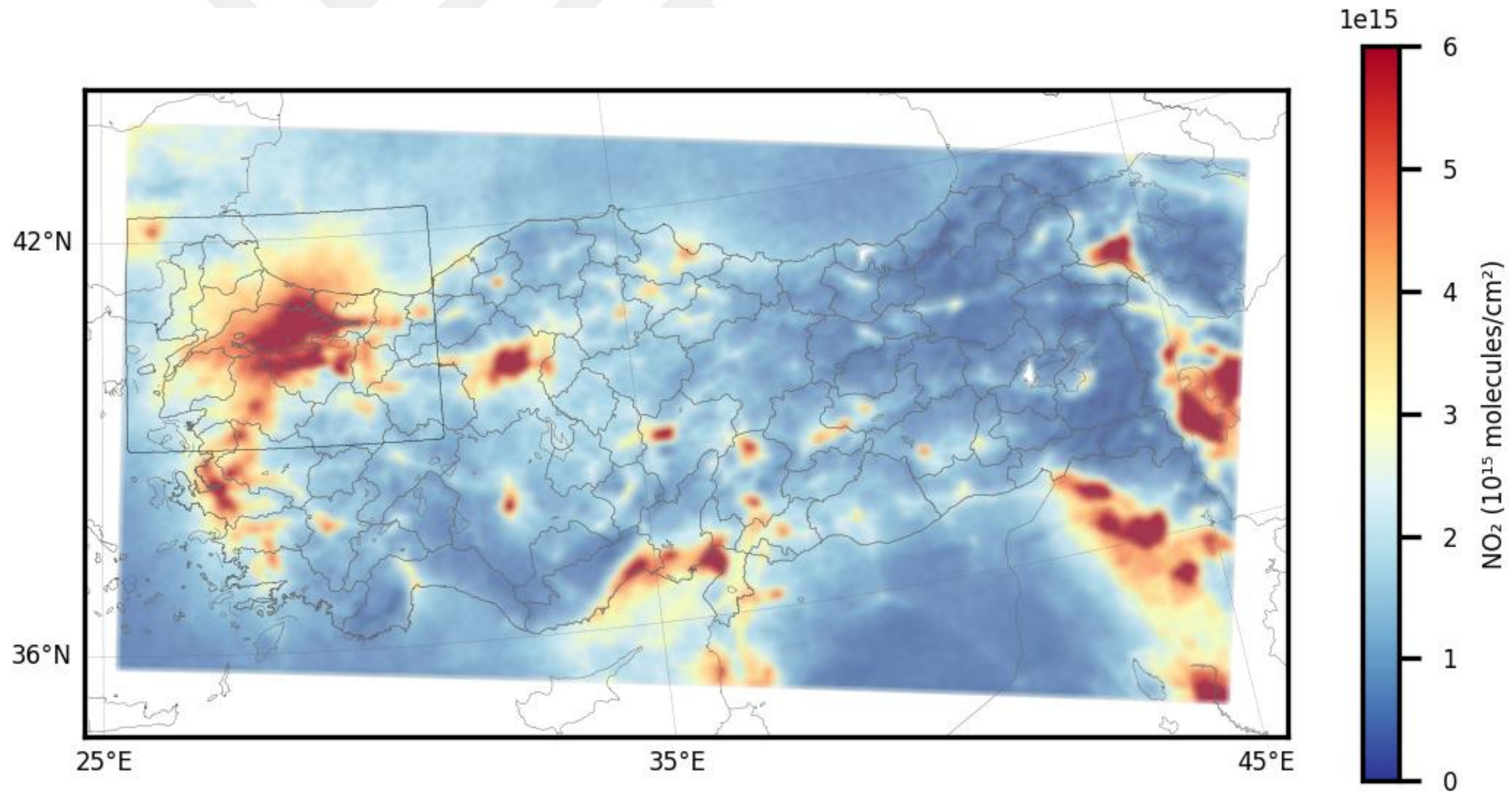

Figure A.22 : NO_2 distribution of Turkey for December 2020

APPENDIX B. Time Series of NO_2 Satellite and Ground-Based Measurements for Selected Districts

Figure B.1 : NO_2 time series of 2019 for Istanbul Kadikoy station both TROPOMI (top) and ground-based measurements (bottom)

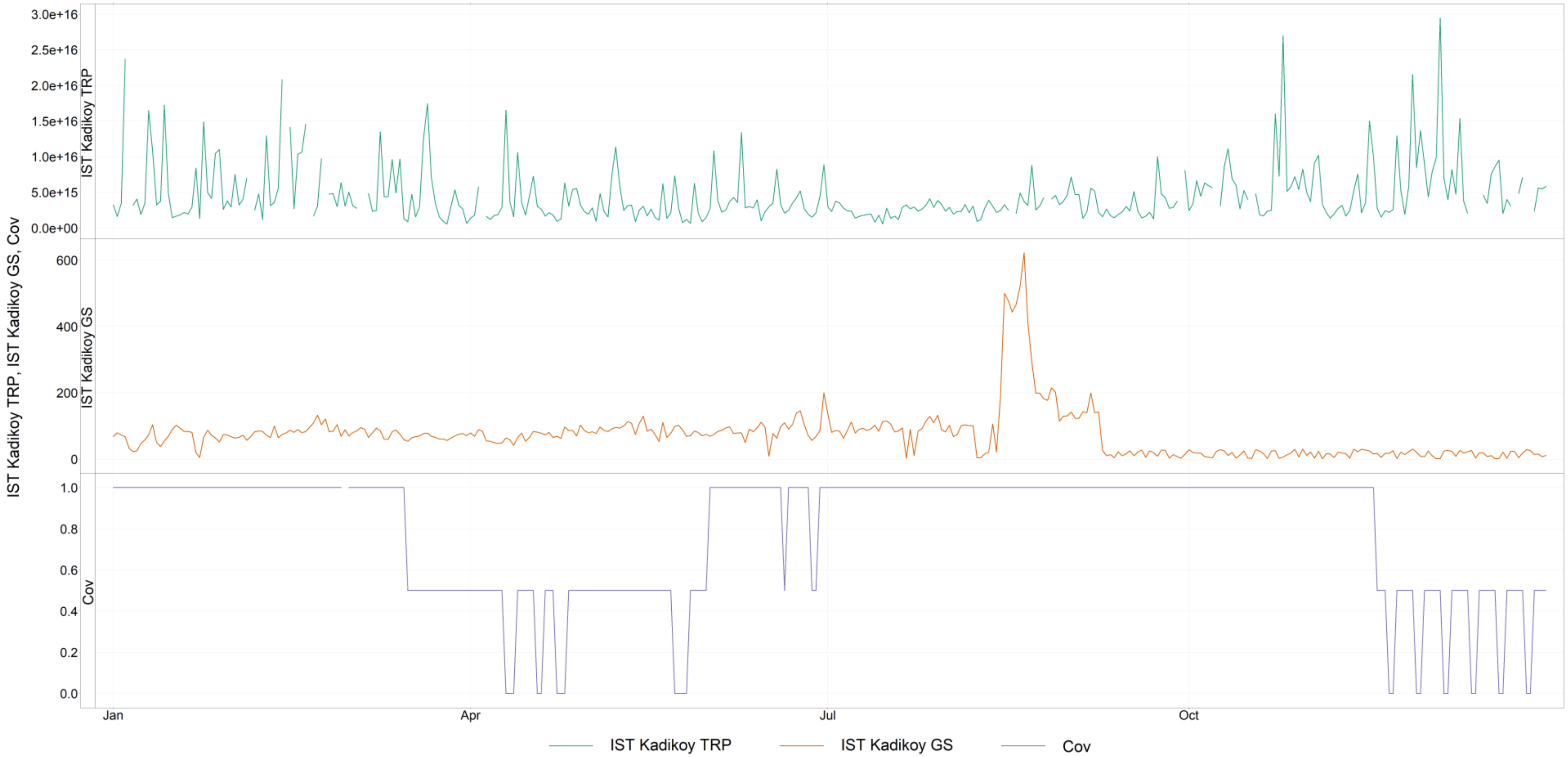

Figure B.2 : NO_2 time series of 2020 for Istanbul Kadikoy station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

Figure B.3 : NO_2 time series of 2019 for Istanbul Avcilar station both TROPOMI (top) and ground-based measurements (bottom)

Figure B.4 : NO_2 time series of 2020 for Istanbul Avcilar station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

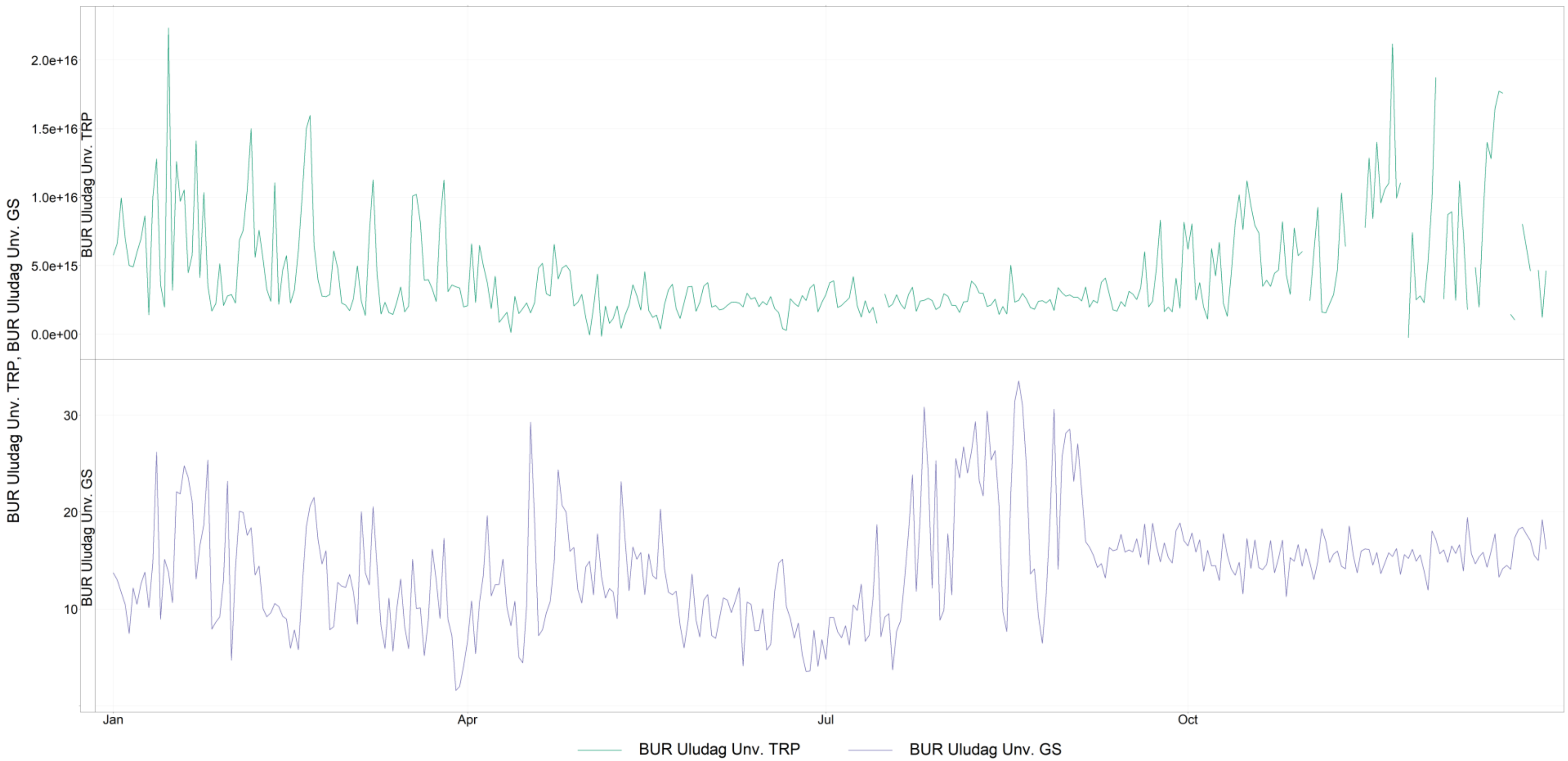

Figure B.5 : NO_2 time series of 2019 for Bursa Uludag Unv. station both TROPOMI (top) and ground-based measurements (bottom)

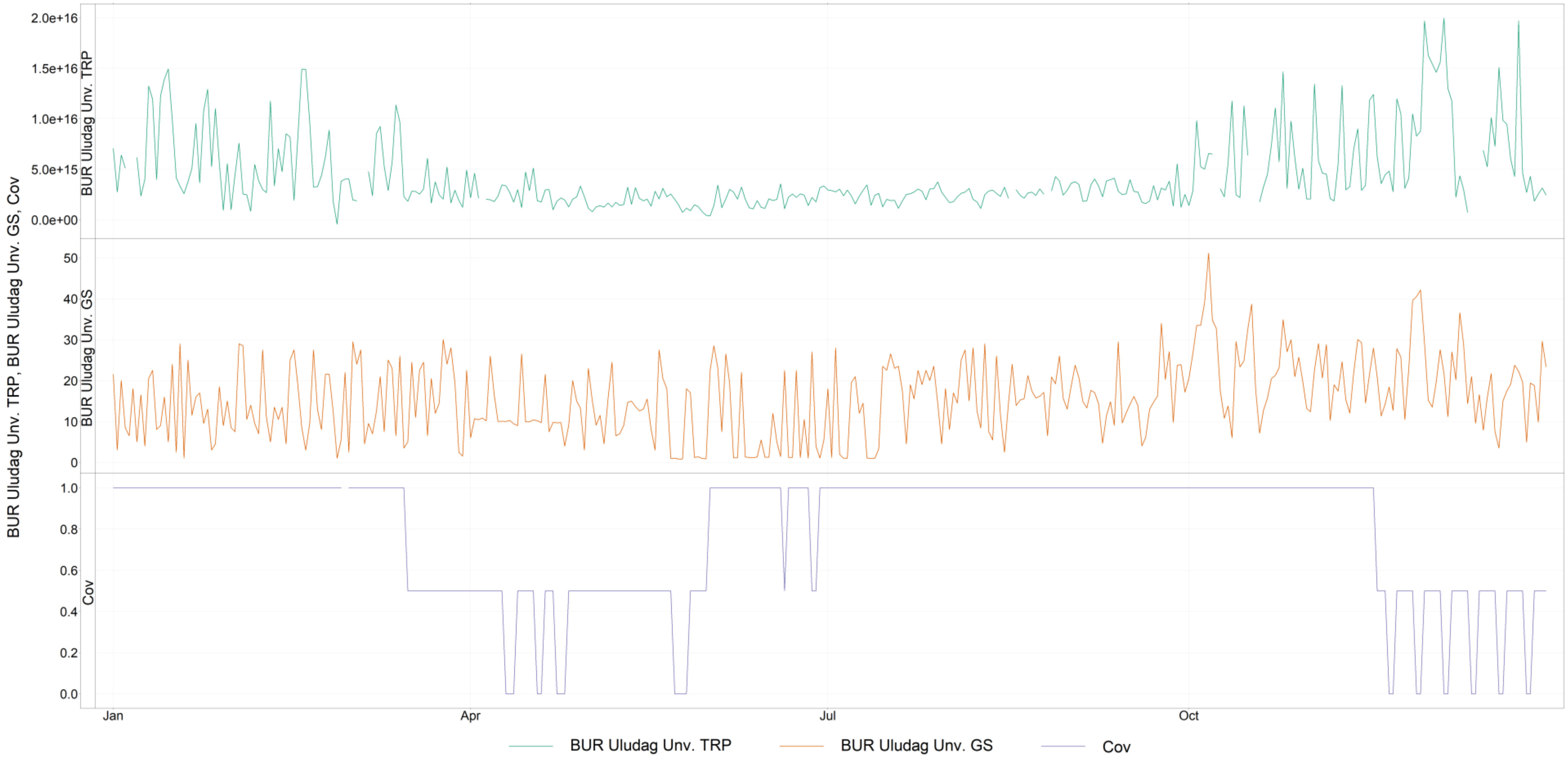

Figure B.6 : NO_2 time series of 2020 for Bursa Uludag Unv. station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

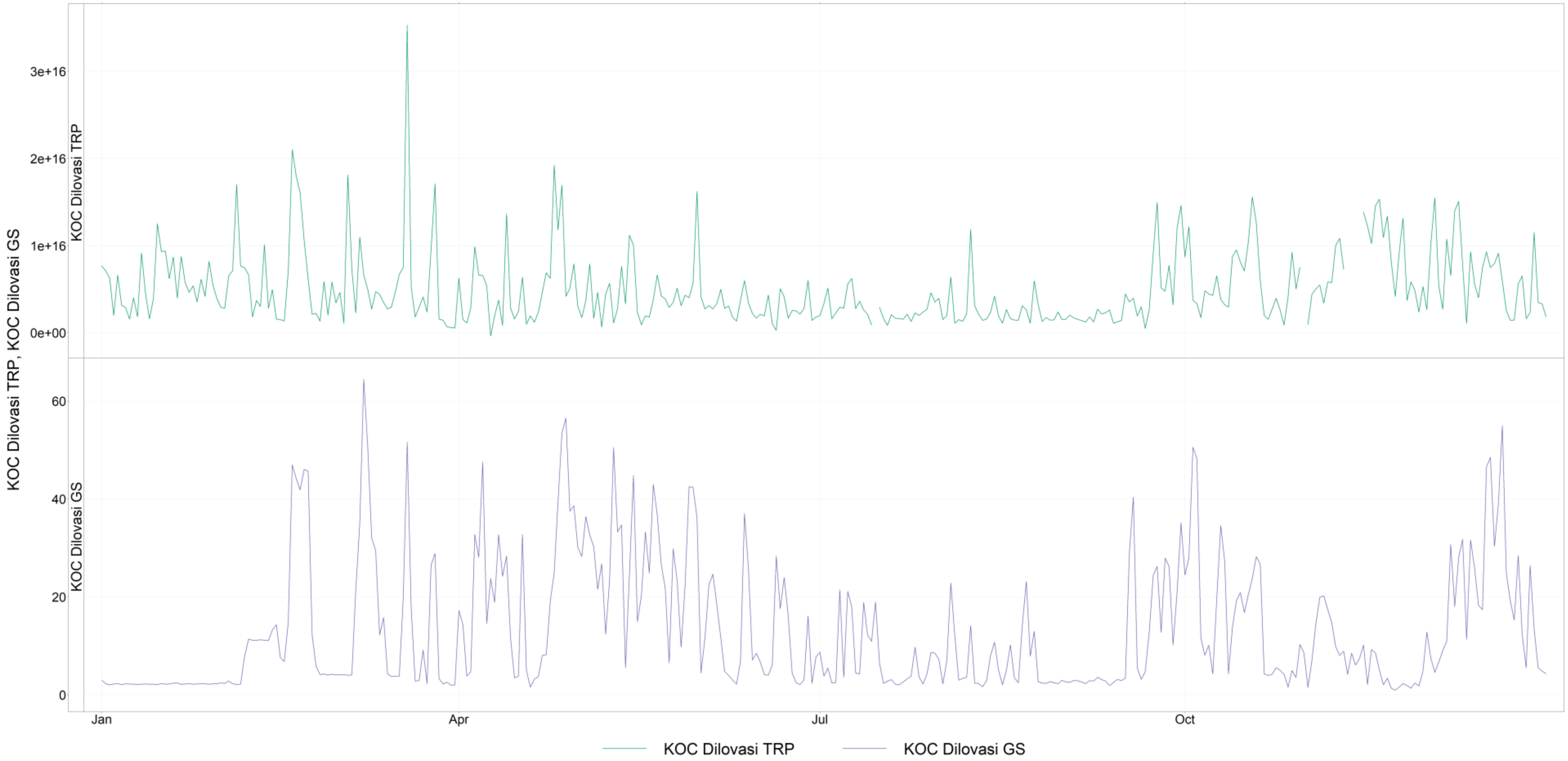

Figure B.7 : NO_2 time series of 2019 for Kocaeli Dilovasi station both TROPOMI (top) and ground-based measurements (bottom)

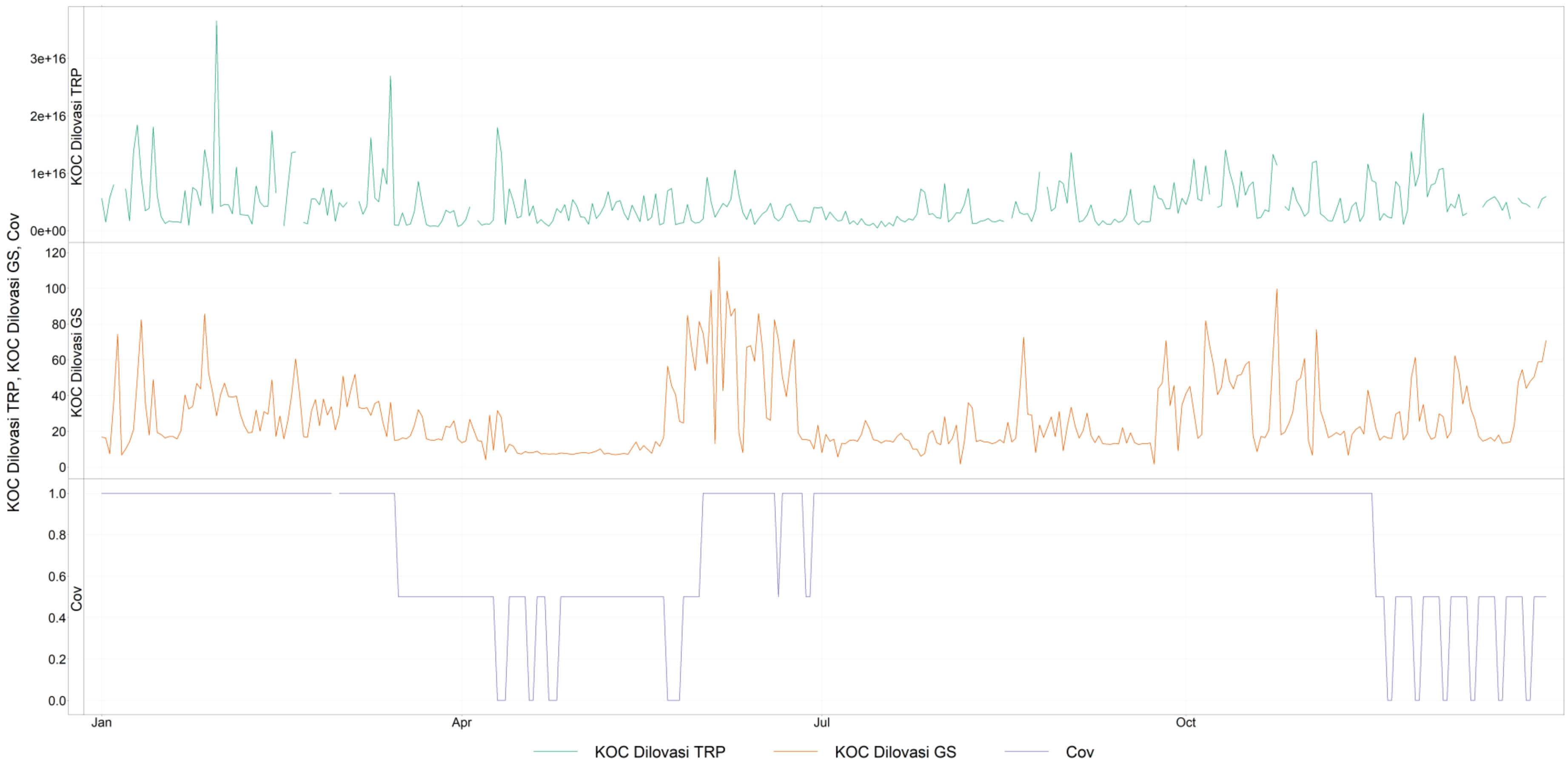

Figure B.8 : NO_2 time series of 2020 for Kocaeli Dilovasi station both TROPOMI (top), Ground-based measurements (middle) and pandemic time line (bottom)

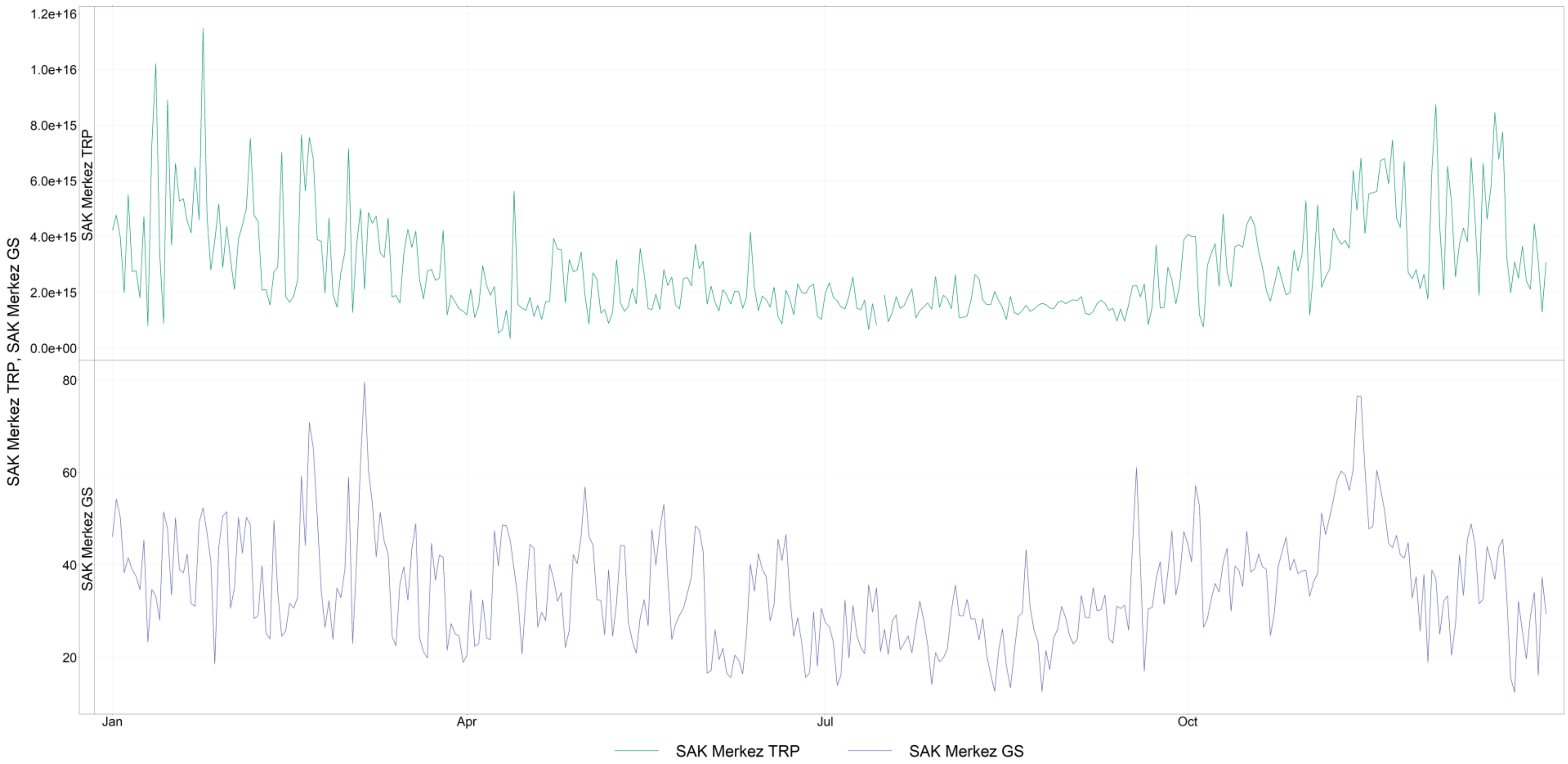

Figure B.9 : NO_2 time series of 2019 for Sakarya Merkez station both TROPOMI (top) and ground-based measurements (bottom)

Figure B.10 : NO_2 time series of 2020 for Sakarya Merkez station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

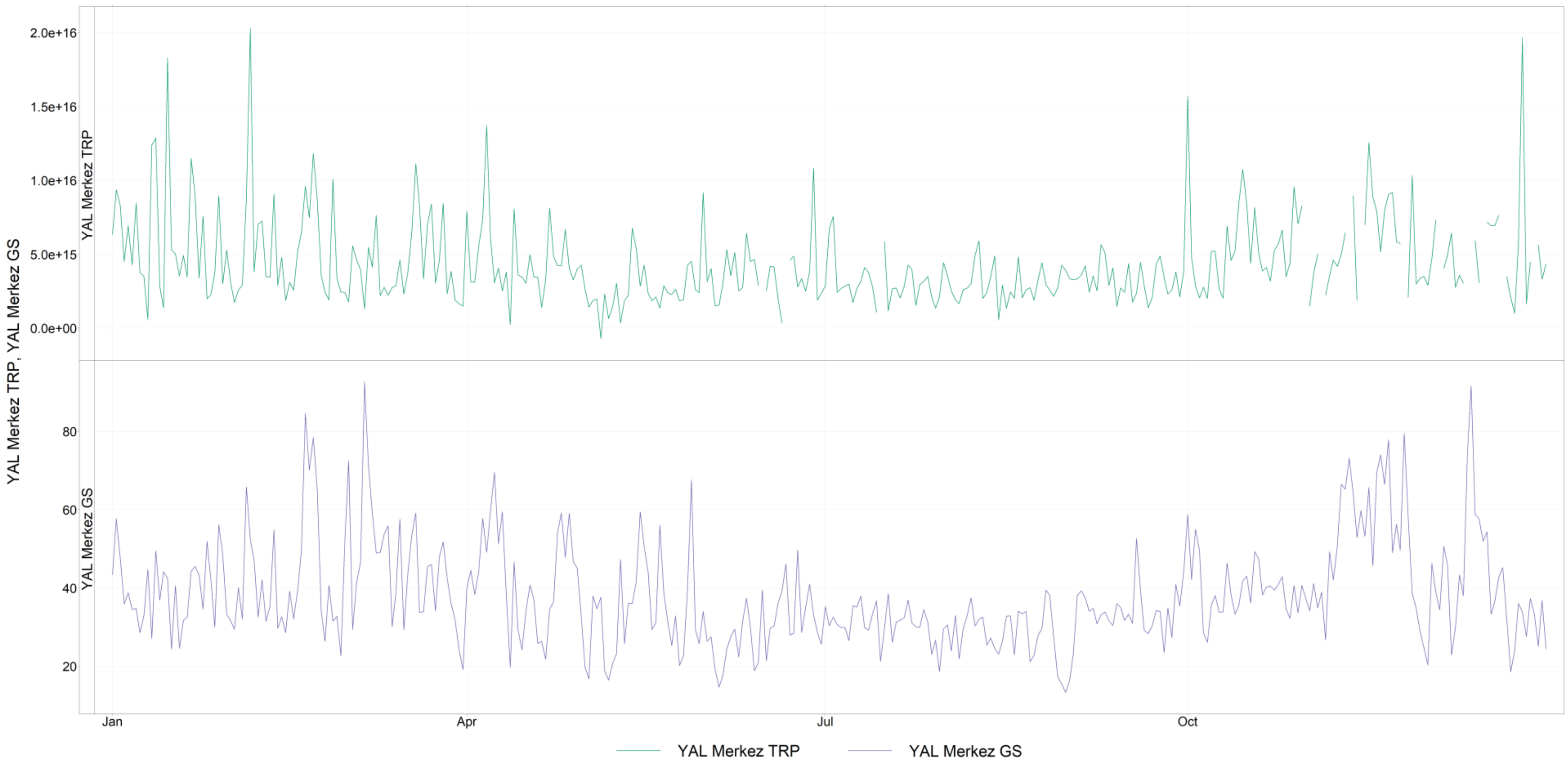

Figure B.11 : NO_2 time series of 2019 for Yalova Merkez station both TROPOMI (top) and ground-based measurements (bottom)

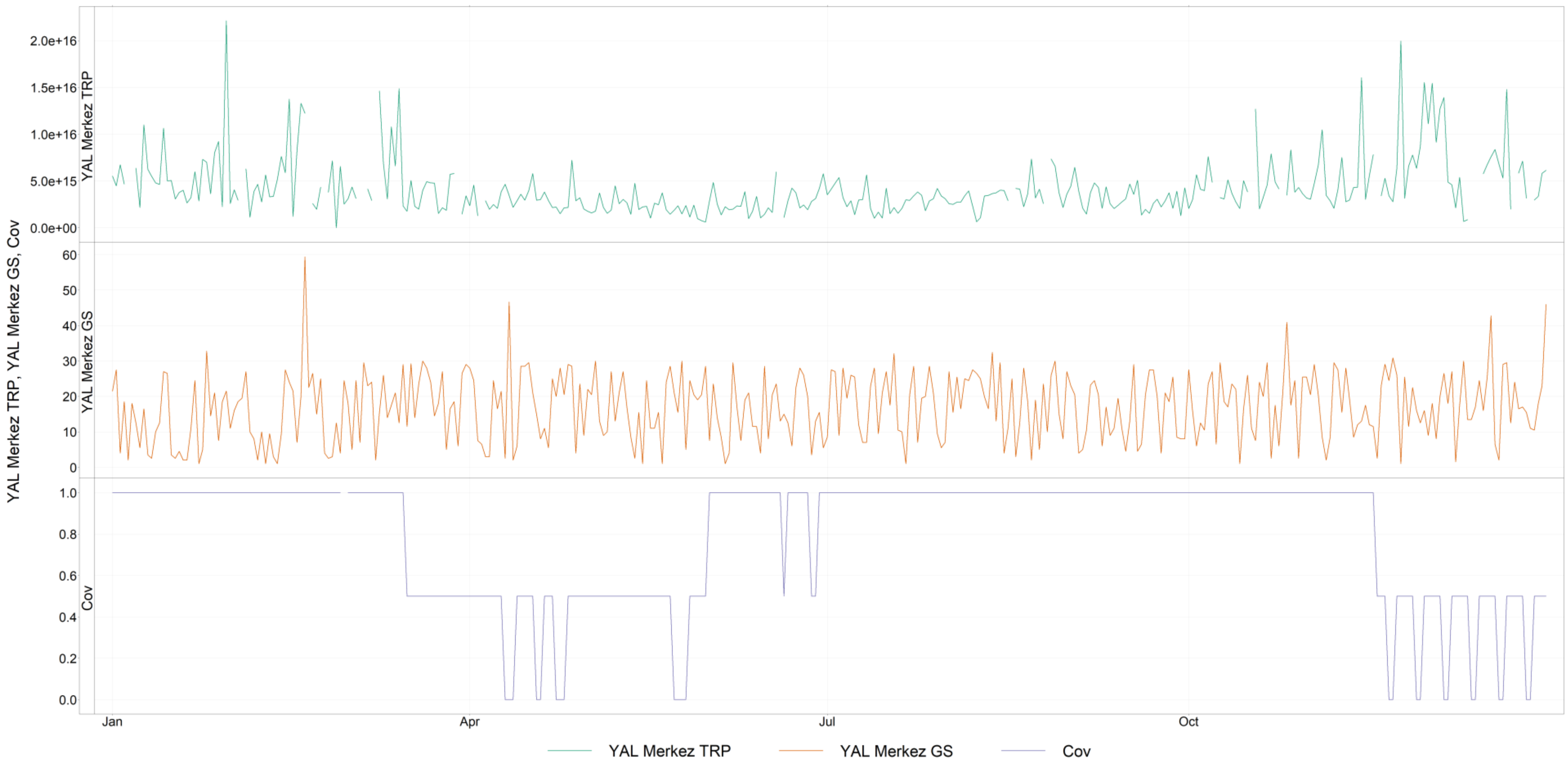

Figure B.12 : NO_2 time series of 2020 for Yalova Merkez station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

Figure B.13 : NO_2 time series of 2019 for Tekirdag Corlu station both TROPOMI (top) and ground-based measurements (bottom)

Figure B.14 : NO_2 time series of 2020 for Tekirdag Corlu station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

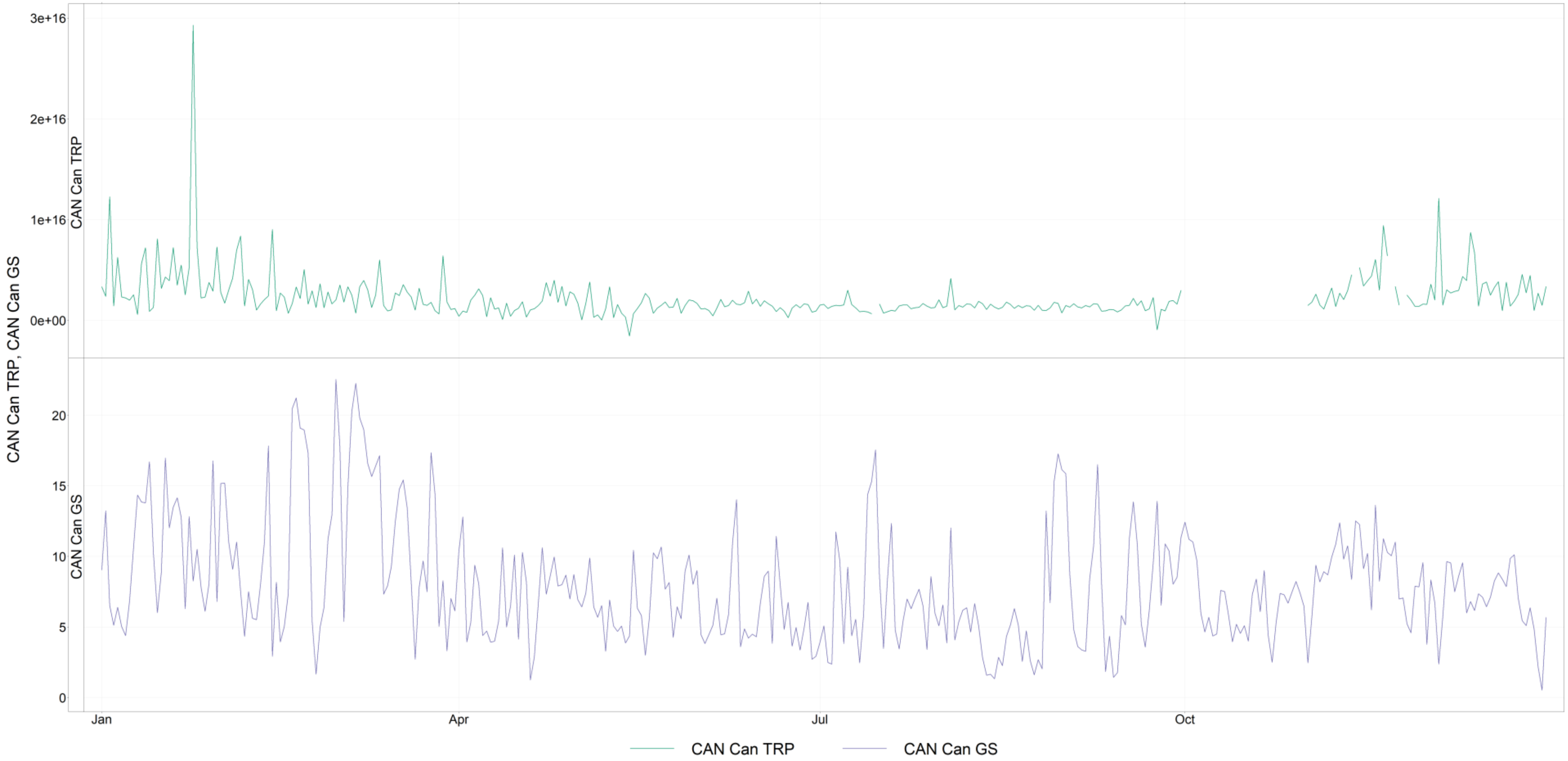

Figure B.15 : NO_2 time series of 2019 for Canakkale Can station both TROPOMI (top) and ground-based measurements (bottom)

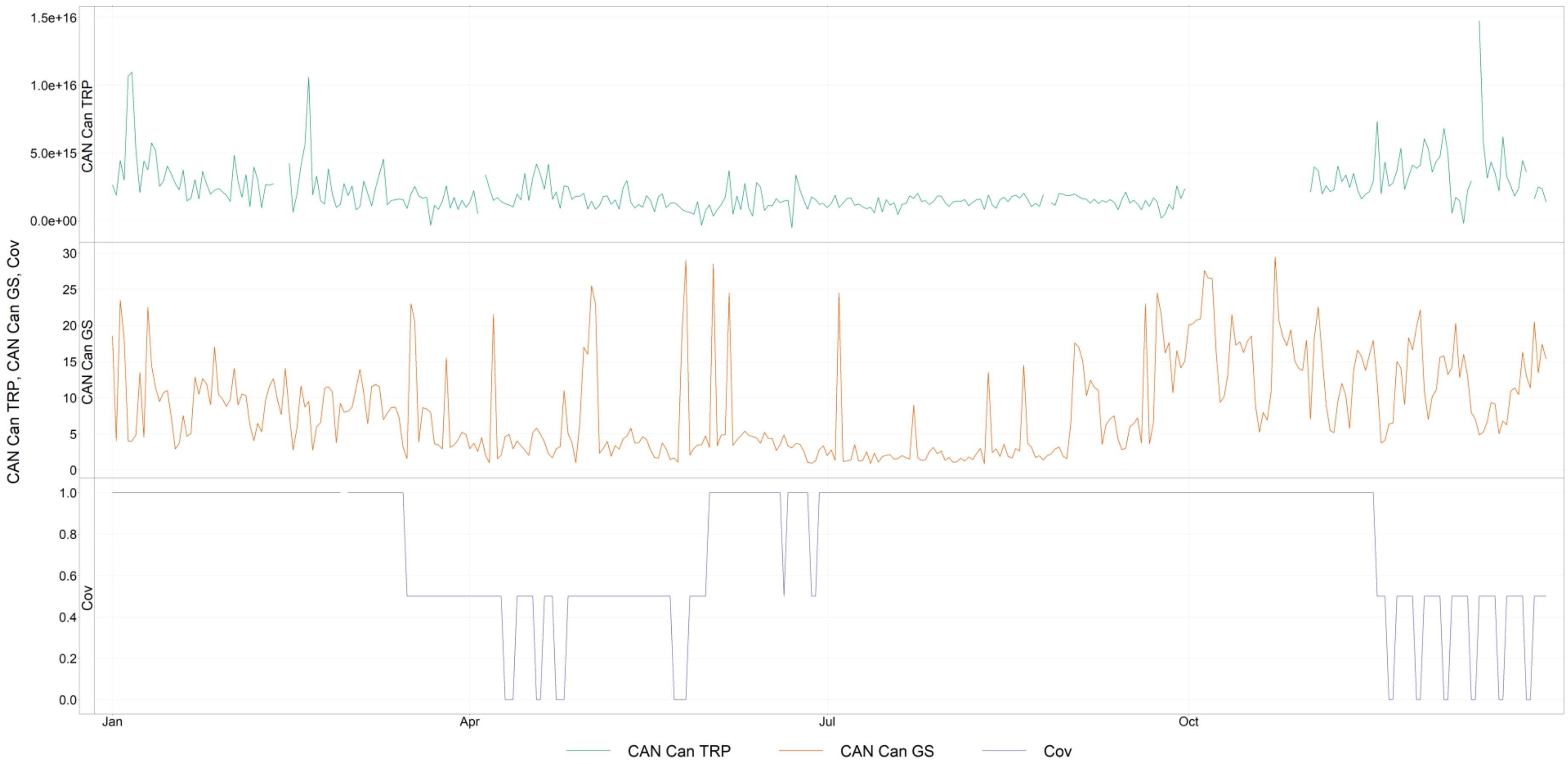

Figure B.16 : NO_2 time series of 2020 for Canakkale Can station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

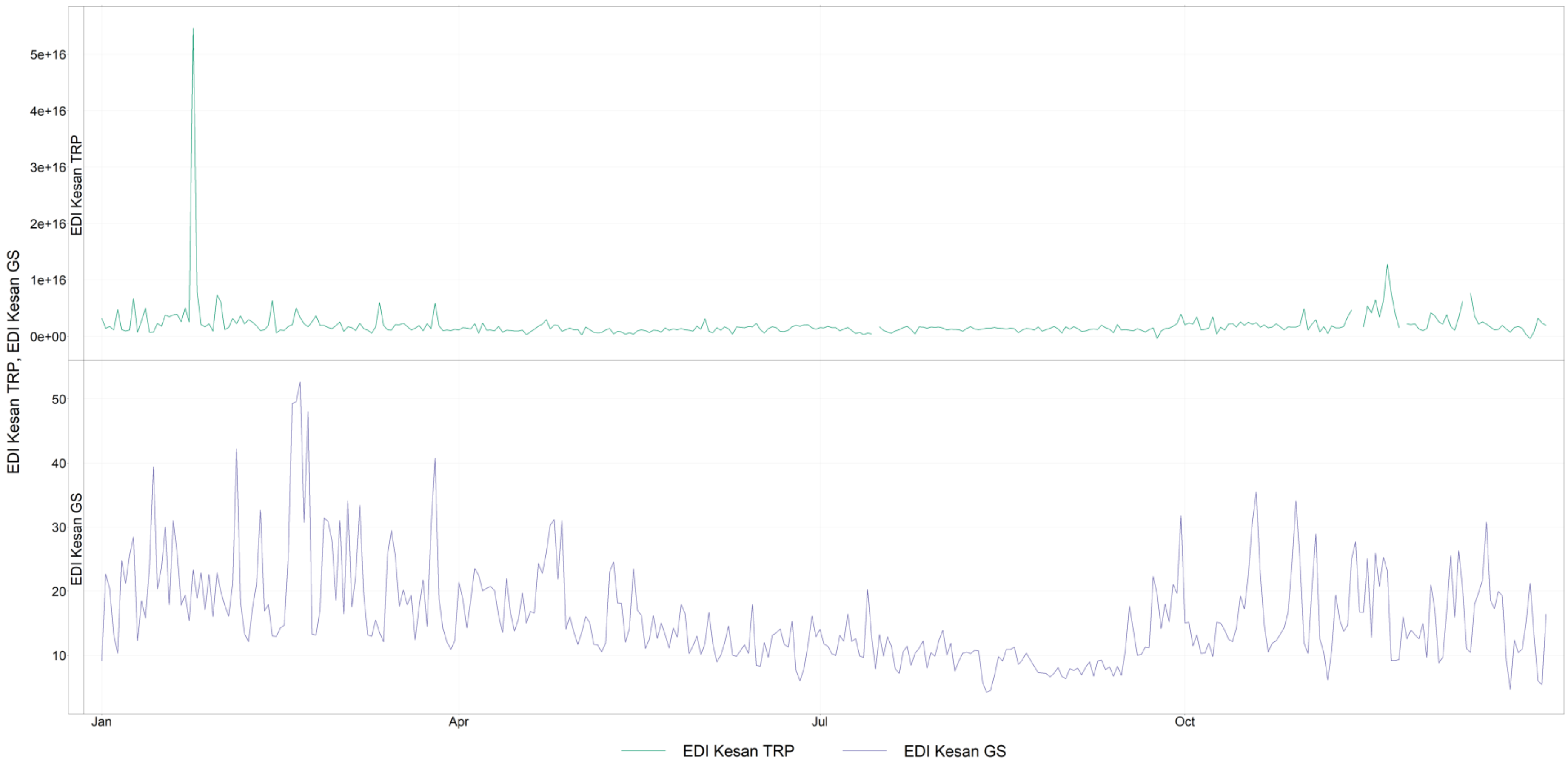

Figure B.17 : NO_2 time series of 2019 for Edirne Kesan station both TROPOMI (top) and ground-based measurements (bottom)

Figure B.18 : NO_2 time series of 2020 for Edirne Kesan station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

Figure B.19 : NO_2 time series of 2019 for Balikesir Edremit station both TROPOMI (top) and ground-based measurements (bottom)

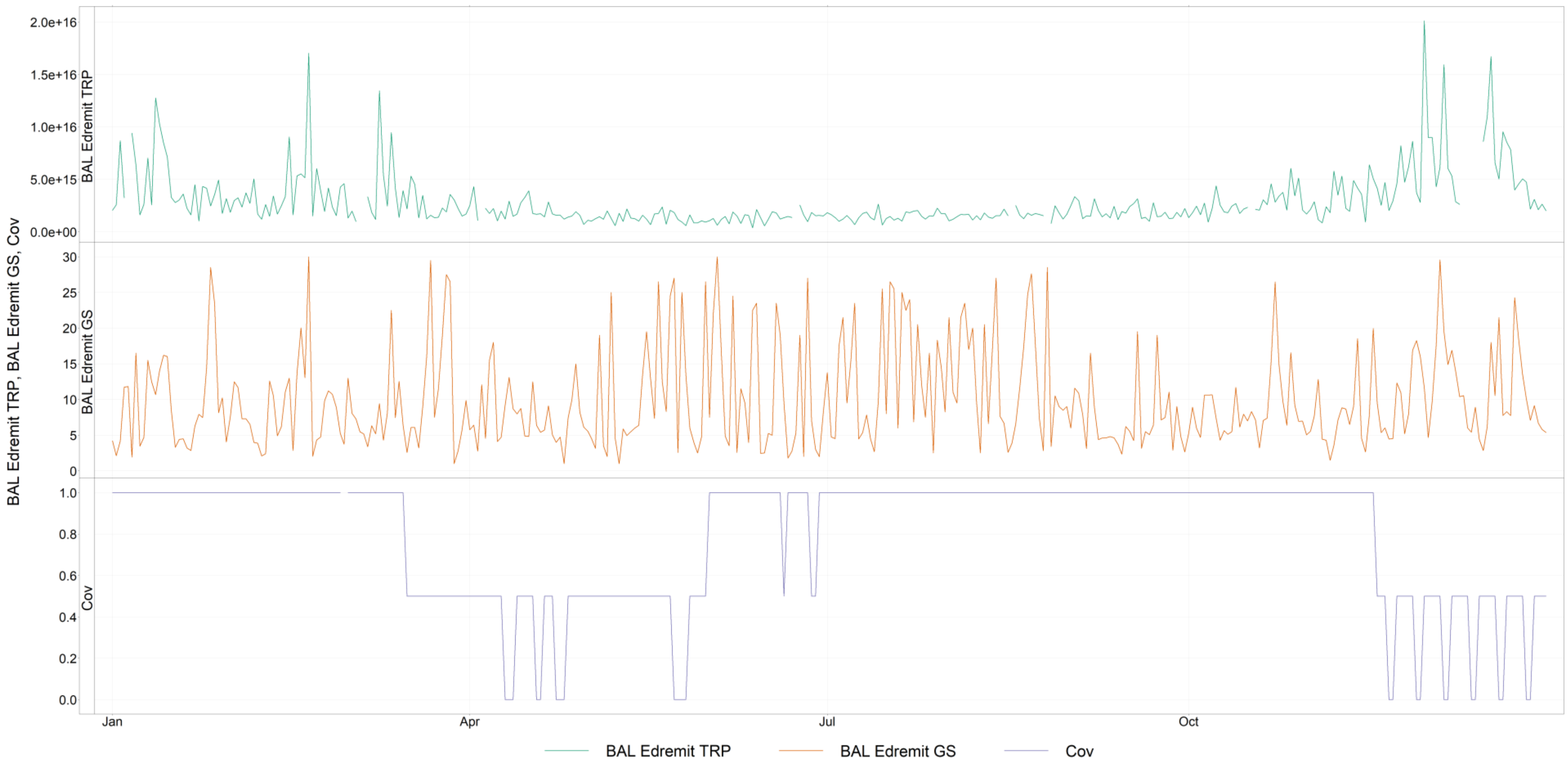

Figure B.20 : NO_2 time series of 2020 for Balikesir Edremit station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

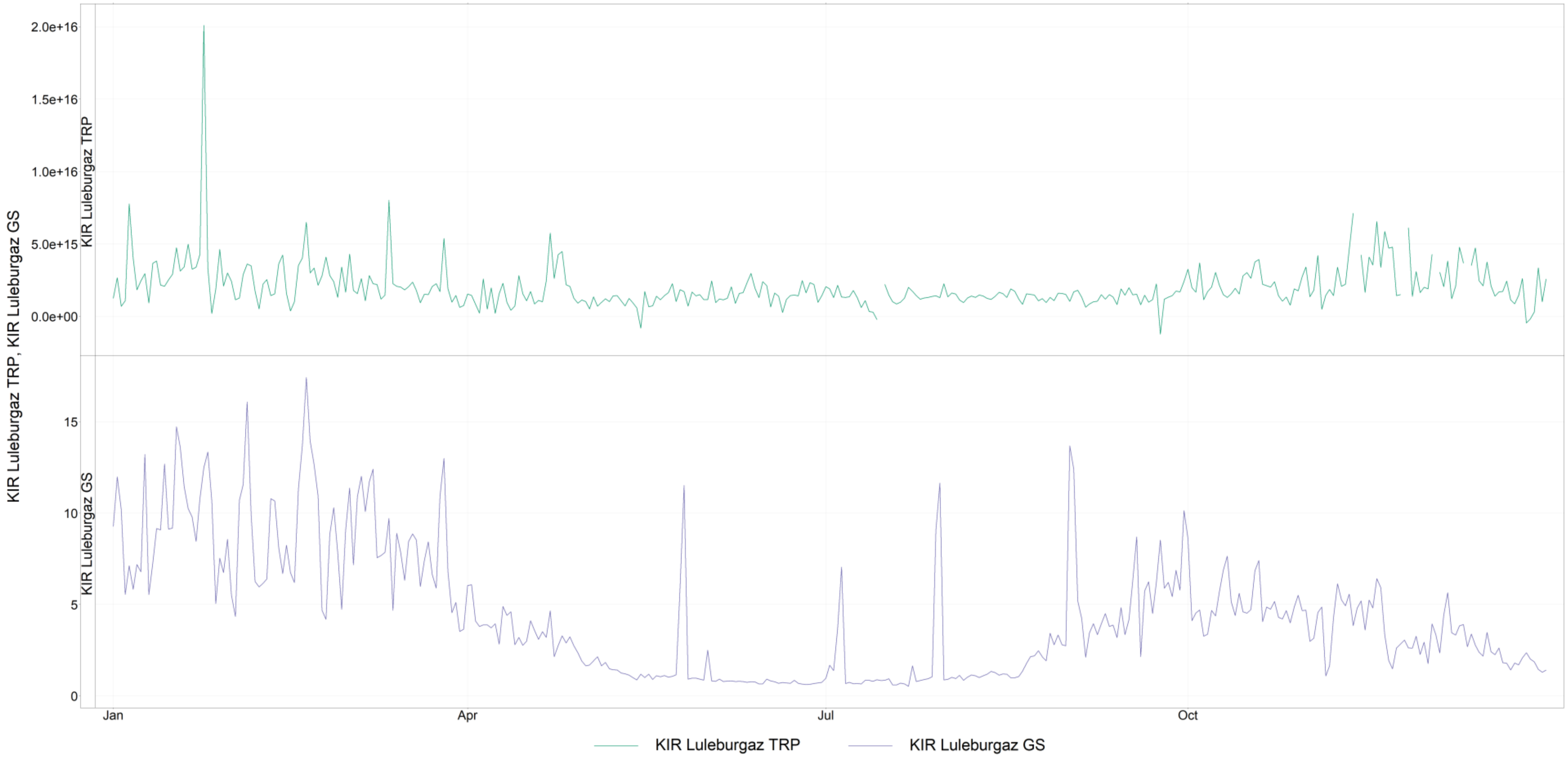

Figure B.21 : NO_2 time series of 2019 for Kirklareli Luleburgaz station both TROPOMI (top) and ground-based measurements (bottom)

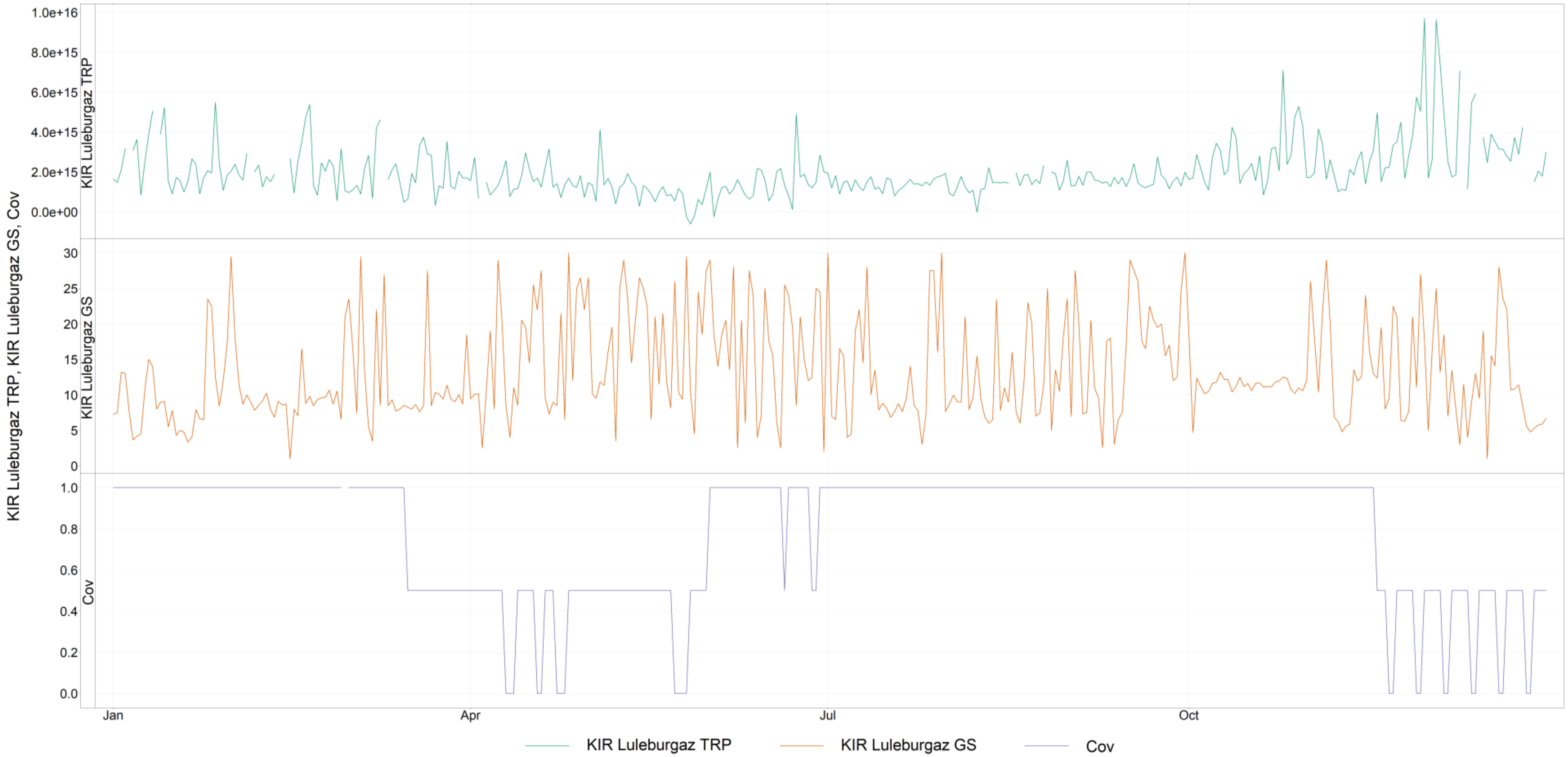

Figure B.22 : NO_2 time series of 2020 for Kirklareli Luleburgaz station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

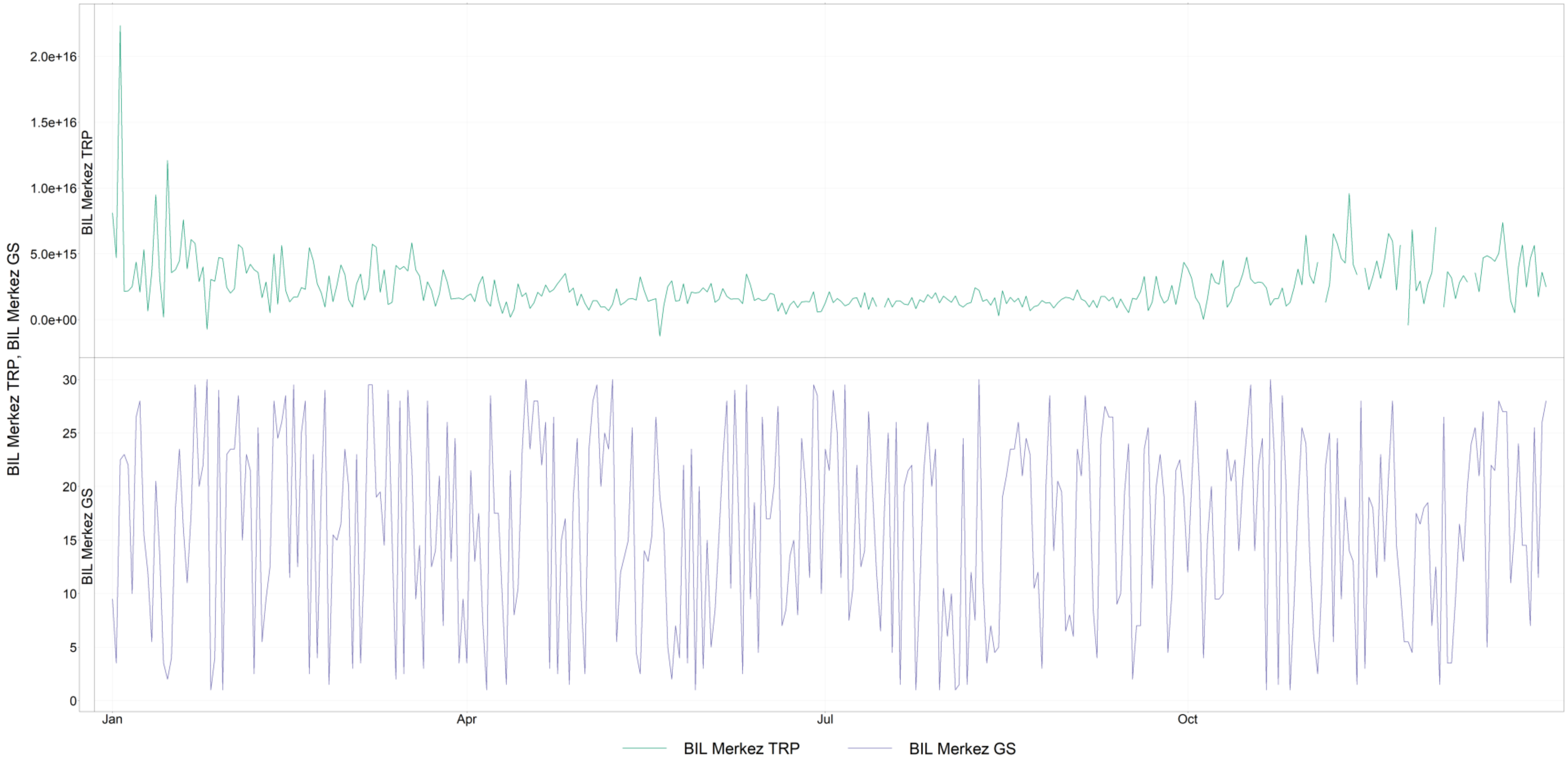

Figure B.23 : NO_2 time series of 2019 for Bilecik Merkez station both TROPOMI (top) and ground-based measurements (bottom)

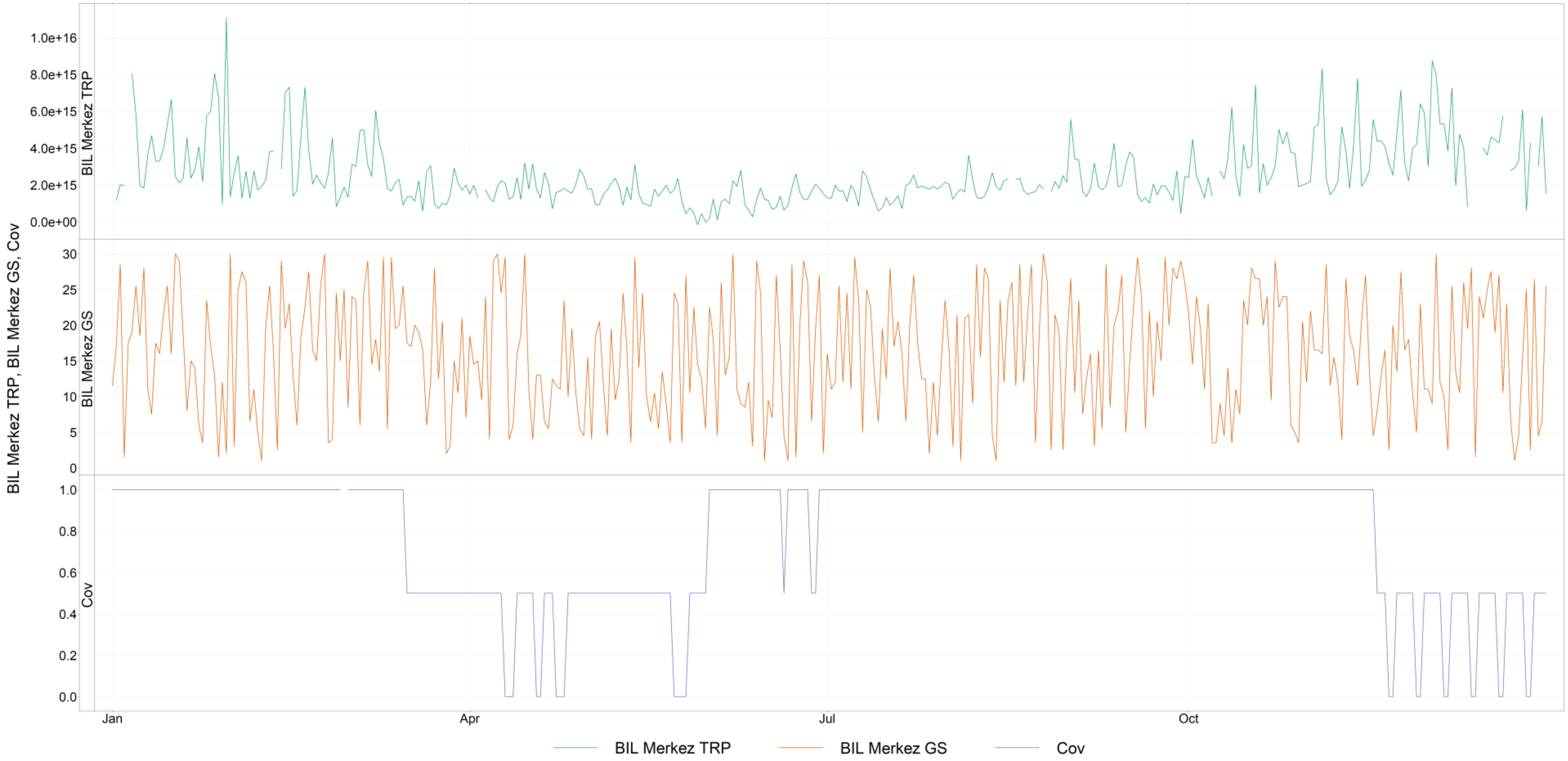

Figure B.24 : NO_2 time series of 2020 for Bilecik Merkez station both TROPOMI (top), ground-based measurements (middle) and pandemic time line (bottom)

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS :

- **Ceker A. O., Cingiroglu F., Akyuz E. and Kaynak B**., (2021), Understanding the relationship between urban development and air pollution for the mega-province Istanbul with remote sensing NO_2 measurements", 14th National 2th International Environmental Engineering Congress (UCMK), 9-11 December 2021.

PUBLICATIONS, PRESENTATIONS AND PATENTS OUTSIDE THE THESIS :

- **Cingiroglu F., Deger S. S., Ceker A. O., Akyuz E., and Kaynak B.,** (2021). TROPOMI NO_2 and SO_2 Temporal Changes over Large Point Sources and Their Relationship with Electricity Production, International Conference Environmental Science & Technology (CEST) 2021, 1-4 September 2021.
- **Aktas, M., Ozdemir, H., Ceker, A. O., Ozcan, H. K. and Demir, G**. (2021). The Effect of Roadside Trees on Traffic-Related Carbon *Aerosols European Journal of Science and Technology,* ***(27)****, 479-488.*