ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DETERMINATION OF LARGE-SCALE SO_2 POINT SOURCES IN TURKEY USING SATELLITE RETRIEVALS

M.Sc. THESIS

Ertuğ FIRATLI

Department of Environmental Engineering

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<u>İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ</u>

TÜRKİYE'DEKİ BÜYÜK BOYUTLU NOKTASAL SO_2 KAYNAKLARININ UYDU VERİLERİ İLE BELİRLENMESİ

YÜKSEK LİSANS TEZİ

Ertuğ FIRATLI
(501141712)

Çevre Mühendisliği Anabilim Dalı

Çevre Bilimleri ve Mühendisliği Programı

Tez Danışmanı: Y. Doç. Dr. Burçak KAYNAK TEZEL

HAZİRAN, 2016

Ertuğ FIRATLI, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 501141712, successfully defended the thesis entitled "Determination of Large Scale SO_2 Point Sources in Turkey Using Satellite Retrievals", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assist. Prof. Burçak KAYNAK TEZEL**
İstanbul Technical University

Jury Members : **Prof. Kadir ALP**
İstanbul Technical University

Prof. Arslan SARAL
Yıldız Technical University

Date of Submission : 2 May 2016
Date of Defense : 9 June 2016

To my family,
Aileme,

FOREWORD

I would like to start with thanking my academic advisor, Burçak Kaynak Tezel, for her guidance, patience and encouragement during two years. I feel very lucky to be her student.

I am also grateful to my jury members Prof. Kadir Alp and Prof. Arslan Saral for their helpful suggestions and comments.

I also would like to thank my family and friends for their support during two years.

This thesis is supported by TUBİTAK project (114Y159) titled "*Evaluation of SO_2 Pollution in Turkey with Remote Sensing*".

June 2016

Ertuğ FIRATLI
(Environmental Engineer)

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ABBREVIATIONS

A	: Activity rate
AIRS	: Atmospheric Infrared Sounder
AMF	: Air Mass Factor
ASCII	: American Standard Code for Information Interchange
AQS	: Air Quality System
CALIOP	: Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	: The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
C_{cal}	: Calorific value of coal
C_{CMAQ}	: Concentration of CMAQ Column
C_{OMI}	: Concentration of OMI Column
CEIP	: Centre on Emission Inventories and Projections
CMAQ	: Community Multi-scale Air Quality
CO	: Carbon monoxide
COMS	: Communication, Ocean and Meteorological Satellite
E	: Emission
ECD	: Emission Control Device
EDGAR	: Emission Database for Global Atmospheric Research
EEA	: Environment European Agency
EF	: Emission Factor
EMEP	: European Monitoring Evaluation Programme
ENVISAT	: Environmental Satellite
EOS	: Earth Observing System
E_p	: Electricity production
EPA	: Environment Protection Agency
ER	: Overall Emission Reduction Efficiency, percentage
ESA	: European Space Agency
EUAS	: Electricity generation company, Turkey
GEMS	: Geostationary Environmental Monitoring Spectrometer
GEOS-Chem	: Goddard Earth Observing System
GIS	: Geographic Information System
GOME	: Global Ozone Monitoring Experiment
GOME-2	: Global Ozone Monitoring Experiment-2
GOSAT	: The Greenhouse Gases Observing Satellite
GNFR	: Gridded Nomenclature for Reporting
GPS	: Global Positioning System
IASI	: The Infrared Atmospheric Sounding Interferometer
IFOV	: Instantaneous Field of View
IMNOXE	: IMprovement of NO_x Emissions with Satellite NO2 Retrievals and Ground Observations
IPCC	: Intergovernmental Panel on Climate Change
JAXA	: Japan Aerospace Exploration Agency
JAVA	: A general purpose, high-level, object-oriented, cross platform programming language developed by Sun Microsystems
MoEU	: Ministry of Environment and Urbanization
MISR	: Multi-angle Imaging SpectroRadiometer
MODIS	: MODerate resolution Imaging Spectroradiometer
MOPITT	: Measurement Of Pollution In The Troposphere

NASA	:	National Aeronautics and Space Administration
NECC	:	National Environment Coordinating Committee
NFR	:	Nomenclature For Reporting
NH_3	:	Ammonia
NO	:	Nitrogen monoxide
NO_2	:	Nitrogen dioxide
OMI	:	Ozone Monitoring Instrument
O_3	:	Ozone
PAN	:	Peroxyacetyl nitrate
PARASOL	:	Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PBL	:	Planetary Boundary Layer
PM	:	Particulate Matter
$PM_{2.5}$	:	Particulate Matter up to 2.5 micrometers in size
PM_{10}	:	Particulate Matter up to 10 micrometers in size
RS	:	Remote Sensing
S	:	Sulfur content of coal
SCIAMACHY	:	Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY
SNAP	:	Selected Nomenclature of Air Pollutants
SO_2	:	Sulfur dioxide
TANSO-FTS	:	Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer
TEIAS	:	Turkey Electricity Transmission Corporation
TEMPO	:	Tropospheric Emissions: Monitoring of Pollution
TES	:	Technology Experiment Satellite
Y_t	:	Thermal Yield
TNO	:	Netherlands Organization for Applied Scientific Research
TOMS	:	Total Ozone Mapping Spectrometer
TROPOMI	:	The TROPOspheric Monitoring Instrument
UNFCC	:	United Nations Framework Convention on Climate Change
UV	:	Ultraviolet
VOCs	:	Volatile Organic Compounds
WRF-Chem	:	Weather Research and Forecasting - Chemistry

SYMBOLS

Ω	**:** Column concentration
σ_x	**:** Determines the shape of the fitted 2D Gaussian function in x axis
σ_y	**:** Determines the shape of the fitted 2D Gaussian function in y axis
μ_x	**:** Change of the position of maximum value in x axis
μ_y	**:** Change of the position of maximum value in y axis

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DETERMINATION OF LARGE-SCALE SO_2 POINT SOURCES IN TURKEY USING SATELLITE RETRIEVALS

SUMMARY

The aim of this thesis is to evaluate and improve SO_2 emissions from large-scale point sources by satellite retrievals in and around Turkey. Satellite retrievals supply SO_2 PBL (planetary boundary layer) column back to 1995 by GOME, which is the first instrument to detect tropospheric pollution from space. Satellite retrievals have the advantage of better spatial coverage compared to ground monitoring measurements in understanding the overall effect of the pollution sources.

In this study, SO_2 pollution in and around Turkey using satellite retrievals of Ozone Monitoring Instrument (OMI) were observed. Firstly, SO_2 pollution of Turkey was investigated by reviewing the previous literature and available emission inventories such as EMEP. Then, SO_2 pollution hotspots and areas observed by OMI between the years of 2005 and 2015 were determined. Mostly, the visible signals were related with large-scale point sources such as large-scale coal power plants and industries those are releasing significant amount of SO_2 to the atmosphere.

Coal power plants, which have installed electricity production capacity larger than 50 MWe, were selected for this study. Coal power plants are very important SO_2 emitters since the coal reserves are mainly lignite with low calorific value and high S and ash content in Turkey. Aside from EMEP, there was not a detailed national emission inventory for Turkey reporting the emissions of these point sources. Because of that reason, evaluation of current emission inventories with satellite retrievals and estimating these large contributors are the major contributions of this study.

Secondly, high OMI signals observed for Turkey were compared with EMEP 0.1˚ × 0.1˚ gridded emission inventory for the years of 2012 and 2013 that were available. Emission inventory for 2011 were not included in the comparison due to higher noise of OMI SO_2 column for that year. As a result, there was not a good spatial agreement between OMI and EMEP, other than some large-scale sources such as Afşin Elbistan in Kahramanmaraş, Tunçbilek and Seyitömer in Kütahya. Furthermore, EMEP inventory does not include some large-scale sources such as Ankara, Çayırhan, or indicating very low emissions such as Silopi where the significantly high signals was observed by OMI.

In addition, emission estimation of large-scale point sources was investigated in the thesis. A 60×60 km^2 domain was created with 2×2 km^2 grids around selected large-scale sources. Oversampling was applied to OMI retrievals and the effect of background pollution was removed by subtracting the yearly OMI SO_2 average within 300 km in data processing. Then, 2-D Gaussian fitting method was applied to OMI retrievals to investigate SO_2 emissions. As a case study, Afşin Elbistan power plant were investigated in detail for 11 years, and a moderate correlation (R^2 = 0.57) was found between emission estimations and calculated a values from OMI retrievals. After the case study, Gaussian-fitting method was applied to other selected power plants. Different from the case study, 11 years averages were used in the fitting method. As a result better correlation were found (R^2=0.75) than yearly averages. There were some outliers, for example, OMI SO_2 columns were indicating higher

values for Çayırhan than calculated emissions, Both OMI SO_2 columns and calculated emissions were indicating low values for Sivas Kangal and Manisa Soma power plants. At the end of the study, for Şırnak Silopi power plant, emissions were estimated using linear regression line. As a result, SO_2 emission was calculated for Şırnak Silopi power plant as approximately 112 kton/yr where no electricity production data was available.

Lastly, in order to understand the differences between different observation platforms, ground-monitoring SO_2 observations were compared with OMI retrievals around large-scale power plants. Hourly and daily averages were compared with OMI SO_2 retrievals in both DU and µg/m^3. In comparison of ground monitoring measurements and OMI SO_2 retrievals, increase-decrease trends and similarity of magnitudes were investigated. The comparison of Afşin Elbistan power plant was performed initially as a case study, after that the same method was applied to six other selected power plants. In general, ground monitoring and OMI SO_2 retrievals are not in good agreement to each other. Ground monitoring and OMI SO_2 retrievals had opposite trends for Afşin Elbistan. There are some similarities in trend of pollution changes for Muğla power plants. Ground measurements indicate very high values for Manisa Soma while OMI SO_2 retrievals indicate very low values. OMI SO_2 retrievals for Sivas Kangal are very low, too and there is no similarity with ground measurements. Çayırhan power plant is one of the largest pollution region in the domain, however the closest ground monitoring station is 68 km away from the power plant, therefore there is no agreement with the ground monitoring observations. For Silopi power plant ground measurements indicate very high values especially after 2009 when the power plant was installed. There is moderate signals of OMI for Silopi power plants. Secondly, OMI SO_2 retrievals were converted into surface concentrations using a model output for better comparison with ground monitoring statistics. However in the comparison of OMI SO_2 retrievals in µg/m^3 with ground monitoring statistics, low agreement were found due to too low OMI SO_2 values (µg/m^3) except Afşin Elbistan and Muğla power plants.

TÜRKİYE’DEKİ BÜYÜK BOYUTLU NOKTASAL SO_2 KAYNAKLARININ UYDU VERİLERİ İLE BELİRLENMESİ

ÖZET

Hava kirliliği çevre ve insan sağlığı için önemli problemlerden biridir. Özellikle, sanayi devriminden sonra hava kirliliği daha ciddi bir problem haline gelmiştir. Günümüzde, hava kirliliği akciğer kanseri, astım, çeşitli cilt ve göz problemlerine neden olurken, aynı zamanda asit yağmurları, sis, toz oluşumu gibi çevresel zararları bulunmaktadır.

Sülfür dioksit (SO_2) kirliliği başlıca kömür kullanan elektrik üretim santrallerinden ve endüstriyel tesislerdeki proseslerden kaynaklanmaktadır. Türkiye’de kükürt içeriği yüksek kömür kullanan yakma tesisi ve endüstri sayısı fazladır ve hala SO_2 kirliliği önemli bir problemdir.

Uydu verileri kullanarak hava kirleticilerin belirlenmesi 1982 yılına dayanmaktadır. Uydu verilerini kirletici belirlemekte kullanılmasındaki amaç, kirleticilerin daha geniş bir alanda araştırılılabilmesi ve az sayıda bulunan yer ölçüm istasyonlarının dezavantajını giderebilme özelliğidir. İlk olarak, 1982 yılında, TOMS enstrümanı kullanılarak El Chichón volkanından kaynaklanan SO_2 belirlenmiştir. Daha sonra, 1995 yılından itibaren troposferdeki SO_2, GOME enstrümanı kullanılarak belirlenmiştir. Takip eden yıllarda, daha iyi mekansal çözünürlükteki SCIAMACHY (30×60 km^2), OMI (13×24 km^2), GOME-2 (40×80 km^2) gibi enstrümanlar kullanılarak troposferik SO_2 kirliliği uydu kaynaklı verilerle takip edilmiştir.

Tezin amacı, Türkiyede hala önemli bir problem olan SO_2 kirliliğinin uydu verileri kullanılarak belirlenmesi, kirlilik haritalarının çıkarılması, ve emisyon envanterleri ve yer istasyon ölçümleriyle karşılaştırılmasıdır. Bu çalışma Türkiye’de uydu verileri kullanılarak SO_2 kirliliği belirlenen ilk çalışmadır.

Çalışma AURA uydusu üzerinde bulunan OMI enstrümanı verileri kullanılarak 2005 ve 2015 yılları için Türkiye’deki büyük boyutlu noktasal SO_2 kirliliğinin belirlenmesi için gerçekleştirilmiştir. Çalışmada ayrıca yer ölçüm istasyonlarının çok daha az olduğu (2007 öncesi) yıllardaki kirliliğin belirlenmesi, ve Türkiye’nin içinde bulunduğu EMEP gibi emisyon envanterlerinin geliştirilmesine katkı sağlama hedeflenmiştir.

Öncelikle Türkiye’deki SO_2 kirliliği literatür ve EMEP ve TNO gibi çeşitli emisyon envanterleri taranarak araştırılmıştır. Daha sonra OMI PBL SO_2 verileri NASA internet sitesinden indirilip, önerilen aralıklara göre filtrelenmiştir. Ardından istenilen formatta bir GIS yazılımına aktarılarak burada hatiralandırılmıştır. Türkiye’nin genel SO_2 haritası 2005 ve 2015 yılları arasında çıkarılarak kuvvetli sinyaller veren noktaların özellikle kömür kullanan termik santraller civarında olduğu gözlenmiştir.

İlk olarak termik santraller için bir çalışma yürütülmüş, 50 MWe’den yüksek enerji üretim kapasitesine sahip olan kömür yakan termik santraller incelenmiştir. Türkiyedeki kömür santrallerin çoğunda yerli rezerv açısından zengin olan linyit kullanılmaktadır. Türkiyede bulunan linyit ise genellikle düşük kalorifik değere ve yüksek kükürt içeriğine sahiptir. Bu da ülkemiz için SO_2 kirliliğinin artmasına sebep olmaktadır. Yapılan ilk çalışmalarda en yüksek kirliliğin Kahramanmaraş ilinde bulunan Afşin Elbistan A ve B termik santralleri civarında olduğu bulunmuştur. SO_2 kirlilik sinyalleri Kahramanmaraşı takiben, büyük boyutlu termik santraller barındıran

Muğla, Kütahya, Ankara, Şırnak gibi illerde kuvvetli olarak görülmüştür. Aynı zamanda kükürt emisyonu yoğun olan bazı endüstri bölgelerinde kirlilik sinyallerine rastlanmıştır. Türkiye'deki SO_2 kirliliğini gösteren detaylı bir envanter çalışması olmadığından bu çalışma hem mevcut envanterleri değerlendirmek hem de uydu verileri kullanarak kirlilik takibi gerçekleştirmek açısından büyük bir önem arz etmektedir.

Bir sonraki aşamada, uydu verileri EMEP envanteriyle karşılaştırılmıştır. Çalışma EMEP envanterinde en son bulunan 2012 ve 2013 yılları arası için gerçekleştirilmişir. EMEP envanterinde bulunan 2011 verisi ise o yılda OMI verisindeki yüksek gürültü nedeniyle incelemeye alınmamıştır. EMEP envanterinin $0.1^{\circ}\times0.1^{\circ}$ dereceli yeni grid sisteminde bulunan emisyonlar incelenmiş, haritaları çıkarılarak aynı yıllardaki uydu verileriyle karşılaştırılmıştır. Bu karşılaştırma sonucunda, envanterde bazı büyük ölçekli santrallerden kaynaklanan emisyonların varlığı saptanmış fakat envanter ve uydu verilerinin önemli ölçüde uyuşmadığı görülmüştür. Afşin Elbistan, Seyitömer, Tunçbilek (Kütahya) çevresi gibi çok büyük kirlilik bölgelerinde bazı uyuşmalar görülmesine ragmen bu uyuşma çok düşük seviyededir, ve bunun yüksek kirlilikten dolayı olduğu düşünülmektedir. Ayrıca, OMI verilerinde çalışma alanındaki en yüksek kirlilik sinyallerinden birisine sahip olan Ankara Çayırhan termik santral emisyonlarının EMEP envanterinde bulunmadığı saptanmıştır. Aynı zamanda, bazı Manisa Soma ve Sivas Kangal gibi bazı termik santraller için envanterde yüksek emisyonlar verilmiş olmasına ragmen, OMI verileri düşük sinyaller vermektedir. EMEP envanterinde genellikle noktasal olarak değil fakat tüm şehri kapsayacak şekilde emisyon yerleştirildiği görülmüş bunun neticesinde, önemli bir coğrafi uyuşma gözlemlenmemiştir. Bunun yanı sıra, İstanbul için EMEP emisyonlar çok yüksek değerler göstermekte fakat OMI SO_2 kolon verileri bunun aksi yönde olduğunu işaret etmektedir.

Türkiyedeki SO_2 kaynaklarını temsil eden bütüncül bir emisyon envanteri olmadığı için, uydu verileri kullanılarak emisyon tahmini çalışması yapılmıştır. Buna göre, büyük SO_2 kaynakları seçilerek, çevresine $60\times60km^2$ ve $2\times2km^2$ alt gridlere sahip olan bir çalışma alanı oluşturulmuştur. Daha sonra, geçmiş çalışmalarda aynı şekilde uygulanan, bir çap etrafında ortalama metodu uygulanarak, uydu verilerindeki gürültü azaltılmıştır. Ayrıca, kirlilik kaynağının 300 km çevresindeki yıllık ortalama alınıp, her bir griddeki ortalama değerlerden çıkarılarak, arka plan gürültüsündeki yıllara göre değişim azaltılmıştır. Daha sonra 2 boyutlu gaussian fit formulü uydu verisine uygulanıp yıllık emisyon tahmin verileri elde edilmiştir. Buna göre tahmin edilen değerler ile hesaplanan emisyonlar arasında, orta seviyede bir uyuşma ($R^2 = 0.57$) gözlenmiştir.

Aynı çalışma OMI SO_2 yıllık haritalarında yüksek sinyaller veren altı diğer termik santral için 11 yıllık olarak yapılmış. Burada elde edilen verilerde yıllık tahmine göre daha iyi bir uyuşma ($R^2 = 0.75$) olduğu gözlenmiştir. Bu çalışmada OMI verilerinin Çayırhan santrali için yüksek veriler işaret ettiğini diğer yandan OMI verilerinin Kangal ve Soma santralleri için hesaplanan emisyonlara göre düşük seviyede kaldığı belirlenmiştir. Hiçbir elektrik üretim verisi olmayan Şırnak Silopi için emisyon tahmini yapıldığında yıllık yaklaşık 112 kton SO_2 emisyonu olduğu belirlenmiştir.

Son olarak, uydu verileri yer istasyon ölçümleriyle mukayese edilmiştir. Türkiye'deki SO_2 yer ölçüm istasyonu sayısı 2005 yılında 30 civarında iken günümüzde bu sayı 190 civarındadır. Bu sayılar, 2005'te yer ölçüm istasyonları için çok az veri sahibi olunduğunu göstermekte, özellikle ölçüm istasyonlarının çok az olduğu bu yıllardan başlayarak günümüze kadar uzanan yıllık kirlilik değişim çalışmalarında uydu verilerinin avantajı ortaya çıkmıştır. Buna göre yer ölçüm istasyonları verileri, saatlik ve günlük ortalama değerler için uydu verileriyle karşılaştırılmıştır. Öncelikle uydu verileri belirli bir kolondaki kirliliği temsil ettiğinden model çıktıları kullanılarak yer seviyesindeki kirlilik oranı belirlenmiş ve DU (Dobson Birimi) olan verileri model dikey profile kullanılarak yüzey konsantrasyonuna (µg/m^3) çevrilerek karşılaştırma yapılmıştır. Daha sonra, şehirlerdeki toplam kirlilik uydu verileri ve yer ölçümleri karşılaştırılarak incelenmiştir. Öncelikle incelenen bazı santraller için en yakındaki ölçüm istasyonlarının santrallerden çok uzakta olduğu tespit edilmiştir. Bu sebeple, bu istasyonlarda verimli bir karşılaştırma yapılamamıştır. İstasyona yakın santrallerde yapılan çalışmalarda ise, büyük farklılıklar görülmüştür. Afşin Elbistan'a 30 km yakında bulunan Elbistan ölçüm istasyonuyla aynı alanda bulunan OMI SO_2 verileri incelenmiş, bunun sonucunda, yıllık değişim trendlerinin tamamen farklı olduğu, aynı zamanda yapılan değerlendirmede OMI yüzey konsantrasyon kirliliğinin yer ölçüm konsantrasyonlarına göre çok düşük seviyede kaldığı görülmüştür. Manisa Soma, Sivas Kangal, Şırnak Silopi için yapılan karşılaştırmalarda, yer ölçüm değerlerinin çok yüksek olduğu bunun yanında OMI verilerinin çok yüksek kirlilik sinyalleri göstermediği saptanmıştır.

Özetlemek gerekirse, bu tezde aşağıdaki çalışmalar gerçekleştirilmiştir;

- Türkiye ve çevresindeki SO_2 kirliliğinin uydu verileri kullanılarak haritalandırılması
- Mevcut emisyon envanterlerinin uydu verileri ile değerlendirilmesi
- Büyük ölçekli noktasal SO_2 kaynaklarının emisyon tahmini
- SO_2 yer ölçümleri ile uydu verilerinin karşılaştırılması.

1. INTRODUCTION

Air pollution is one of the major problems for environment and human health. Especially after industrialization age, it has become more dangerous for both human health and environment. Nowadays, damaging effects on environment and serious health problems such as lung cancer, asthma, various skin and eye problems, and allergies are directly associated with air pollution.

Ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxides (SO_2), particulate matter (PM), carbon monoxide (CO), lead (Pb) are known six major criteria air pollutants which are dangerous for human health and environment. Therefore, monitoring those pollutants is essential for us.

Remote sensing of atmospheric pollution is rather a recent area for air pollution monitoring. It has been widely used in meteorology, ocean sciences and geosciences. In the last decades, it has been used for detecting occurrence and magnitude of air pollutants beginning from detecting SO_2 pollution from a volcano eruption in 1982 (Krueger et al., 1995).

1.1 Aim and Scope

The aim of this thesis is to evaluate and improve SO_2 emission inventories by satellite retrievals in and around Turkey. Satellite retrievals supply SO_2 PBL (planetary boundary layer) column amounts back to 1995 by GOME that is the first instrument detects tropospheric pollution from space. For satellite retrievals, spatial discontinuity of ground monitoring stations is not a problem, and global coverage can be obtained in the order of days.

In this study, SO_2 pollution in and around Turkey using satellite retrievals of Ozone Monitoring Instrument (OMI) were performed. Firstly, SO_2 pollution for Turkey was investigated, by reviewing literature and available emission inventor, EMEP. Later spatial SO_2 pollution distribution was determined using OMI SO_2 column amounts between the years of 2005 and 2015. Mostly, observed pollution signals relate with large point sources such as large-scale coal power plants, large-scale industries that are emitting significant amount of SO_2 to the atmosphere. For the first evaluation, large-scale coal power plants were selected since the coal reserves are in significant amount for Turkey. In addition, coal power plants are very important in electricity production for public use. It is in the range 25-30% since 1970s.

Coal power plants that are larger than 50 MWe installed capacity were selected for detailed evaluation under the scope of this study. Coal power plants were significant SO_2 sources since the coal reserves of Turkey, which are mainly lignite, have low calorific value and high S and ash content. There was not a detailed emission inventory reported for these emission sources for Turkey, which makes this study very important for evaluation of the current emission inventories based on satellite retrievals.

Finally, measurements from national ground-monitoring stations were compared with satellite retrievals. There are 190 SO_2 ground-monitoring stations around Turkey as of 2015, while it was around 30 in 2005. Hourly and daily average SO_2 concentrations were compared with OMI SO_2 PBL column amounts. Satellite derived ground concentrations were also calculated and compared with ground-based observations using a vertical profile obtained from an air quality model.

In summary, the following tasks were performed for this study

- determination of the spatial distribution of SO_2 pollution in and around Turkey
- evaluation of available SO_2 emission inventories
- emission estimation of SO_2 from large point sources
- comparison of SO_2 pollution observed from satellite retrievals and ground based measurements around large point sources

2. BACKGROUND INFORMATION

2.1 Sulfur Dioxide (SO_2)

SO_2 is one of the major air pollutants in the atmosphere and it is in the group of criteria pollutants that are known as harmful to environment and health (EPA, 2016a). It is an odorous and invisible gas. It also has some harmful compounds such as sulfuric acid, sulfurous acid and sulfate particles. In troposphere, about 99% of SO_2 comes from anthropogenic activities. Mainly, it is produced by volcanoes, power plants, refineries, smelters, burning of fossil fuels and biofuels (Krotkov et al., 2008). Anthropogenic and natural SO_2 emissions are oxidized fast in the atmosphere, which leads to aerosol formation and acid deposition by formation of sulfuric acid that then causes atmospheric pollution and acid rain (Fioletov et al., 2013). Sulfate aerosol negatively affects human health, reduces visibility and has effects on climate as well (Lee et al., 2011).

2.1.1 SO_2 sources

SO_2 sources are categorized into two groups as natural and anthropogenic sources. Natural sources are volcanoes, oceans and anthropogenic sources are power plants and other industrial facilities those have the largest contribution to SO_2 emissions with 73% and 20%, respectively (EPA, 2016a). Other anthropogenic sources are smelters, motor vehicles, industrial activities that contain sulfur.

2.1.2 Effects of SO_2 on environment and health

Current studies show that SO_2 has respiratory effects such as asthma symptoms and bronchoconstriction. It is said that there is a connection between increased visits to emergency departments and short-term exposure especially for sensitive groups such as asthmatics, the elderly and children (EPA, 2016a). Acid rains are primarily danger for environment because of SO_2 emissions. Emitted SO_2 is chemically converted to sulfuric acid in the atmosphere. After precipitation of this acid, it causes damages on buildings and environment (Chin and Jacob, 1996). Formation of sulfuric acid aerosols have negative impacts on human respiratory and it can cause mortality, too. Sulfate aerosols cool Earth's surface (IPCC, 2001).

2.1.3 Air quality standards for SO_2

Polluted air can adversely affect human health and environment as discussed in the previous section. Therefore, some limit values has been set to control SO_2 emissions to protect human and environment. Those limit values can vary from country to country, below in the table 2.1 there are limit values of SO_2 for European Union (EU), Environment Protection Agency(EPA), Turkey.

Table 2.1 : SO_2 limit values for EPA, EU and Turkey (EC, 2016; EPA, 2016a; MoEU, 2016a)

	EPA			EU			Turkey		
Pollutant	Average Time	Limit Value (ppb)	Limit Value (µg/m³)	Average Time	Limit Value (µg/m³)	Number of exceedance	Average Time	Limit Value (µg/m³)	Number of exceedance
SO_2	Primary[1]	75	141	1 hour	350	24	1 hour	440	24
	Secondary[2]	500	941	24 hours	125	3	24 hours	200	3

[1] 99th percentile of 1-hour daily maximum concentrations, averaged over 3 years

[2] Not to be exceeded more than once per year

2.1.4 Emission inventories

EPA states "An emissions inventory is a database that lists, by source, the amount of air pollutants discharged into the atmosphere of a community during a given time period" as a definition for emission inventory (EPA, 2016b).

2.1.4.1 EMEP emission inventory

After Convention on Long-range Transboundary Air Pollution (LRTAP) agreement in 1979, EMEP (Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) was established to supply scientific information for governments and subsidiary bodies while making decisions on emission reductions in protocols. There are three main elements that EMEP based on: emission data collection, air measurements and quality of precipitation, air pollution deposition and atmospheric transport modelling. (EMEP, 2016).

In this study EMEP grid system was used that is recently updated to 0.1°×0.1° (longitude-latitude) resolution beginning from 2015. Three years (2011-2013) of emissions are available with this resolution in EMEP website (CEIP, 2016). In this new reporting system, there are GNFR codes for each NFR (Nomenclature for Reporting) sectors, which were explained in Table 2.2 below with comparison with

SNAP sectors that previously used. In the inventory following pollutants are reported; SO_2, NO_x, NH_3, CO, NMVOC, PM_{coarse}, PM_{10} and $PM_{2.5}$.

Table 2.2 : GNFR and SNAP sectors and sector descriptions

GNFR SECTORS	SNAP SECTORS
GNFR -A Public Power	S1 - Combustion in energy and transformation industries
GNFR - B Industry	S2 - Non-industrial combustion plants
GNFR - C Other Stationary Combustion	S3 - Combustion in manufacturing industry
GNFR - D Fugitive	S4 - Production processes
GNFR - F Road Transport	S5 - Extraction and distribution of fossil fuels and geothermal energy
GNFR - G Shipping	S6 - Solvent use and other product use
GNFR - H Aviation	S7 - Road transport
GNFR - I Offroad	S8 - Other mobile sources and machinery
GNFR - J Waste	S9 - Waste treatment and disposal
GNFR - L AgriOther	S10 - Agriculture
	S11- Other sources and sinks

2.2 Satellite Retrievals

Satellite retrievals of tropospheric pollution dates back to 1982, beginning with SO_2 detection of a volcanic eruption from Total Ozone Mapping Spectrometer (TOMS) (Krueger et al., 1995). Tropospheric SO_2 measurements begin with Global Ozone Monitoring Experiment (GOME) in 1995. It has some advantages over ground-monitoring stations such as broad coverage, continuous measurements and data availability back to 1995. After GOME, other instruments were sent to space with higher spatial resolution such as; Scanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIMACHY) on Envisat since 2002, Ozone Monitoring Instrument (OMI) on AURA since 2004, Global Ozone Monitoring Experiment-2 (GOME-2) on MetOp A and MetOp B since 2006 and 2012 respectively. Those instruments could detect many tropospheric pollution species such as nitrogen dioxide, sulfur dioxide, carbon monoxide, methane, non-methane volatile organic compounds, ammonia, particulate matter (aerosol optical depth) and carbon dioxide (Table 2.3).

Satellite retrievals are getting much deserved attention since they provide data with better spatial resolution day by day. In late 2016, Tropospheric Monitoring Instrument (TROPOMI) will be launched with significantly higher spatial resolution (7×7 km^2) (Veefkind et al., 2012).

Table 2.3 : Major satellite instruments, their specifications and species detected (Martin, 2008; Streets et al., 2013**)**

Instrument	Platform	Meas. Period	Spectral Region	Resolution at nadir (km^2)	Local crossing time	Global Coverage (days)	Spectral Range (µm)	SO_2	NO_2	HCHO	CO	CH_4	NMVOC	PM (AOD)	CO_2	NH_3	O_3
GOME	ERS-2	1995-2003	UV - Vis	40 × 320	10:30	3	0.23 - 0.79	×	×	×			×	×			×
MOPITT	Terra	2000 -	IR	22 × 22	10:30	3.5	4.7				×	×					
MISR	Terra	2000 -	Vis - IR	18 × 18	10:30	7	4[1] λ, 0.45 - 0.87							×			
MODIS	Terra	2000 -	Vis - IR	10 × 10	10:30	2	36[1] λ							×			
	Aqua	2002 -	Vis - IR		13:30		0.41 - 14.2							×			
AIRS	Aqua	2002 -	Vis - IR	14 × 14	13:30	1	3.7 - 16	×			×	×			×		
SCIAMACHY	ENVISAT	2002-2012	UV - Vis	30 × 60	10:00	6	0.23 - 2.3	×	×	×	×	×	×	×	×		×
OMI	Aura	2004 -	UV - Vis	13 × 24	13:45	1	0.27 - 0.50	×	×	×			×	×			×
TES	Aura	2004 -	IR	5 × 8	13:45	n/a	3.3 - 15.4				×	×			×	×	×
PARASOL	PARASOL	2004-2013	Lidar	16 × 18	13:30	1	9[1] λ, 0.44 - 1.0										
CALIOP	CALIPSO	2006 -	Lidar	40 × 40	13:30	n/a	0.53, 1.06										
GOME-2	MetOp	2006 -	UV - Vis	40 × 80	9:30	1	0.24 - 0.79	×	×				×	×			×
IASI	MetOp	2006 -	IR	12 × 12	9:30	0.5	3.6 - 15.5	×			×	×	×		×	×	×
TANSO - FTS	GOSAT	2009 -	IR	10 × 10	13:00	3	0.76 - 14.3					×			×		
GEMS	COMS	2010 -	UV - Vis	0.5 × 0.5	-	GeSt[2]	0.41 - 0.87										
OMPS	SNPP	2011 -	UV	50 × 50	13:30	1	0.3- 0.38	×						×			×
TROPOMI	Sentinel-5P	2016-	UVN	7 × 7	13:30	1	0.27 - 2.39	×	×	×	×	×		×			×
TEMPO		2017-	UV - Vis	2 × 4.5	-	GeSt[2]	0.29 - 0.74	×	×	×				×			×
Sentinel - 4	MTG - S1		UVN	8 × 8		GeSt[2]	0.31 - 0.78	×	×	×				×			×

[1] Number of discrete wavelengths [2] On geostationary satellites, over only a determined area

3. LITERATURE REVIEW

3.1 Satellite Retrievals

In the recent years, remote sensing of air quality had been developing significantly due to advancements in satellite instruments. After first detection of SO_2 using TOMS (Total Ozone Mapping Spectrometer) in 1982 for El Chicón volcanic eruption, satellite retrievals of air pollution species evolved strikingly (Krueger, 1983; Krueger et al., 2009; Krueger et al., 1995). After El Chicón eruption, TOMS as well such as Pinatubo (1991), Cerro Hudson (1991) and St. Helena eruptions had observed some other volcanic eruptions from space. TOMS mission continued over different satellites (Meteor-3, ADEOS, Earth Probe) for 21 years (Chance et al., 2002). Subsequently, in 1995, GOME, in 2002 SCIMACHY, in 2004 OMI and in 2006 GOME-2 were launched to the space to start their missions (Bovensmann et al., 1999; Callies et al., 2000; Eisinger and Burrows, 1998; Levelt et al., 2006).

Beginning from 1995, GOME as the first instrument were used to detect tropospheric pollution from space (Eisinger and Burrows, 1998). SCIAMACHY, OMI and GOME-2 were launched later on with better spatial resolutions (at nadir, 30×60, 13×24, 50×80 km^2). Those instruments have more sensitivity to atmospheric species and larger spatial resolution than TOMS. Therefore, those instruments could detect many tropospheric pollution species from space such as nitrogen dioxide, sulfur dioxide, carbon monoxide, methane, non-methane volatile organic compounds, ammonia, particulate matter and carbon dioxide.

In the near future, some instruments are going to be launched to space with better spatial resolution such as TROPOMI with 7×7 km^2 resolution at nadir (Tropospheric Monitoring Instrument) by ESA (European Space Agency) in late 2016 (Veefkind et al., 2012). In addition, some geostationary instruments will be launched to space those provides better spatial resolution for a certain area, for example TEMPO (Tropospheric Emissions: Monitoring of Pollution) over U.S., Sentinel 4 UVN over Europe and GEMS (The Geostationary Environmental Monitoring Spectrometer) over South Korea.

3.2 OMI SO_2 Retrievals

In this thesis, OMI retrievals were used to evaluate SO_2 pollution in and around Turkey. OMI is Finnish-Dutch built instrument on AURA satellite that was launched on July 2004 to space by NASA. AURA is a sun-synchonorous satellite with 1:45 pm local equator crossing time. OMI is providing data continuously since August 2004 with only exceptional gaps. OMI has fully global coverage each day. Normally, 14 or 15 data granule (product file) are produced by OMI every day from 2600 km wide swath each containing 1600 viewing lines with 60 cross-track positions (pixels) (OMI, 2014). OMI pixel size is 13×24 km^2 at nadir (Figure 3.1). OMI providing data for 12 years continuously which is the longest data record. Since 2007, row anomaly (signal suppression) affects OMI Level 1B data, some rows of CCD detector were affected from row anomaly. There are some efforts by scientists to flag the data that were affected by row anomaly so far (KNMI, 2012). Recent advices are only using not affected data within certain cross track positions.

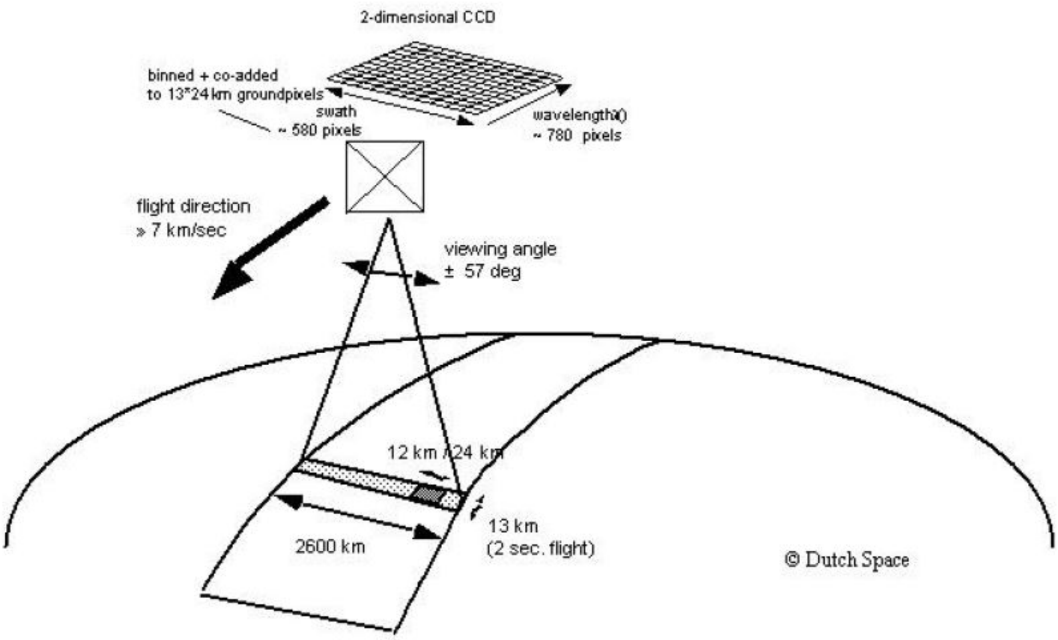

Figure 3.1: OMI pixel size and swath (adapted from OMSO$_2$ Read Me)

Many studies has been performed to detect tropospheric SO_2 pollution from power plants (Fioletov et al., 2015; Fioletov et al., 2011; Fioletov et al., 2013; Lu et al., 2013; Song and Yang, 2014; Zhang et al., 2009), volcano eruptions and degassing (Beirle et al., 2014; Campion, 2014; Campion et al., 2012; de Foy et al., 2009; Hooper et al., 2012; Ialongo et al., 2015; McCormick et al., 2015; McCormick et al., 2014; Schmidt et al., 2015; Telling et al., 2015; Yang et al., 2007), comparison with ground measurements (Kramer et al., 2008; Lee et al., 2011; Theys et al., 2015), Canadian oil sands (McLinden et al., 2014; McLinden et al., 2012) and smelters (Carn et al., 2007) by using OMI instrument.

There were also used different algorithms in different studies such as Band Residual Difference (BRD) (Krotkov et al., 2006)¸ Principal Component Analysis (PCA) (Li et al., 2013), and Differential Optical Absorption Spectroscopy (DOAS) (Theys et al., 2015) since OMI was launched to space on AURA satellite. BRD algorithm provided better results for OMI compare to TOMS instrument from 10 to 20 times depending on location. In 2013, PCA algorithm was developed for OMI SO_2 product and in the algorithm, it was found that, the bias was reduced by a factor of two compare to previous algorithm. In 2015, DOAS algorithm was developed in preparation of TROPOMI for SO_2 retrievals. Algorithm was applied to SO_2 datasets between 2004 and 2013, and a good agreement was found between anthropogenic and volcanic emissions. There were also other studies evaluating algorithms and row anomalies (Yan et. al., 2012).

Yan et al. (2012) investigated row anomalies, which affects OMI products since 2007. For SO_2 columns retrieved by BRD (Band Residual Difference) algorithm row anomalies lead large biases. In the study, in order to fix the problem two-correction methods were developed which were for northern latitudes and full orbit. For northern latitude, residual correction approach with median residual from a sliding 10^0-latitude range and near equator was used to remove anomalous high SO_2 columns. For full orbit row anomalies, the SO_2 biases caused by the anomalous ozone (O_3) column and underestimated Lambertian effective reflectivity (LER) were reduced, respectively using unaffected adjacent O_3 column and residual correction with median residual from a sliding 10^0-latitude range. At the end of both correction methods, it was seen that row anomaly biases were reduced in great amounts. Therefore, the valid range of data was extended to a higher range when using BRD algorithm (Yan et al., 2012).

Another application of OMI retrievals are about oil sands. First study about Canadian oil sands by McLinden et al. (2012) were about air quality over Canadian oil sands including SO_2 and NO_2. In the study, increased SO_2 values were found but it is not statistically significant due to large uncertainties. On the other hand, there was an increase in NO_2 between 2005 and 2010 by 10.4-3.5 percent/year respectively (McLinden et al., 2012).

McLinden et al. (2014) studied SO_2 and NO_2 emissions over Canadian oil sands with corrected air mass factors (AMFs). AMFs were recalculated by Environment Canada (EC) for this area with updated and higher input resolution information and absorber profiles from a regional scale air quality model (GEM-MACH). An improved snow treatment and higher spatial resolution surface reflectivity (MODIS satellite instruments) were also included in the study. This new AMFs caused higher SO_2 and NO_2 peak vertical column density (VCD) by a magnitude of 1.4 and 2 respectively compared with the previous AMF over surface mining. NO_2 and SO_2 spatial distribution of the in situ instruments could be captured by OMI-EC surface concentrations. The absolute values were in reasonable agreement with OMI-EC surface NO_2 and SO_2 biased low by roughly 10–30 %. The results explains importance of using input information for the spatial and temporal variability at the location (McLinden et al., 2014).

In China, SO_2 pollution is a very important problem since China's energy production policy is mainly based on coal power plants due to their large coal reserves. However, before 2005, using flue gas desulphurization (FGD) were not compulsory and SO_2 pollution were in higher amounts. After 2005, China government put stricter rules to control SO_2 pollution by making FGD installation compulsory. Therefore, before Beijing Olympic Games in 2008, some reduction in SO_2 pollution was observed in China especially in Beijing. Many studies performed for China pollution by using OMI retrievals.

In these studies, many different aspects were investigated by using satellite retrievals from OMI. For example, Yan et al. (2014) studied about, anthropogenic SO_2 emissions over China between 2005 and 2010 by using OMI and GOME-2. In Beijing and Chongqing, high SO_2 columns were reported probably due to use of coal power plant, meteorology and terrain characteristics. It was also found out that SO_2 columns were reduced in 2008 around Pearl River Delta when Olympic Games took place and strict controls were applied due to reduce traffic and pollution emissions in that year (Yan et al., 2014).

He et al. (2012) studied remote sensing of SO_2 by OMI and aircraft campaign over central China. Sulfur chemistry was simulated by CMAQ (Community Multiscale Air Quality) model. OMI SO_2 columns were found in good correlation with ground measurement (R^2=0.84) but low bias (slope=0.54). When using iterative spectral fitting (ISF) algorithm, OMI data showed similar correlation with ground measurements (R^2=0.87) but less noise (slope=0.86) compared to BRD algorithm. ISF products were produced off-line during aircraft campaign (2008). CMAQ results showed an agreement with the mean aircraft measurements with 30% overestimation but it didn't capture the SO_2 vertical distribution well, because of low model resolution for calculating vertical mixing (He et al., 2012).

Jiang et al. (2012) studied SO_2 column concentration changes over China observed by OMI. This study was conducted between 2005 and 2008. There was an increasing trend in SO_2 concentrations between 2002 and 2005. In China, there is a huge amount of coal consumption by coal power plants, which led a high SO_2 concentration around the country. (68.7% coal consumption in energy sector) According to pollution control plans of China government, the aim was decreasing of SO_2 concentrations for 2005-2010. For this reason, monitoring was considered essential. OMI Planetary Boundary Layer data was used by processing with Band Residual Difference Algorithm. At the end of this study, it was seen for eight provinces of China SO_2 concentrations were decreased. Especially in Beijing $SO_{2,}$ concentrations were reduced in great amount during preparation of Olympic Games. At some regions although coal consumption was increased, there was a decrease in SO_2 concentration. That means some efficient desulphurization technologies were used in those regions. At the end of this study, it was advice that clean energy should be used for a sustainable development in China (Jiang et al., 2012).

Emission estimation studies were also performed using OMI retrievals (Fioletov et al., 2015; Fioletov et al., 2011; Lu et al., 2013). Those studies showed that satellite retrievals could be used for completing emission inventories.

Fioletov et al. (2011) studied about SO_2 emission estimation from large point sources for U.S. between 2005 and 2010 by using OMI retrievals. The study is one of the earliest studies showing emissions can be estimated by using OMI retrievals. A geographical grid was established around the source and the average of all OMI pixels centered within a 12 km radius from each grid point was calculated. Gaussian function was used for emission estimation. Local bias removal was also applied by subtracting average of 300 km around the source to remove background pollution. At the end of study, it was found that emissions below 70 kton/yr were not statistically significant for OMI signals. Because there were some large errors for these data. Another output of this study was that according to maps created from SO2 retrievals, it was seen that SO_2 concentration was declined for 2005-2007 and 2008-2010

In another study about detection of large emission sources by OMI was conducted by Fioletov et al. (2013). The study was not only about OMI retrievals but also about SCIAMACHY and GOME-2 SO_2 retrievals. Comparison of those instruments were performed with OMI for detecting SO_2 emission sources. At the end it was found that, the three instruments have agreement for mean averages near large-scale emission sources in general. In addition, OMI have better capability to detect smaller emission sources than other two instruments.

Lu et al. (2013) studied about emission estimation of SO_2 from large point sources in India (Lu et al., 2013). In the study, similar methodology were applied to OMI SO_2 retrievals as it was in previous study of emission estimation for U.S. from large point sources (Fioletov et al., 2011). The study was conducted for India between 2005-2012 using OMI SO_2 retrievals. Due to increasing industrial activities and energy production in India, large increasing in SO_2 pollution was detected in the study (71%). The findings were compared with reported emissions, which were indicating decreasing trends for SO_2 emissions for India. It was advised in the study that pollution monitoring network should be optimized since both total OMI-observed SO_2 and SO_2 around coal power plants showed significant increases for India.

Fioletov et al. (2015) studied about emission estimation of SO_2 from large point sources in U.S. and a Norilsk smelter as a case study by OMI. A new method and a new algorithm were used in the study different from the previous methods. The pixel rotation method was applied to the wind direction data, and 3-D fitting method was applied to OMI SO_2 retrievals. Principal component analysis (PCA) were applied to OMI retrievals different from previous studies (Li et al., 2013). As a result, a good correlation were found between estimated and reported emissions (R^2=0.91). At the end of the study, it was found that minimum detectable mass of SO_2 were developed to 30 kton/yr from 70 kton/yr by OMI, which means higher than two times develop in the study.

In one of the most recent study about OMI SO_2 retrievals, regional SO_2 pollution changes between 2005 and 2014 were investigated (Krotkov et al., 2015). In the study, PCA algorithm was used for OMI SO_2 retrievals. Pollution changes for heavily polluted areas were investigated between 2005 and 2014. A significant decrease (more than 80 %) was found over U.S. from 2005 to 2014 due to stricter policies. After installation of FGD systems to large-scale coal power plants, large reduction was found over Eastern Europe. After 2011, due to stricter regulations and economic slowdown in China, 50% reduction was found in SO_2 emissions between 2012 and 2014. On the other hand, a remarkable increase of SO_2 emissions was detected over India (100%). Largest SO_2 emissions were detected over Persian Gulf due to oil and gas processing. Turkey SO_2 pollution increase was observed in the study.

4. METHODOLOGY

4.1 SO_2 Satellite Retrievals

OMI is UV-visible spectrometer measuring trace gases and aerosols with daily coverage beginning from October 2004 on AURA satellite. OMI SO_2 satellite retrievals data were downloaded from NASA website (NASA, 2016). In the study, OMI SO_2 PBL Level 2 (L2) product was used. SO_2 satellite retrievals data were downloaded in ASCII format and filtered according to the OMI guidelines (OMI, 2012) to eliminate the low quality data. The filtration was performed using a JAVA programming code because of the data load (approximately 5000 files/year). The filtration performs the following tasks: merging all the files, removal of metadata, eliminating data with radiative cloud fraction (RCF) greater than 0.3, solar zenith angle greater than 70^0C, and missing values of SO_2 PBL column which were assigned as -1.27E+30. Finally, date, weekday and month information were added to data.

After filtration of yearly data, the file opened in ArcGIS software and exported to shape files (.shp). According to intend of the data usage, the data inside EMEP domain, and Turkey were selected. Finally, averaged SO_2 retrievals were plotted to see pollution areas within the domain (Figure 4.1).

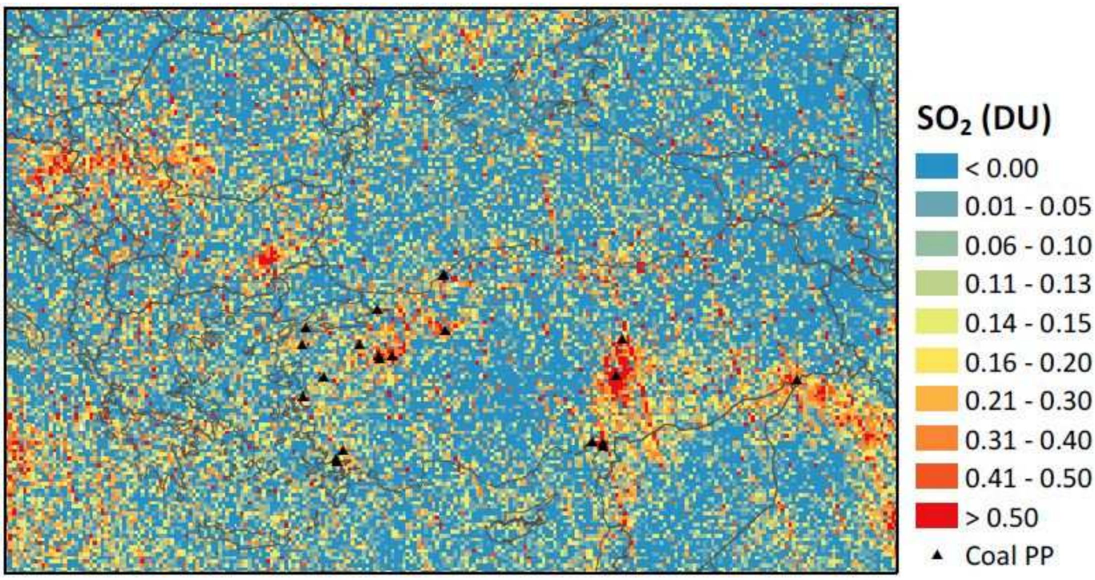

Figure 4.1 : SO_2 pollution distiribution map in Turkey for 2005 using ArcGIS.

4.2 SO_x Emissions

European Monitoring Emission Programme (EMEP) emission inventory was used in this thesis (EMEP, 2016). EMEP emission inventory data are available until 2013 but for some of the large-scale coal power plants are not in the inventory such as Çayırhan and İsken Sugözü. Before 2011, EMEP does not contain Afşin Elbistan as well which is the largest installed capacity power plants in Turkey. In the literature, there are some studies indicating emission inventories for Turkey, one of the important studies were also used in the thesis study which presented emission inventory of Turkey coal power plants for 2010 (Sözen et al., 2010). EMEP inventory, $0.1^o \times 0.1^o$ gridded data that was explained in detail in previous sections (2.1.4), was used.

4.3 SO_2 Ground Observations

Ground observation data were downloaded from National Air Quality Observation Network of Ministry of Environment and Urbanization (MoEU, 2016b). There are 187 stations in Turkey those are monitoring SO_2 ($\mu g/m^3$) as of the year 2016. Some of the stations are under the control of Ministry of Environment and Urbanization and some of Marmara Clean Air Center Directory (MTHM) located in İstanbul. MTHM data was taken directly from the directory. Hourly data were processed between 2005 and 2015 and daily averages and averages of two consecutive hours of 13:00-14:00 were calculated, since OMI has 13:45 local passing time. OMI SO_2 retrievals and ground observations were compared in the thesis, which were explained in detail in Chapter 6.

5. SO_2 POLLUTION AROUND TURKEY USING OMI RETRIEVALS

5.1 Introduction

The Ozone Monitoring Instrument (OMI) on NASA's EOS Aura satellite was launched on July 2004. OMI has a finer spatial resolution than other satellite instruments with its 13×24 km^2 resolution at nadir than GOME (320×40 km^2) and SCIAMACHY (60×30 km^2). AURA is a sun-synchonorous satellite that has 13:40 local passing time and global coverage in one day. OMI's resolution is changing between 13×24 km^2 and 13×128 km^2 depending on its point of view (Boersma et al., 2008).

OMI L2 product were downloaded from National Aeronautics and Space Administration (NASA) Goddard Earth Sciences Data and Information Services Center (GES DISC). In the L2 data, SO_2 vertical columns are given for four layers; planetary boundary layer (PBL), lower tropospheric layer (TRL), middle tropospheric (TRM), and upper tropospheric and stratospheric layer (STL). In this study, the SO_2 PBL data were used. PBL data were processed by Principal Component Analysis (PCA) after 2013, and all the data were reprocessed according to this algorithm. This algorithm has some advantages over the previous method, Band Residual Algorithm (BRD), by means of spatial smoothing and local bias correction (Li et al., 2013).

5.2 Methodology

Two different methodology were used to process OMI PBL L2 data for detecting SO_2 pollution in Turkey and surrounding area. One of the methodology was used in the initial steps of the study, there were large noises observed in the results. Secondly, another methodology was applied and this method provided better results with less noise in SO_2 distributions (Figure 5.1). In the initial methodology 10×10 km^2 gridded domain were used covering Turkey and around. OMI data were analyzed seasonally, and it was found that the available winter retrievals was very low than other seasons due to low quality data and cloudy days. This also lead no data in some regions (North East Anatolia – East Blacksea) and noise in the data. For spring and summer seasons, there was less noise in OMI data, thus SO_2 pollution regions could be seen better for that period.

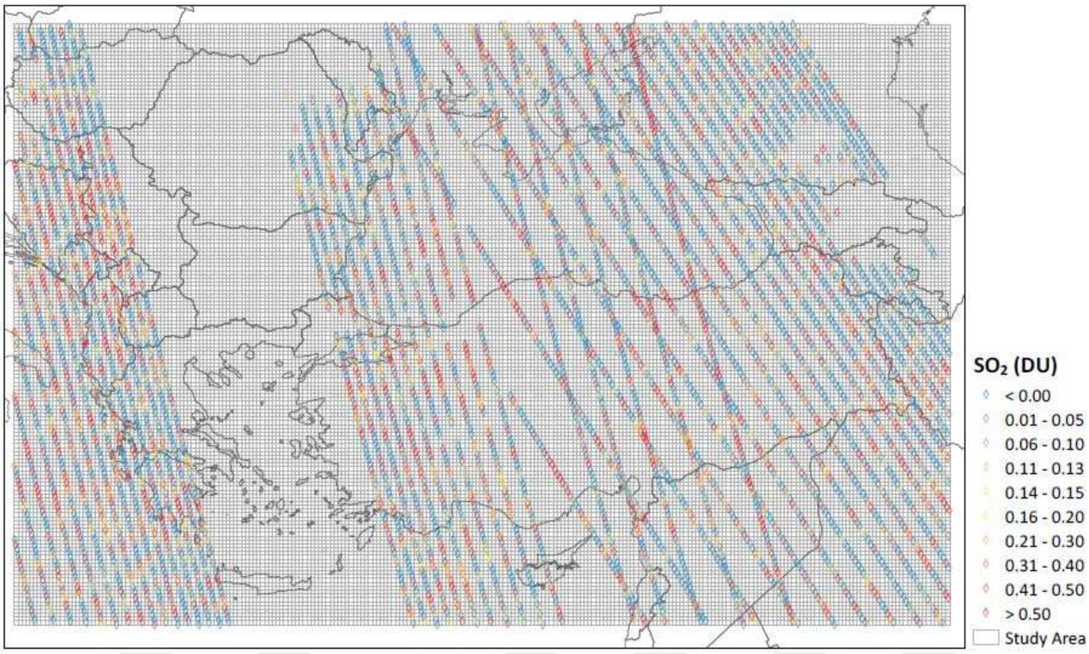

Figure 5.1 : Study area for Turkey and surrounding and OMI SO_2 retrievals passing over the study area for one day (1st July 2014)

In many other previous studies, summer and spring (Fioletov et al., 2015; Song and Yang, 2014) and only summer data (Li et al., 2010) were used. The other seasons than winter, pollution maps are similar to each other, on the other hand for fall and summer seaons, higher SO_2 column values and larger pollution regions were observed.

According to those values, high SO_2 columns were observed around large-scale coal power plants in Turkey which are Afşin-Elbistan, Ankara-Çayırhan and Muğla-Yatağan, Yeniköy and Kemerköy thermal power plants. Following those, in the cities of Kütahya, İskenderun, Şırnak and Sivas high SO_2 columns were observed possibly due to coal power plants located in those cities.

Other than those areas, in South East Marmara, East Blacksea and South East Anatolia regiouns, high SO_2 columns were observed.

Other than Turkey, in its immediate vicinity, there are some large SO_2 areas, such as in Bulgaria, 90 km close to Turkey's border, a large pollution was observed. There are four large scale coal power plant (3275 MWe) which are called Maritsa power plants (Maritsa, 2015).

Furthermore, around south of More Island a large SO_2 region was observed. There is a large-scale coal power plant called Megalopolis in the Island (Enipedia, 2016).

5.2.1 Initial findings with OMI SO_2 retrievals

SO_2 pollution still is a problem for Turkey, unlike many European and other developed countries. Main source of SO_2 pollution in Turkey is related to coal combustion for producing electricity in power plants. Turkish local coal, lignite, has low calorific value and high sulfur content compare to hard coal (Say, 2006). There are 15 large-scale power plants using lignite for producing electricity in Turkey. Among Turkish power plants, different than western countries, treatment technologies of SO_2 pollution is not as common.

Kahramanmaraş, Muğla, Ankara and Kütahya cities are the highest SO_2 regions within the domain observed by OMI SO_2 retrievals (Figure 5.2, Figure 5.3). All these regions were associated with coal power plants. Afşin Elbistan power plants are consisting of two different plants those are plant A and plant B. Plant A was installed in 1984 and plant B in 2006, there is an increasing SO_2 pollution beginning from 2006 when Afşin Elbistan B power plant was installed and operating capacity of power plants in the domain was doubled.

There is a decreasing trend for Muğla city since 2005. It has the biggest SO_2 plume in 2005 in Turkey, after that year, there is a consistent decreasing. It could be due to installation of a SO_2 treatment technology since electricity production did not change dramatically except the years 2009 and 2010. In these years, the pollution plume is very small.

Ankara Çayırhan power plant has a considerable SO_2 plume that is detected by OMI retrievals. This could be due to high S content (4.7%) of the lignite used in the power plant (Say, 2006). There is a visible decrease from 2005 to 2014.

In Kutahya city, an increase in the SO_2 pollution is seen by OMI PBL data. There is a new power plant that was built in 2014 which is called Kütahya Polatlı-1 power plant. This could be one of the reasons for increasing SO_2 pollution in the area. At the same time, Kütahya Tunçbilek and Kütahya Seyiömer power plants were both privatized recently. In other words, different management may cause changing in the emission amounts.

There are also some minor hot spots in Turkey such as, Şırnak, Şanlıurfa, Mardin, Gaziantep, Karabük and Aydın cities. In Şırnak, 135 MWe capacity asphaltit power plant were built in 2009. After that year, there was a remarkable increasing in the pollution plume. Before that year, there was still some pollution in the city, this could be due to an existing fuel oil power plant (135 MWe) and also residential heating by using coal in the region.

Other than close areas of power plants, there are some different areas those are affected by SO_2 pollution and that is seen by OMI in the pollution maps. In Şanlıurfa and Mardin cities, there are some SO_2 pollution seen by OMI, although those are not as much as in nearby large-scale power plants. This pollution may be as a result of coal using in house heating system in the city. Mardin city, is next to Şırnak, therefore it can be said for the city pollution that could be affected by Şırnak pollution due to wind direction. There is also a pollution plume in Gaziantep which is one of the most industrialized city in Turkey. That pollution plume could be attributed to that reason. In that area, there is a pollution captured by OMI for Osmaniye city as well, this is possibly coming from Kahramanmaraş where Afşin Elbistan power plant takes place. Karabük is another city where SO_2 pollution is seen in pollution maps. This could be due to one of largest iron and steel production facility and coal power plant inside this facility which is 50 MWe. In Aydın city, there is detected some SO_2 pollution by OMI, it is probably effect of wind transport from Muğla where three large-scale power plants are located.

Other than Turkey, there are some large SO_2 plumes in close proximity of Turkey in the study area. These are mainly, in Bulgaria (close to Turkey border), east of Iraq, west of Syria, between Armenia and Georgia border.

One of the biggest SO_2 plumes of the research domain is in Bulgaria. In Bulgaria, there are 4 coal power plants called Maritsa which are close to the border of Turkey (around 90kms). The plume has a decreasing trend among the years. It was very small in 2014 compared to 2005. This could be due to stricter regulations of European Union for SO_2 pollution after membership of Bulgaria in 2007.

Other interesting SO_2 plume for the domain is around east of Iraq. High increase were detected between 2005 and 2014 in SO_2 plume around Kerkuq and Musul where fuel oil processing activities were high. There is another SO_2 plume below the current plumes that is consistently big since 2005 . In the area, it is known that there are big oil processing companies and the pollution could be due to this. In Iraq, there are six large-scale fuel oil or oil power plants mainly around Baghdad city.

In between borders of Georgia and Armenia, a small SO_2 plume is seen by OMI PBL data. There is no coal power plants in Armenia nor in Georgia although in Georgia there are three natural gas power plants 70 km northeast of that plume. Since, SO_2 pollution is not expected from natural gas power plants, the SO_2 pollution plume could be due to industrial activities.

In Aleppo and Homs cities of Syria, SO_2 pollution is detected by OMI which is seen in pollution maps. In the inventory, there is no reported coal power plants. Only one cement factory has electricity producing plant with 2×30 MWe installed capacity which is using bituminous coal at 160 km northeast of Aleppo city. Other than that, the pollution could be due to oil processing since Syria has large fuel oil reserves.

SO_2 columns were mapped between 2005 and 2014 to analyze yearly changes in SO_2 pollution in the study area (Figure 5.3).

In the map of 2011, there is a higher noise than the other years in the study area; this could be due to a volcanic eruption in Nabro, Eritrea in 2011. SO_2 PBL data between 15 and 30 June were excluded at which data over Turkey was affected from the volcanic eruption (Clarisse et al., 2014).

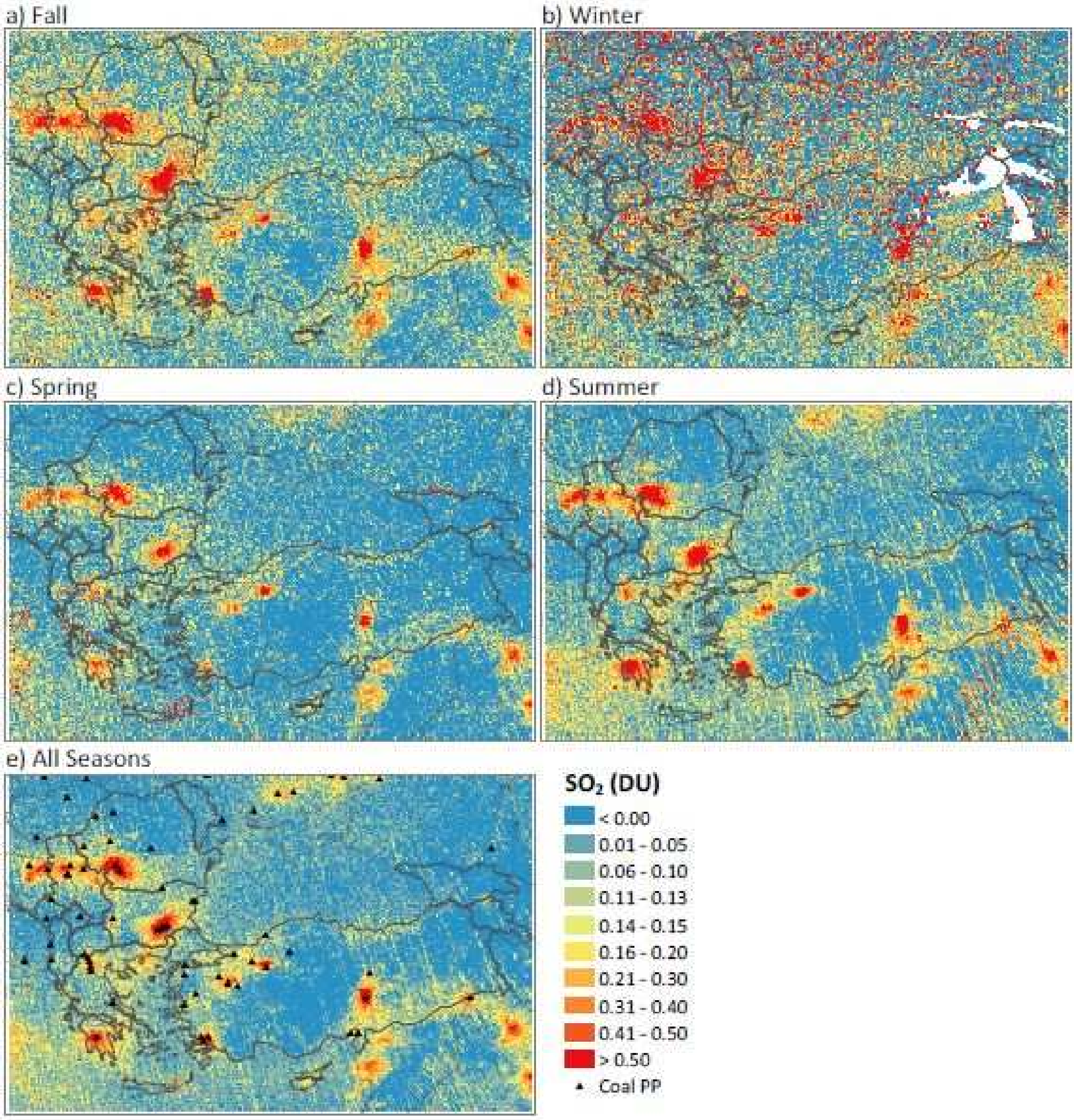

Figure 5.2 : OMI SO_2 columns for the years between 2005 and 2014 according to seasons

Other hotspots SO_2 pollution in the study area are around Romania, Serbia and Bosnia-Herzigowa. In Romania, around the pollution plume there are two large-scale power plants Turceni and Rovinari with installed capacity of 1650 MWe and 1320 MWe, respectively. In Bosnia-Herziogowa, around the pollution plume there are two large-scale coal power plants which are Tuzla and Kakanj with 730 MWe and 450 MWe installed capacity respectively. In Serbia, four large-scale power plants are located around pollution plume which are Nikola Tesla A-B, Kostolac A-B, Kolubara A-B and Morava with installed capacity of 1502-1160 MWe, 640-281 MWe, 245 MWe and 120 MWe respectively (Enipedia, 2016).

In the OMI SO_2 maps, the noise at the background is so high. To reduce this noise, another methodology was applied to OMI data which is oversampling method which was explained in detail in section 5.2.2. As a result of the oversampling data, the noise was reduced efficiently and large-scale point sources were distinguished better using oversampling method compared to initial results (Figure 5.4).

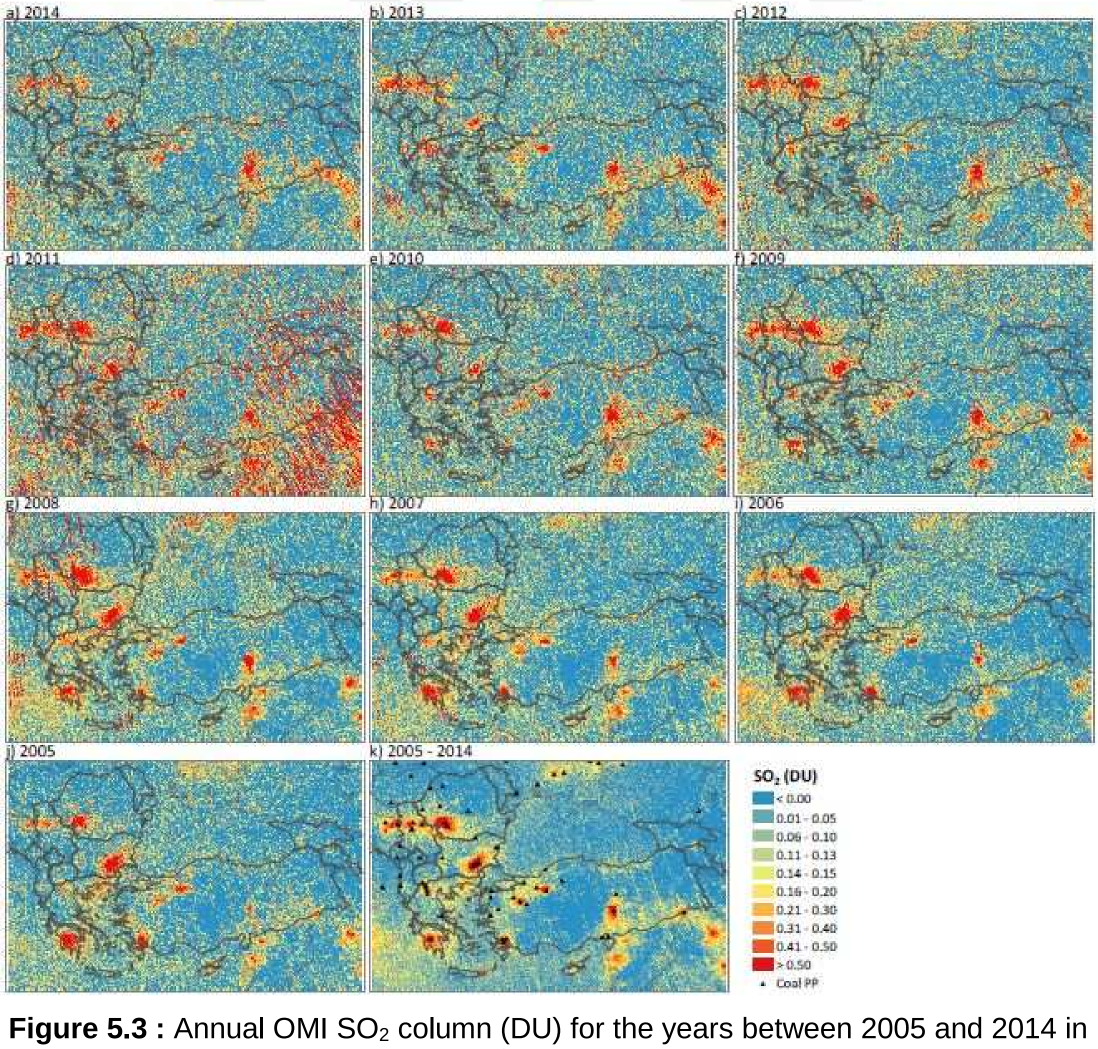

Figure 5.3 : Annual OMI SO_2 column (DU) for the years between 2005 and 2014 in $10 \times 10 km^2$ gridded domain

There are big differences in SO_2 maps between initial method and the updated method. SO_2 signals were seen better and stronger with the new method. Point sources could be distinguished better in developed results compared to initial method (Figure 5.4).

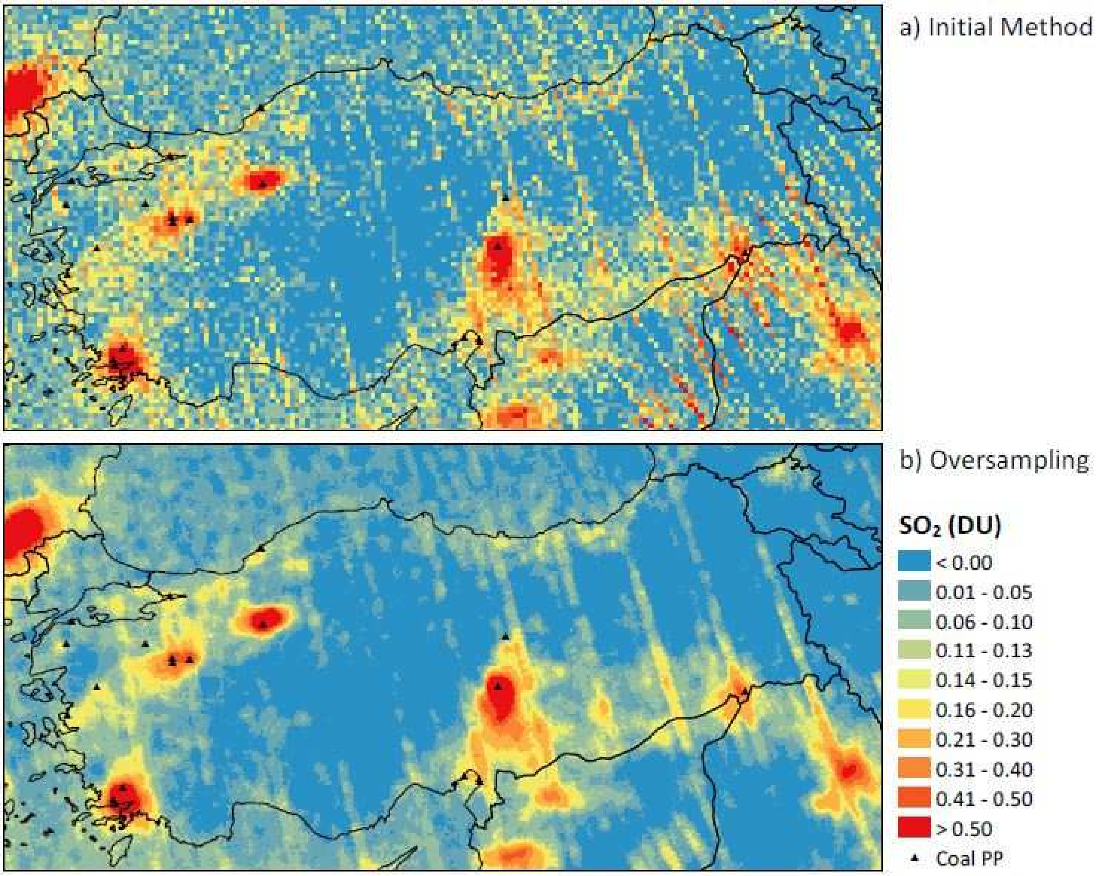

Figure 5.4 : Initial and new (oversampling) methodology results for summer SO_2 columns (DU) between 2005 and 2014

5.2.2 Secondary findings with updated methodology

The initial methodology was updated and a new metholodogy was applied to OMI SO_2 columns in 2×2 km^2 gridded domain. Oversampling by around 12 km of each grid were averaged and assigned to the grid and by this method (Fioletov et al., 2015; Fioletov et al., 2011; Lu et al., 2013), smoothing of the retrievals were performed and the noise were reduced in the spatial SO_2 distribution maps. (Figure 5.5). The averaging radius were applied similar to previous studies which is 12 km around each grid(Fioletov et al., 2011; Lu et al., 2013). When radius is increased, peak concentrations could be reduced, when it is decreased, there could be more noise compared to 12 km. The study domain is different than it was in the previous methodology,this is because, the processing of the oversampling methodology is too low due to high load of data. Because of that reason, study area is smaller for the new methodology than it was in the initial method.

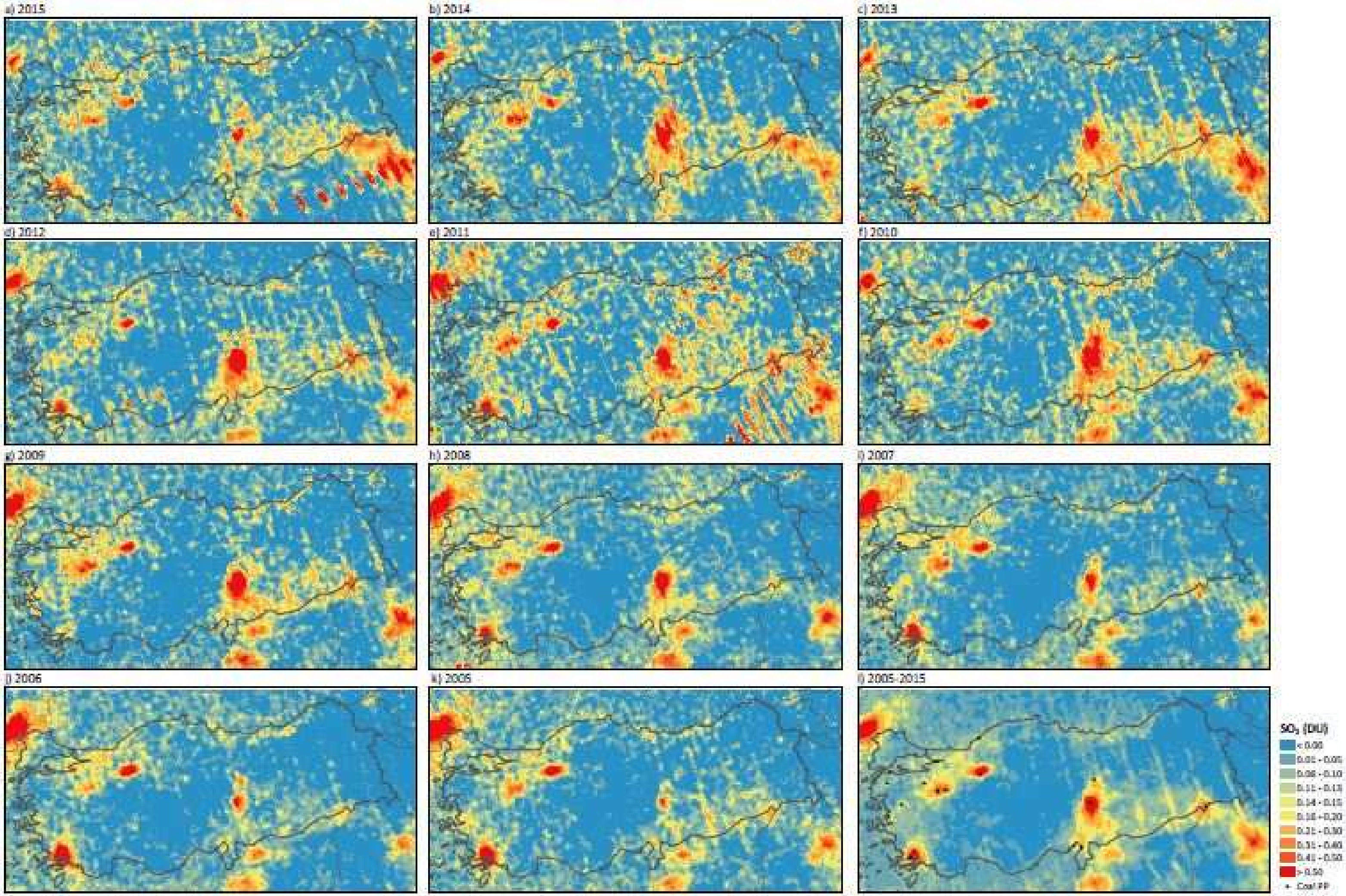

Figure 5.5 : Annual OMI SO_2 column (DU) for the years between 2005 and 2015 in 2×2km^2 gridded domain

After applying oversampling method to OMI SO_2 data, it was possible to get signal from smaller SO_2 emitting sources other than large-scale power plants. Since the noise was reduced, the SO_2 sources were shown clearly in the maps, such as other SO_2 emitting industrial sources; oil and gas production industry, refineries, pulp and paper industry smelters, cement industry, aluminium production industry (Alyuz, 2012).

OMI SO_2 signals for industrial areas are not as strong as signals for power plants but for some industrial areas, it is possible to see high OMI SO_2 retrievals (Figure 5.6).

SO_2 pollution were detected around some industrial areas especially where industrialization is dense in the region such as İzmit, Gaziantep, and İzmir. Possible industrial emissions were seen around İzmit, İzmir, Bursa, Gaziantep, Samsun, Sakarya, Hatay which are highly industrialized cities. Especially around İzmit and İzmir, there are oil refineries which are significantly emitting SO_2 to the atmosphere.

In Samsun, there is only SO_4 smelter of Turkey with a very high capacity (Table 5.1). However, SO_2 pollution area around this smelter were not as big as it was expected according to capacity of smelter.

In Karabük and Hatay there are metal and iron processing factories, probably due to those sources, SO_2 signals are high in those cities. Those factories also have their own coal power plants for energy supply in the factory, so that this is another reason SO_2 signals are high for those cities.

In south-east of Turkey, there are some high SO_2 signals in the 11 year average map, those could be related with coal consumption in house-heating or transportation of the SO_2 by wind from close sources such as Afşin Elbistan and Şırnak Silopi power plants since there are not large-scale industrial facilities as in other regions. Main industrial SO_2 source in south-east region is in Batman due to oil processing, small-scale cement factories and in Gaziantep due to several small-scale industries such as cement, iron-steel and pulp-paper.

In east of Mediterrenean region, in cities of İskenderun and Adana there are cement, iron and steel, pulp and paper industries those could contribute SO_2 emissions in the region. There are also two hard coal power plant. In those two cities, significant signals were seen by OMI indicating SO_2 pollution. Dense industrial regions, and power plants could be related to that pollution seen by OMI retreivals. In the west of the region there is not a significant OMI signal until Muğla power plants in Aegean region of Turkey.

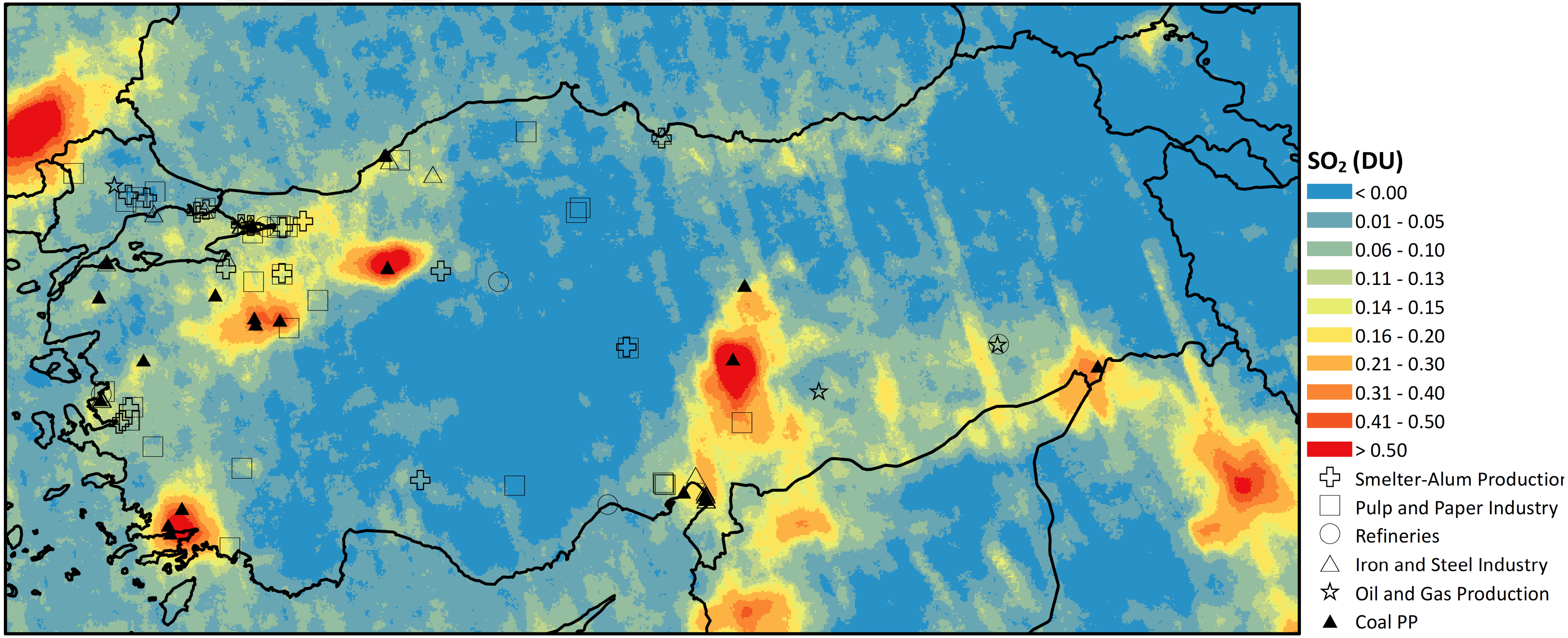

Figure 5.6 : Average SO_2 retrievals between 2005 and 2015 with important industrial plant locations.

Table 5.1 : Large-scale industries emitting S in Turkey

Company	City	Industry	Capacity (ton/year)	Lat	Long	Installation
Samsun Izabe Sulfurik Asit [1]	Samsun	Sulfuric Acid	200,000,000	41.22428	36.45948	1975
Aliaga Tupras [2]	Izmir	Refinery	11,000,000	38.80009	26.93470	1972
Izmit Tupras [2]	Kocaeli	Refinery	11,000,000	40.75308	29.76242	1961
Orta Anadolu Tupras [2]	Kirikkale	Refinery	5,000,000	39.75476	33.46514	1986
Karabük Demir Celik [3]	Karabuk	Iron and Steel	5,268,000	41.19106	32.62077	1937
Iskenderun Demir Celik [3]	Iskenderun	Iron and Steel	5,000,000	36.74828	36.20487	1970
Icdas Celik [3]	Canakkake	Iron and Steel	5,000,000	40.43765	27.13259	1970
Izdemir Demir Celik [3]	Izmır	Iron and Steel	3,000,000	38.75378	26.92611	1975
Akcansa Cimento [4]	Istanbul	Cement	3,000,000	41.02182	28.54835	1967
Akcansa Cimento [4]	Samsun	Cement	3,000,000	40.91291	35.89225	1967
Akcansa Cimento [4]	Canakkale	Cement	3,000,000	39.91433	26.30118	1967
Erdemir Demir Celik [3]	Zonguldak	Iron and Steel	2,500,000	41.41824	31.92375	1960
Colakoglu Metalurji [3]	Kocaeli	Iron and Steel	2,500,000	40.77386	29.54723	1969
Kaptan Demir Celik [3]	Tekirdag	Iron and Steel	2,400,000	41.01306	27.95329	1964
Borusan Boru [3]	Istanbul	Iron and Steel	2,000,000	41.01132	28.79195	1958
Kroman Celik San [3]	Kocaeli	Iron and Steel	2,000,000	40.79847	29.37610	1966
Yazici Demir Celik [3]	Iskenderun	Iron and Steel	2,000,000	36.69359	36.21085	1949
Adocim Cimento [4]	Tokat	Cement	1,800,000	40.11797	36.29919	2007
Diler Demir Celik [3]	Kocaeli	Iron and Steel	1,500,000	40.78352	29.53436	1954
Borcelik Celik San [3]	Bursa	Iron and Steel	1,500,000	40.41082	29.08545	1990
Toscelik [3]	Iskenderun	Iron and Steel	1,500,000	36.68457	36.20601	1997
Cebitas Metal San [3]	Kocaeli	Iron and Steel	1,350,000	40.79361	29.38729	1981
Nursan Metal [3]	Iskenderun	Iron and Steel	1,200,000	36.75223	36.21708	2005
Batman Tupras [2]	Batman	Refinery	1,100,000	37.87793	41.14182	1955
Yesilyurt Demir Celik [3]	Samsun	Iron and Steel	1,100,000	41.24539	36.47559	1985
Yolbulan Demir Celik [3]	Iskenderun	Iron and Steel	1,000,000	37.00846	36.10774	2008
Egecelik [3]	Izmir	Iron and Steel	1,000,000	38.73488	26.94140	1986

[1] www.etibakir.com.tr [2] www.tupras.com.tr [3] www.dcud.org.tr [4] www.akcansa.com.tr

There is high variation in SO_2 emissions from 2005 to 2015. There are some new power plant installation such as Afşin Elbistan B in 2006, and it seriously affects the area increasing the emissions as twice after installation. In some areas, there is remarkable decrease in SO_2 signals. Most visible decreases are around Muğla and Bulgaria where large-scale power plants are located. This decrease in Bulgaria could be due to being a member in European Union in 2008. Most visible For Muğla, the decrease could be because of better treatment technologies (Figure 5.7).

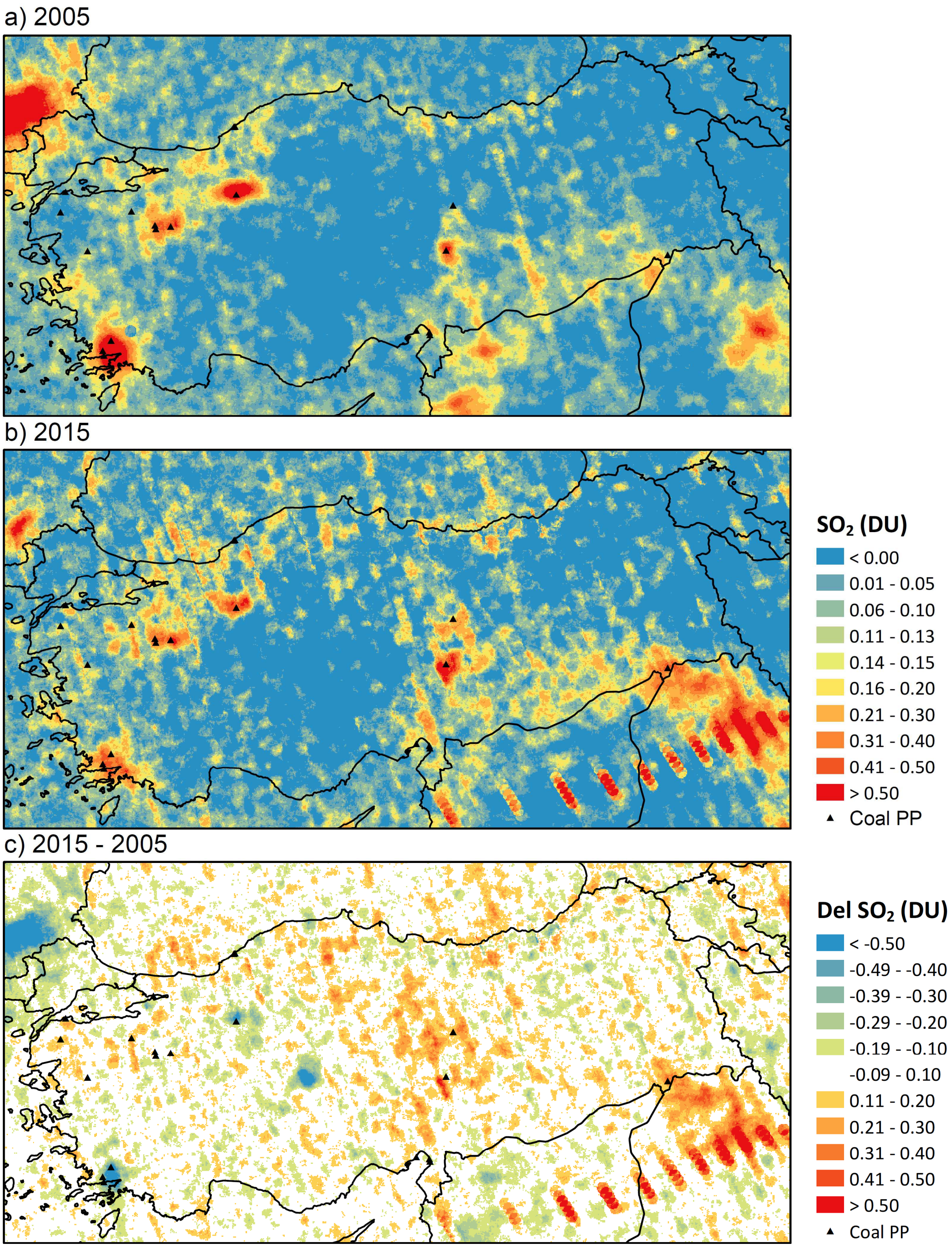

Figure 5.7 : SO_2 column for a) 2005 b) 2015 and c) the change from 2005 to 2015

In the study winter and summer conditions were compared as well (Figure 5.8). In summer more smoothed results were found due to lower noise in the OMI SO_2 data. However for 10 years average winter data showed hotspots in Turkey domain where large pollution regions were detected especially around coal power plants such as Afşin Elbistan, Ankara Çayırhan, Seyitömer and Tuçbilek (Kütahya) and Yeniköy, Kemerköy, Yatağan (Muğla) power plants. In the difference map of winter and summer, in North Sea and East of Turkey, winter data was observed larger than summer data that may indicate house heating in those areas by burning coal.

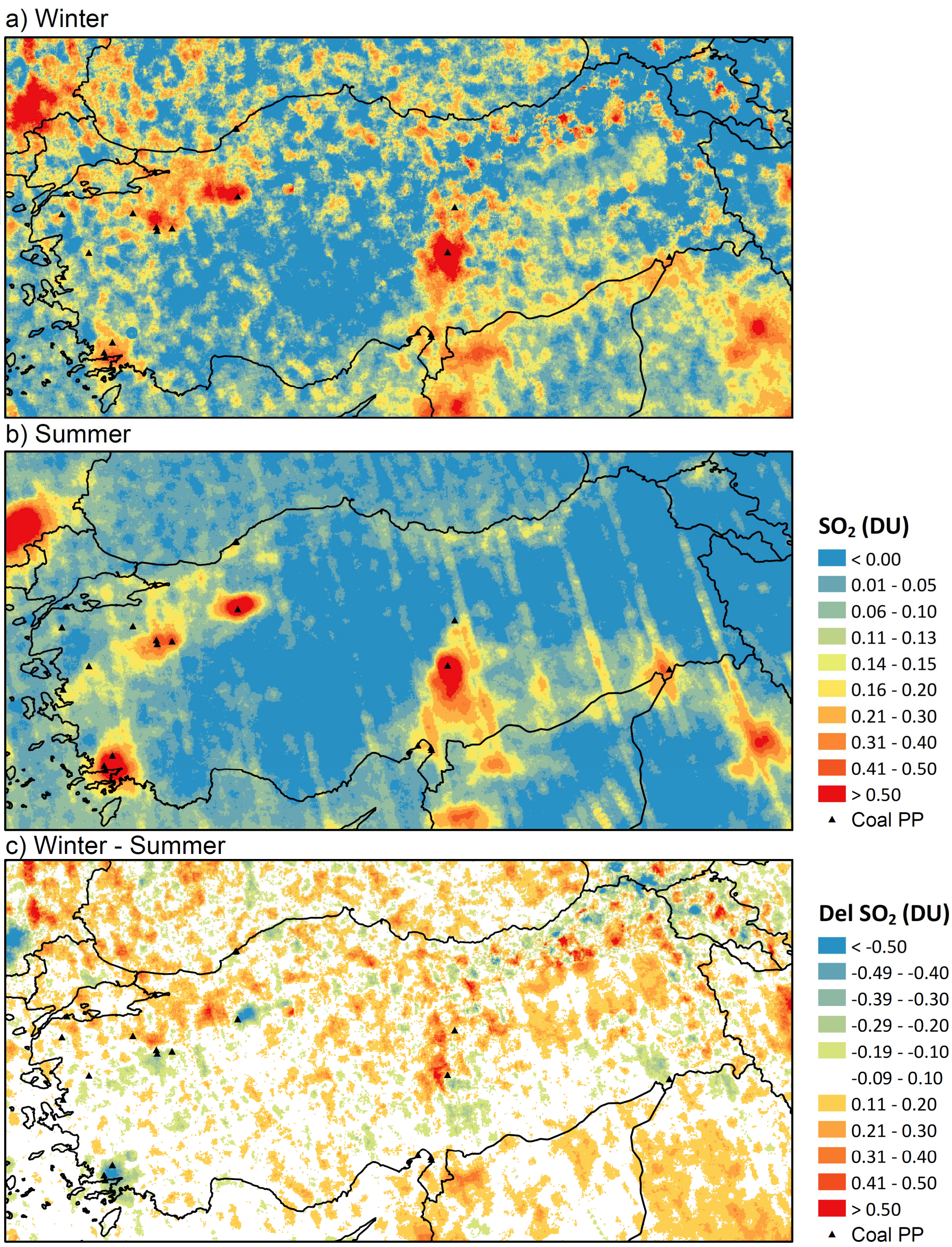

Figure 5.8 : Averaged SO_2 columns for a) winter, b) summer and c) differences between winter and summer

There is also significant decrease in Aleppo and Homs cities of Syria, that decrease could be due to war in Syria since 2011. Another decrease in the domain is around Ankara Çayırhan power plant. Although, there is still high pollution according to the OMI signals, there is slightly decrease in the pollution between 2005 and 2015. One of the most visible increase is around North Iraq. It is seen that OMI signals are so high around the region, while there is not much signal in 2005. This could be oil processing facilities were founded in the region after 2008. In 2015, and difference maps, there are some anomalies around Iraq and Syria regions. This anomaly possible due to row anomaly which was explained in Chapter 4 in detail.

5.3 Emission Inventories and OMI SO_2 Retrievals

OMI SO_2 retrievals were firstly compared with existing EMEP emission inventory. EMEP inventory for 2011, 2012 and 2013 were used. EMEP GNFR sectoral emissions for the years between 2011 and 2013 indicates public power sector has the highest contribution to SO_2 emissions with more than 50% for all three years (EMEP, 2016). Second largest contributor of national SO_2 emissions is industry with more than 20% for all years (Table 5.2).

Table 5.2 : Annual reported total SO_x emissions of Turkey for three consecutive years (EMEP, 2016)

	SO_2 (2011)		**SO_2 (2012)**		**SO_2 (2013)**	
GNFR SECTORS	**(Gg)**	**(%)**	**(Gg)**	**(%)**	**(Gg)**	**(%)**
A Public Power	1475.72	55.10	1362.11	50.16	1152.03	59.41
B Industry	587.79	21.95	682.43	25.13	459.19	23.68
C Other Stationary Combustion	573.44	21.41	657.05	24.20	319.87	16.50
D Fugitive	–	–	–	–	–	–
F Road Transport	20.56	0.77	–	–	–	–
G Shipping	13.88	0.52	13.88	0.51	8.00	0.41
H Aviation	0.80	0.03	–	–	–	–
I Off-road	–	–	–	–	–	–
J Waste	0.01	–	0.01	–	0.01	–
K Agriculture-Livestock	–	–	–	–	–	–
L Agriculture-Other	6.17	0.23	–	–	–	–
National Total	**2678.36**	**100**	**2715.49**	**100**	**1939.10**	**100**

Other stationary combustion sector is reported as third largest sector with around 20% contribution according to the EMEP emission inventory. It is seen that SO_2 emissions are decreasing significantly in 2013 compare to previous years. In national total emissions, it is reported that there is almost a 30% decrease in 2013 from 2012.

5.3.1 Results and conclusion

EMEP (European Monitoring and Evaluation Programme) emission inventory for Turkey domain and selected power plants are obtained for comparison with OMI SO_2 retrievals. Although EMEP emission inventory is available for the new grid system between 2011 and 2013, the study was performed for the years 2012 and 2013 due to high noisy retrievals in 2011. In the study, the temporal SO_2 trends for the power plants were evaluated. EMEP national emissions for Turkey for the years between 2012 and 2013 are indicating high emissions for some of the power plants selected (Figure 5.9, Figure 5.10). Public power SO_2 emissions from stationary combustion sources in energy and transformation industries indicate that some of the significant coal power plants such as Ankara Çayırhan and İsken Sugözü were not reported in EMEP emission inventory (Figure 5.9, Figure 5.10) According to public power sector emissions (GNFR A), highest emissions are in the cities of Kahramanmaraş, Adana, Muğla, Manisa and Kırşehir. In Kahramanmaraş, there are two coal power plants with total operating capacity of 2795 MWe those are called Afşin Elbistan A and Afşin Elbistan P power plants. It is also one of the highlights according to OMI SO_2 retrievals in Turkey. In Adana, there is no large scale source around the given emission value but there is İsken Sugözü (1210 MWe) power plant around 50 km away from the high emission location given by EMEP. According to that, the location of emission could be given wrong for Adana in EMEP inventory. In Muğla, around the given emissions, there are three coal power plants with total operating capacity of 1680 MWe. In Manisa, there is a coal power plant that is Manisa Soma around the given emission value. In Kırşehir, there is no public power generation source around the given emission value but there is Orta Anadolu Tüpraş Refinery in Kırıkkale which is around 40 km away from the inventory emission location. The location of emission possibly wrong for Kırıkkale as well in the inventory.

Since more than 50% of the SO_2 pollution is caused by public power plants for electricity production purposes, power plants emissions are investigated in detail (Figure 5.11). Point emission sources of public power sectors were shown in the map by coal and other power plants between 2011 and 2013 (Figure 5.11).

In the inventory, a decrease were reported for power plants that producing electricity from 2011 up to 2013. Between 2011 and 2013, there is around 22% decrease for electricity producing power plants. Main sources are almost same for all three years, they are mainly located around coal power plants, industries, and other power plants.

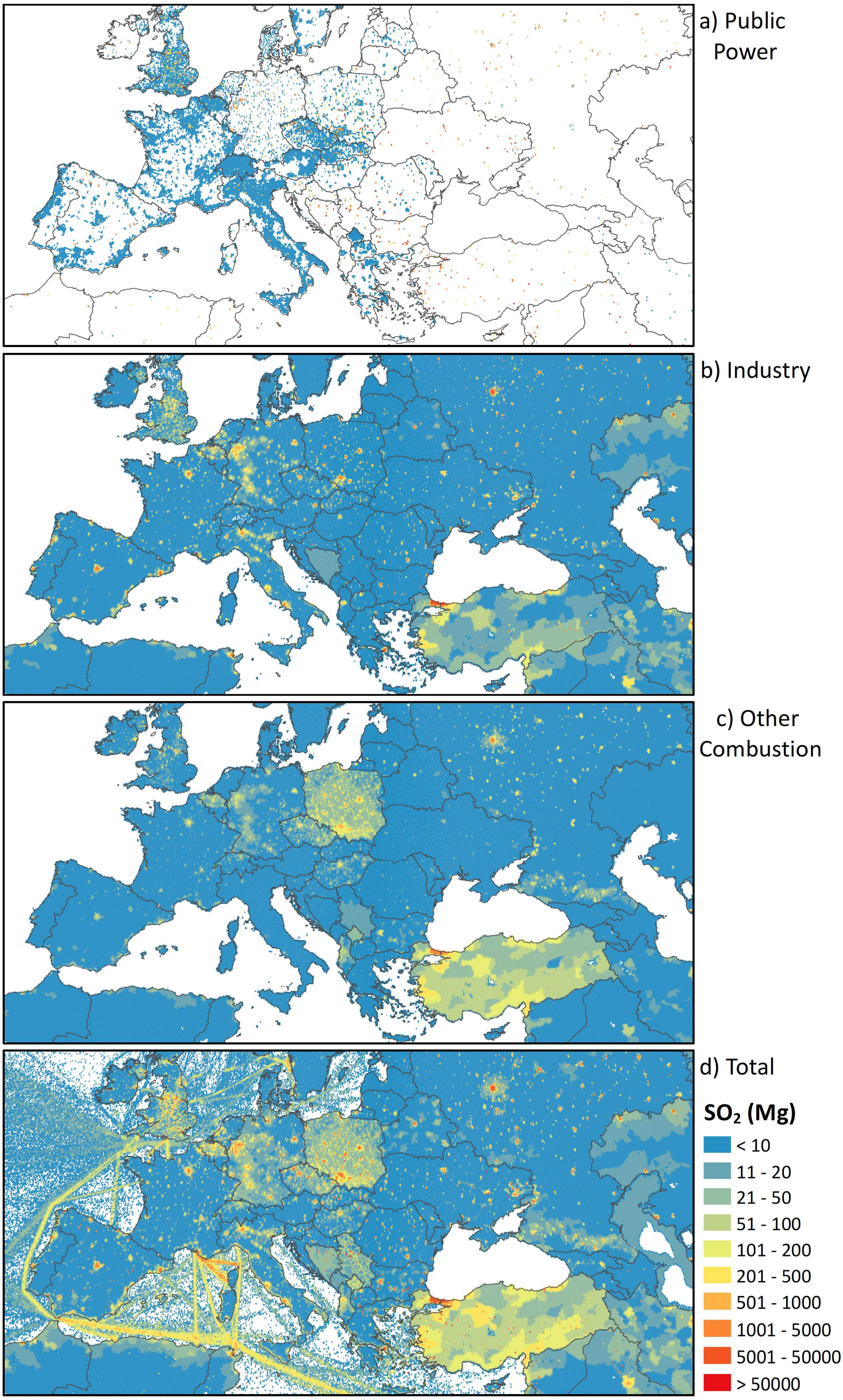

Figure 5.9 : EMEP 2012 a) Public Power, b) Industry, c) Other Combustion and d) Total emissions

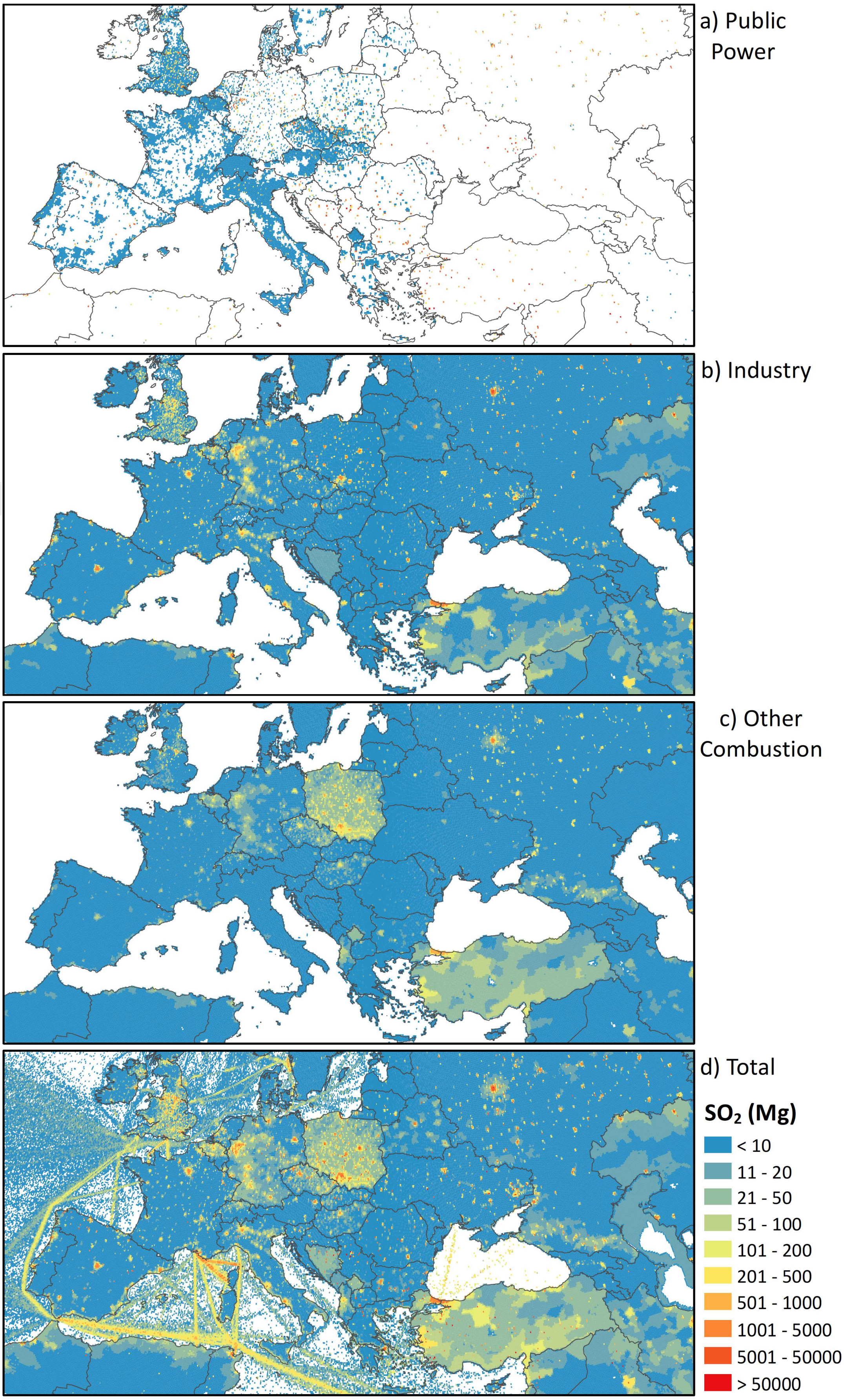

Figure 5.10 : EMEP 2013 a) Public Power, b) Industry, c) Other Combustion and d) Total emissions

Comparison of EMEP emissions and OMI SO_2 values were conducted for 2012 and 2013. Comparison for the year 2011 was not conducted because of the noisy satellite retrievals in 2011 due to unreliable OMI retrievals because of volcanic eruption in that year (Clarisse et al., 2014). For 2012 and 2013, detailed analysis were done by evaluating geographically correlation, point sources and provinces comparison.

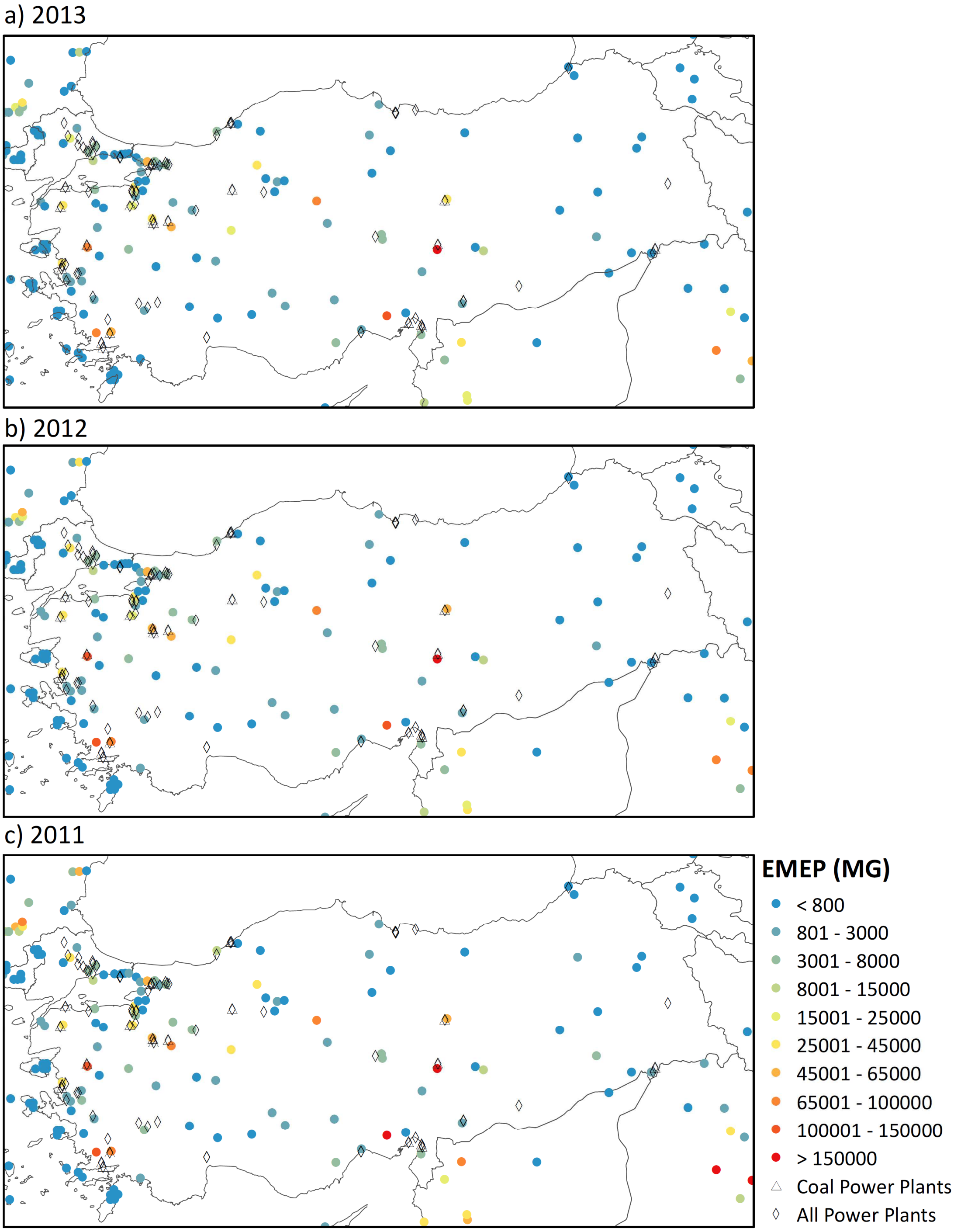

Figure 5.11 : EMEP public power sector SO_2 emissions for Turkey domain for the years between 2011 and 2013.

According to the comparison, EMEP emissions and OMI SO_2 columns were not in good agreement to each other. EMEP emissions were distributed uniformly within the province borders, however OMI SO_2 columns showed a different distribution. For example, after plotting EMEP emissions for Turkey, borders of the cities could be seen due to equally distribution of point sources in cities. EMEP emissions indiciates high emissions for İstanbul city, although OMI SO_2 columns indicates lower columns for the city. From 2012 to 2013, there is also some variations in the emission amounts. Although the sources are similar, there is almost 30% of decrease in SO_2 emissions in 2013 (Figure 5.12, Figure 5.13).

Geographically weighted regression (GWR) were used to analyze, correlation between OMI retreivals and EMEP emissions. GWR is a local type of lineer regression to understand spatial correlation between two dataset. While preparing the data, explanatory field was EMEP emissions and dependent field was OMI SO_2 retreivals. For overall, the correlation is around 0.75 for both years but there is large differences between point sources (Figure 5.12, Figure 5.13).

For large pollution regions such as around Afşin Elbistan, Manisa Soma, Kütahya there is a slight agreement between EMEP emissions and OMI SO_2 columns indicating high OMI SO_2 values around the large point sources. However, around other large point sources, such as Muğla, İsken Sugözü, Sivas Kangal and Ankara Çayırhan, there is no correlation between OMI retrievals and EMEP inventory. As indicated before, Ankara Çayırhan power plant is not in the inventory. In some regions, GWR, indicates high correlations where there is no emissions sources such as Antalya, Van, Erzincan where there is no large-scale emissions sources and both OMI retrievals and EMEP inventory agrees in that. Residuals were obtained for two years (2012 and 2013) after applying GWR and it was normalized with observed OMI SO_2 retrievals. Due to normalized geographically weighted data, it was seen that, emissions where there is no large scale sources around, indicate that EMEP emissions estimate high emissions for those areas.

EMEP emissions and OMI SO_2 retrievals were compared on province level in Turkey. For cities such as Kahramanmaraş, Muğla, Kütahya, Manisa, Sivas, Bursa, Ankara, Adana, where large-scale power plants take place, an agreement were seen between EMEP emissions and OMI SO_2 retrievals. For cities where no large-scale power plant were located, industrial activities, residential heating and transportation of SO_2 pollution were discussed as sources of high OMI SO_2 column concentrations suh as Gaziantep, Osmaniye, Karabük, Batman, Diyarbakır, Malatya, Mardin, Sakarya.

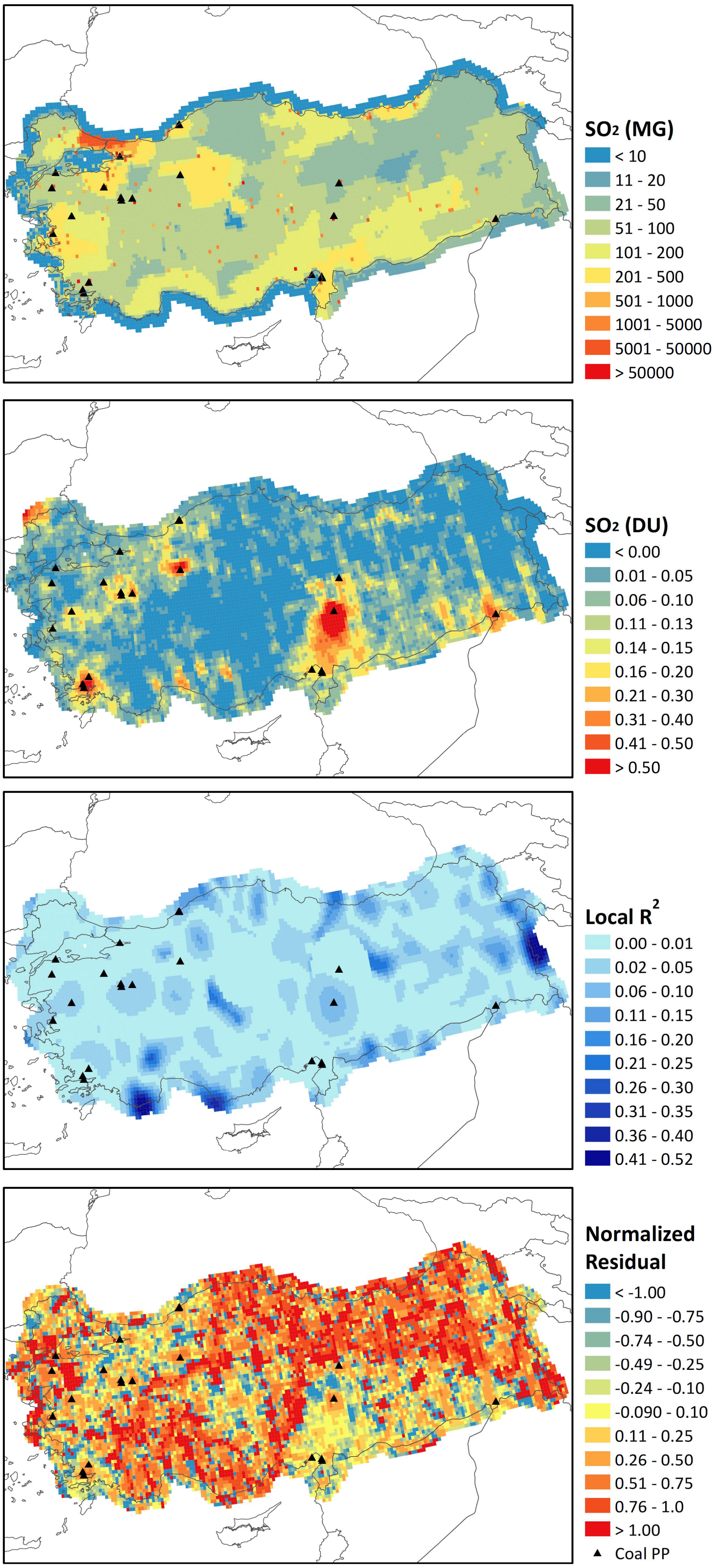

Figure 5.12 : EMEP emissions and OMI SO_2 column comparison for 2012

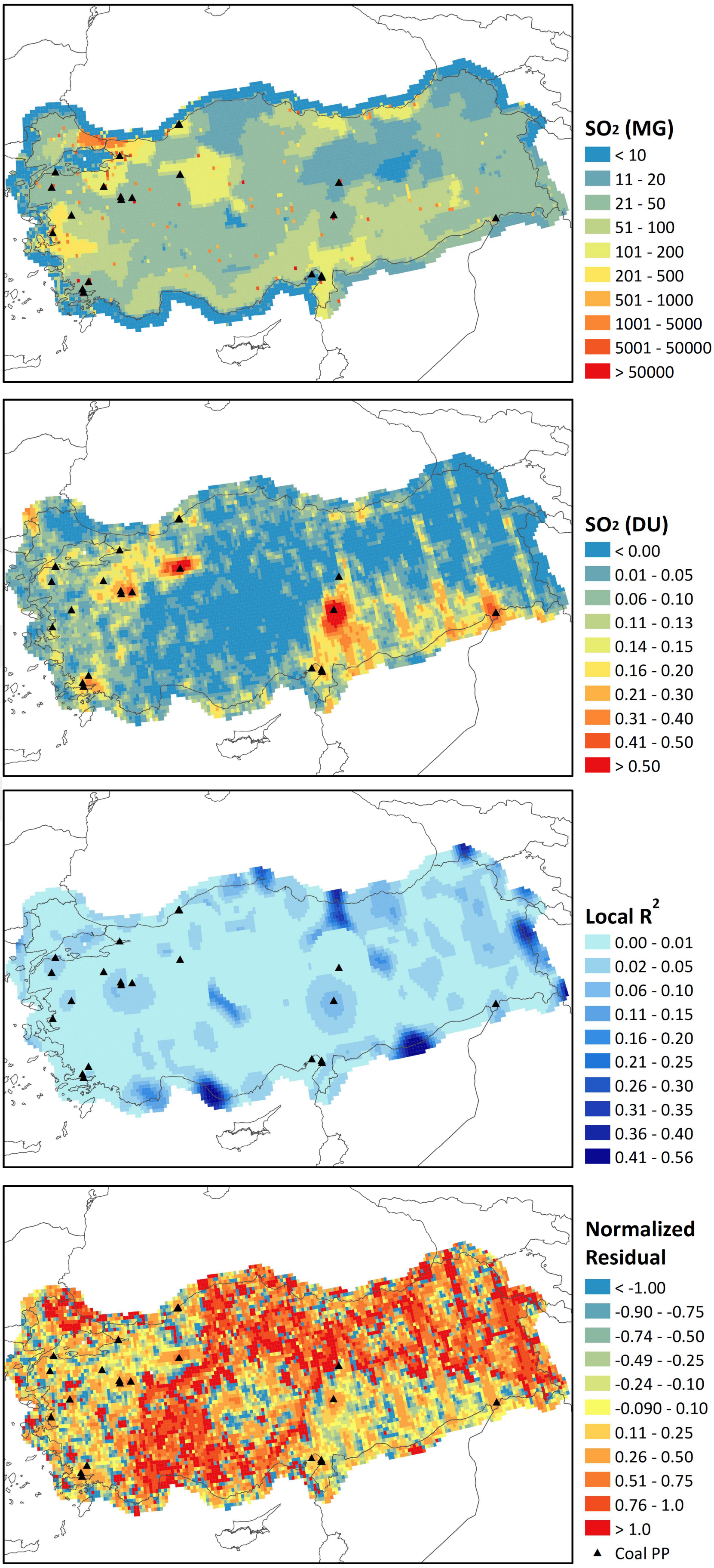

Figure 5.13 : EMEP emissions and OMI SO_2 column comparison for 2013

EMEP emission inventory indicate high emissisons for İstanbul athough OMI SO_2 retreivals does not. Especially, industrial emissions were reported in high amounts for İstanbul. For Zonguldak and Hatay cities, EMEP inventory does not indicate an emission while OMI indicates high SO_2 retreivals. In both cities, there are two coal power plants, therefore, EMEP emission inventory might have missing point sources for Turkey.

For some cities, OMI indicates high retrievals while EMEP inventory does not. Those cities are, Aydın, Bilecik, Düzce, Diyarbakır, Gaziantep, Osmaniye. Those cities are mostly neighboor to cities where large-scale power plants take place. The pollution by OMI could be due to the close location of large-scale power plants. Anohter interesting results were for Batman city. While OMI retrievals indicating high SO_2 for the city, the inventory does not. Although, there is a oil refinery in the city, emission inventory migh have missing emission for that source.

EMEP inventory and OMI SO_2 retreivals do not show a significant difference from 2012 to 2013 for city emissions. In 2013, there is a significant decrease in the emission inventory, but not a significant decrease were observed by OMI (Figure 5.14).

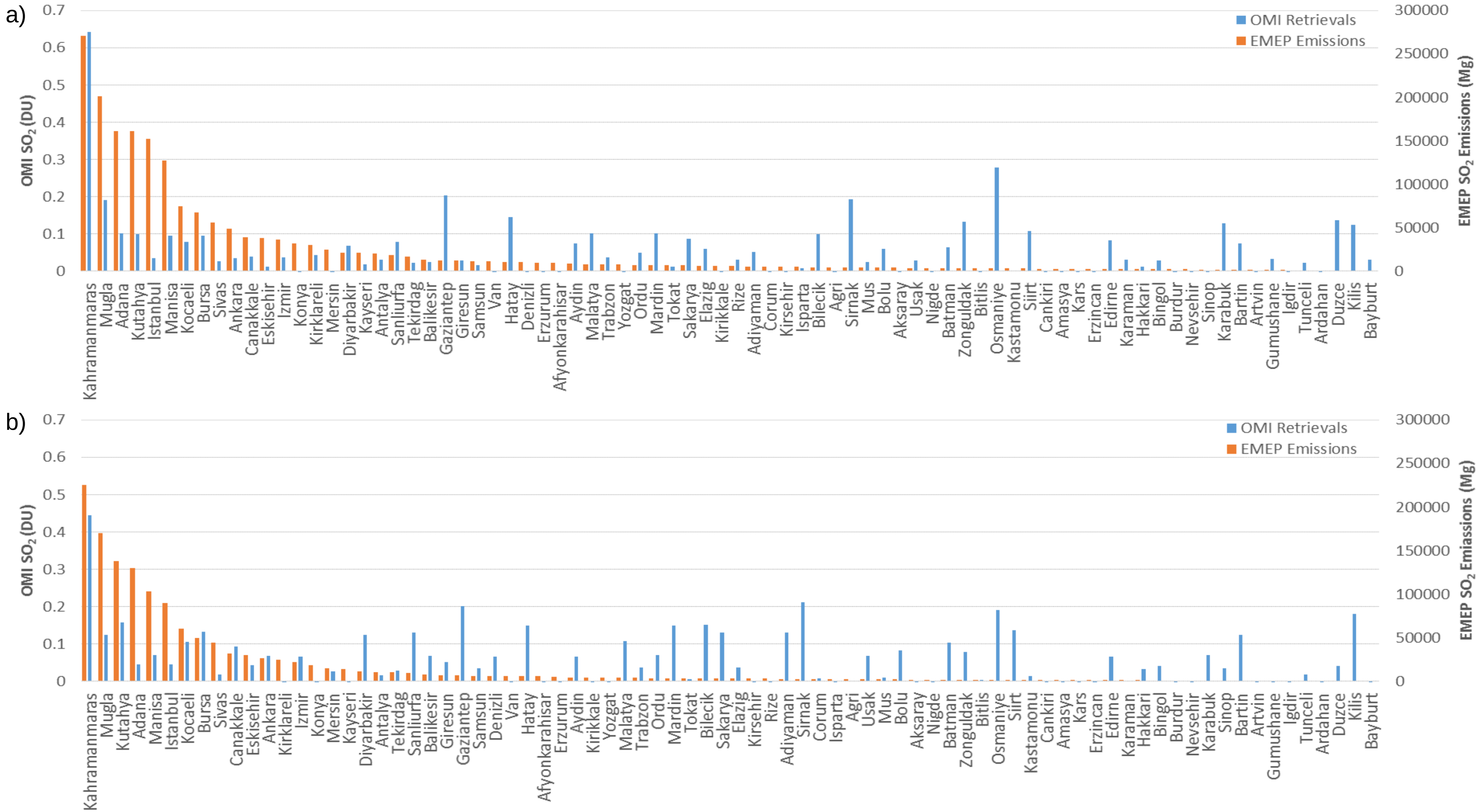

Figure 5.14 : EMEP SO_2 emissions (Mg) and OMI SO_2 (DU) retrievals for cities in Turkey for a) 2012 b) 2013

6. LARGE SCALE SO_2 POINT SOURCES IN AND AROUND TURKEY

Coal power plants are the biggest anthoropogenic SO_2 emitters in the world. In Turkey, more than 50% of the national total emissions are coming from coal power plants producing electricity for public use (EMEP, 2016). Satellite retreivals were also used for detection of SO_2 pollution in many previous studies(Fioletov et al., 2011; Lu et al., 2013). So that, as a case study, Afşin Elbistan were choosen to analyze the SO_2 pollution around the plany by OMI SO_2 retrievals. In this section of the thesis, pollution around large-scale coal using power plants were investigated in detail.

6.1 Afşin Elbistan Power Plant Study

There are 15 large-scale power plants (> 50 MWe) using lignite for producing electricity. Among Turkish power plant, different from western countries, treatment technologies of SO_2 pollution usage is very limited. Afşin Elbistan, Muğla, Ankara Çayırhan and Kütahya are the most visible areas observed by OMI SO_2 retrievals. Among these hotspots, Afşin Elbistan has the highest observed SO_2 columns over Turkey.

6.1.1 Methodology and results

Afşin Elbistan power plants are consisting of 2 different plants those are plant A and plant B. Plant A was installed in 1984 and plant B in 2006, there is an increasing SO_2 pollution beginning from 2006 when Afşin Elbistan B power plant was installed and operating capacity of power plants in the domain was doubled. Afşin-Elbistan Power Plant (AEPP) is the coal power plant with largest installed capacity with 2795 MWe in Turkey. It is located at Kahramanmaraş province, in the southeastern part of Turkey in (Figure 6.1). It consists of two power plants; Afşin Elbistan Power Plant A (AEPP-A) and Afşin Elbistan B (AEPP-B) which are within five kms of each other and both have four units. Because of their close proximity, they were accepted as a single source in this study. There are large lignite reserves in the area which has very low calorific value (1000 kcal/kg) and moderate sulfur content (1%) (Say, 2006). AEPP-A was built in 1984 with 1355 MWe capacity as public (government owned) entity. Its primary goal was to use local lignite in the area and produce electricity for the public.

In 2006, AEPP-B was installed with 1440 MWe. Due to existing significant lignite reserves, future units (C, D, E) are planned to be built in the near future (EPF, 2016). The timetable indicating the important events regarding AEPP-A and B are given (Figure 6.2) in order to analyze the OMI SO_2 column data in detail.

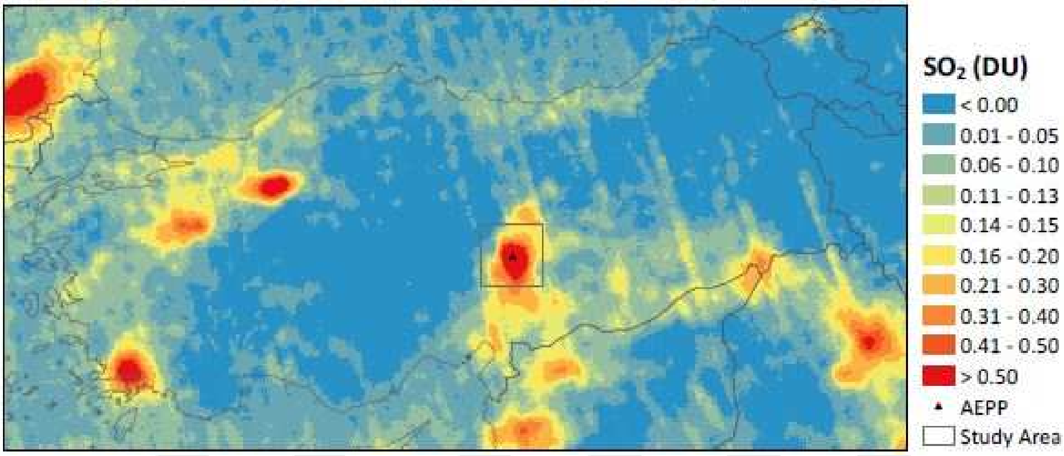

Figure 6.1 : Average OMI SO_2 PBL column (DU) around Turkey between 2005-2015 and the location and the study area of Afşin Elbistan Power Plant (AEPP)

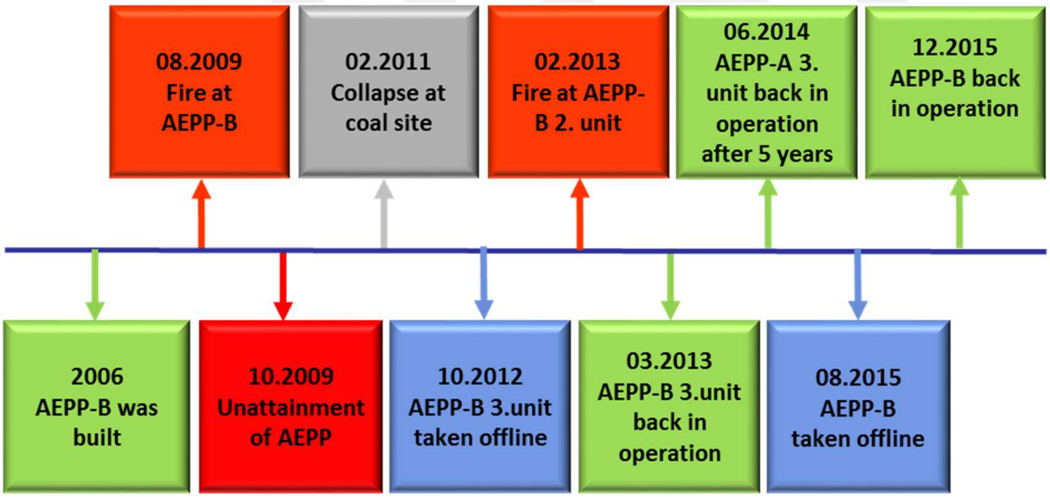

Figure 6.2 : Important events for AEPP between 2005 and 2015

OMI Level 2 (L2) SO_2 Planetary Boundary Layer (PBL) column data for 2005-2015 from NASA (http:mirador.gsfc.nasa.gov) was used with the following filtration in order to sustain data quality: Solar Zenith Angle (SZA) < 70°, Radiative Cloud Fraction (RCF) < 0.3, Ozone Column Amount (O_3) < 1500 DU (OMI, 2014). Firstly, a 60×60 km^2 domain with a grid size of 2×2 km^2 was created with AEPP in the center (Figure 6.1). After those annual SO_2 retrievals for the years between 2005 and 2015 were averaged, around 12 km of each grid center and assigned to the grids. By this smoothing method, noise in the SO_2 pollution maps was reduced. Local bias removal was performed for every year by subtracting the average SO_2 PBL column (background pollution) around 300 km of the source. Similar studies were conducted for U.S. (Fioletov et al., 2011) and India recently (Lu et al., 2013).

2-D Gaussian function was used to estimate the SO_2 emissions from AEPP with smoothed and local bias removed SO_2 column averages. The standard deviation (σ) of the gridded averages were used as weighting ($\frac{1}{\sigma^2}$).

$$f(x,y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{(1-\rho^2)}}\exp\left(-\frac{1}{2(1-\rho^2)}\left[\frac{(x-\mu_x)^2}{\sigma_x{}^2} + \frac{(y-\mu_y)^2}{\sigma_y{}^2} - \frac{2\rho(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}\right]\right) \tag{6.1}$$

Gaussian function $\mathrm{OMI_{SO_2}} = \mathrm{a} \cdot \mathrm{f(x,y)}$ (Equation 6.1) was fit to OMI PBL SO_2 data for the years between 2005 and 2015 where x and y in km indicates coordinates of OMI grid center and μ_x and μ_y are in the equation to show changing of the position of maximum values due to transportation. Parameters μ_x, μ_y, σ_x, σ_y, ρ, and a are estimated from the Gaussian fit. Parameter a represents the total number of OMI SO_2 molecules near the source since $\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{f(x,y)dxdy}$. While OMI SO_2 in DU, σ_x, σ_y are in km and a is in 2.69×10^{26} molecules. After applying Gaussian function, a parameter values were used to estimate emissions for AEPP.

Applying Gaussian method, a 2D Gaussian distribution fit was applied using yearly and 11 year averaged OMI SO_2 retrievals (Figure 6.3).

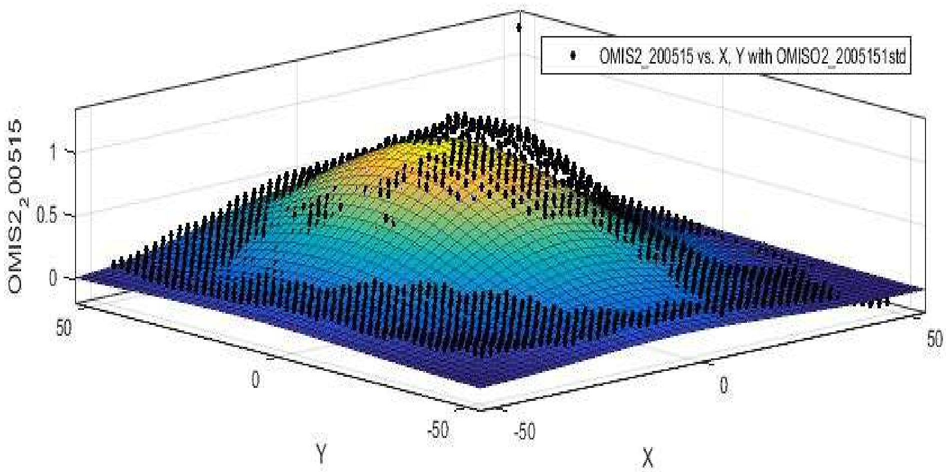

Figure 6.3 : An example of OMI SO_2 columns and gaussian fitting results using MATLAB

The largest SO_2 column values were observed in Kahramanmaraş (AEPP), Kütahya, Ankara, and Muğla provinces (Figure 6.1). All these regions have large-scale coal power plants and the highest SO_2 pollution was observed over AEPP. Annual SO_2 distribution around AEPP calculated using oversampling method (Figure 6.4) and SO_2

emissions from the power plant were calculated using EPA, EMEP emission factors and theoretical calculations by using sulfur content and calorific values of the coal (Say, 2006).

In 2006 with the installation of AEPP-B, a significant increase in SO_2 pollution was observed until 2012 when third unit of AEPP-B was offline due to a malfunction for five months until March 2013. In 2013, there is a moderate decrease in the pollution but it increased again in 2014. There was a fire at AEPP-B in 2013, the plant were offline for several weeks; decrease in the pollution area could be attributed to this. The decrease in 2015 could be due to serious malfunctions in AEPP-B for 2015 summer when the plant was offline for six months. It was clearly seen in the pollution area that peak concentrations were decreased compared to previous years.

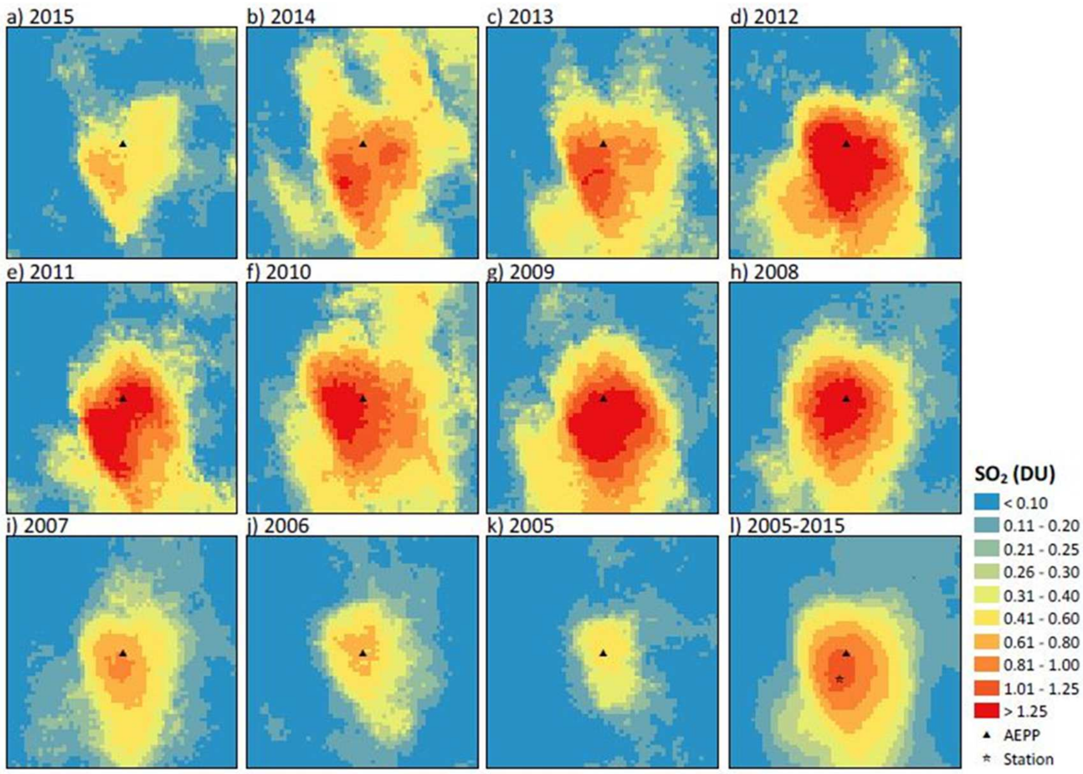

Figure 6.4 : Yearly (a)-(k) and overall (l) distribution of SO_2 pollution within 60 km of AEPP observed by OMI

The yearly wind speed and wind direction for the AEPP (Figure 6.5) from closest meteorological station (Afşin - 13.5km) indicated usually calmer winds. The dominant wind direction is usually from north and with stronger winds for 2011, 2012 and 2013. Strong winds resulted in an uneven distribution around AEPP in 2014, 2012 and 2010 and uniformly distributed until 2009, where winds were weaker.

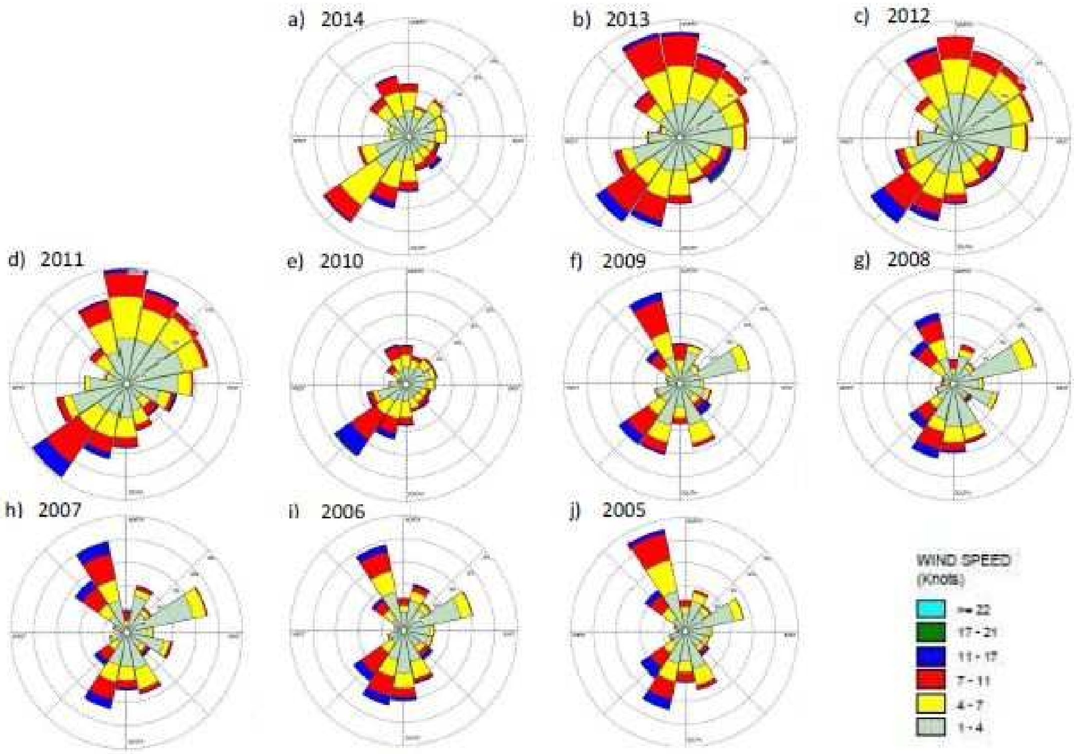

Figure 6.5 : Wind speed and direction between 2005 and 2014 from closest station (Afsin) to AEPP

Elevation profile of the study area were also investigated and it was found that, power plants are in the lowest place of the domain, and there are high hills in west, north-west, south and south-east of the power plants (Figure 6.6).

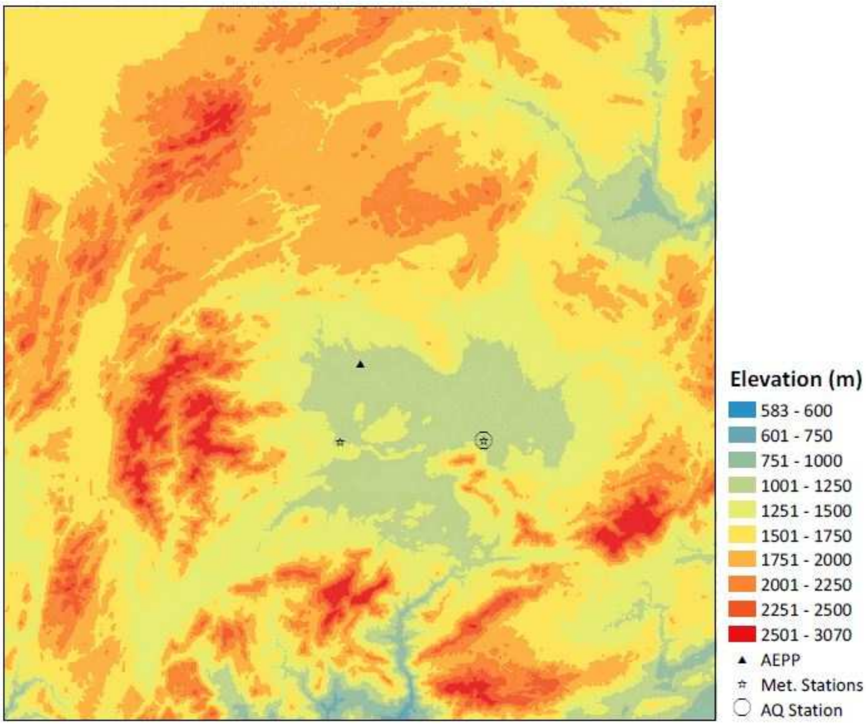

Figure 6.6 : Elevation map of Afşin Elbistan study area

Annual *a* values calculated from Gaussian fit (Table 6.1) indicated significant yearly changes with good correlation (R^2>0.70) except 2013 and 2014, where the pollution was not uniformly distributed (Figure 6.3). Emissions calculated using EPA emission factor (EF) are higher than other calculations, while emissions calculated using EMEP EF were lower (Table 6.1). Emissions extracted from TNO and EMEP emission inventories and Sözen et al. indicated large differences between each other and among different years as well.

EMEP emission factors were taken from tier-1 tables assuming no FGD (flue-gas desulphurization) is used for power plants (EMEP, 2013). Emission calculation using EMEP emission factor is shown in equation (6.2)

$$\mathrm{E} = \mathrm{AR}_{\mathrm{fuelconsumption}} \times \mathrm{EF}_{\mathrm{pollutant}}$$

$$\mathrm{EF}_{\mathrm{pollutant}} = \mathrm{S} \times 20{,}000/\mathrm{CV}_{\mathrm{net}} \qquad (6.2)$$

Emission calculation using EPA emission factor is shown in equation (6.3) (EPA, 1995, 1998b).

$$\mathrm{E} = \mathrm{A} \times \mathrm{EF} \times (1 - \frac{\mathrm{ER}}{100}) \qquad (6.3)$$

where

E = Emission,

A = Activity rate,

EF = Emission factor, and

ER = Overall emission reduction efficiency, %.

Emission factor for lignite coal is 30S where S represents sulphur content of the coal (EPA, 1998b) where it is 38S for sub-bituminous and bituminous coals (EPA, 1998a).

We also calculated emissions theoretically based on calorific value and sulfur content of the coal with equation (6.4).

$$\mathbf{E} = \frac{\mathbf{Ep}}{\mathbf{Yt}} \times \frac{\mathbf{1}}{\mathbf{Ccal}} \times \mathbf{S} \qquad (6.4)$$

where,

E = Emission

E_p = Electricity production

Y_t = Thermal yield

C_{cal} = Calorific value of coal

S = Sulfur content of coal

Yearly electricity production data by power plants were taken from TEİAŞ – EÜAŞ electricity statistics and then calculated yearly coal amount due to yield of power plants and calorific value of the coal (TEIAS, 2016). Calorific value and sulfur content of coal are taken from the literature.

Table 6.1 : Annual values of *a* and calculated emissions using OMI SO_2 around 30 km of around AEPP

Year	a	σ_x	σ_y	RMSE	R^2	OMI SO_2 (DU)	Emission Calculations Theo	EPA EF	EMEP EF	Emission Estimates
2005	959±24	14.5	21.4	0.07	0.85	0.2122	239.00	325.22	167.99	
2006	1437±33	16.5	21.1	0.07	0.85	0.3148	263.27	358.26	185.06	
2007	2155±47	17.6	24.3	0.07	0.89	0.4201	354.71	482.68	249.33	
2008	3987±44	19.7	21.3	0.05	0.95	0.7995	393.71	535.76	276.75	
2009	4705±111	18.5	23.0	0.08	0.95	0.8709	411.53	560.00	289.27	122.19 [1]
2010	5171±170	23.9	26.0	0.11	0.71	0.8814	335.09	455.98	235.54	193.25 [2]
2011	3735±109	17.1	21.8	0.12	0.87	0.7722	309.20	420.75	217.34	280.10 [3]
2012	4631±99	19.8	20.3	0.10	0.91	0.9253	260.99	355.15	183.46	258.54 [3]
2013	3236±123	20.7	23.4	0.12	0.74	0.6124	148.86	202.57	104.64	218.66 [3]
2014	3793±174	22.4	25.0	0.12	0.68	0.6675	146.39	199.20	102.90	
2015	1795±81	20.3	24.0	0.11	0.66	0.3387	84.63	115.16	59.49	
Overall	3090±47	19.1	23.2	0.01	0.95	0.5822	271.45	369.38	190.80	

[1] TNO emission inventory, [2] Sözen et al, 2010, [3] EMEP emission inventory

The yearly averages of OMI SO_2 columns were calculated to investigate the magnitude and the impact area of AEPP. A significant increase in OMI SO_2 observations was observed (over two times) from 2005 to 2009 possibly due to the capacity increase in 2006. Comparison between the yearly gross electricity production of the plant and OMI SO_2 observations indicated consistency until 2009, but OMI SO_2 observations indicated a rapid increase while gross electricity production is decreasing from 2011 to 2012. Excluding the difference for this year, overall there is a good agreement between yearly OMI SO_2 retrievals and electricity productions for AEPPs (Figure 6.7).

As a brief, electricity production and OMI SO_2 retrievals comparison states that OMI can efficiently indicates SO_2 emissions from AEPPs. In the next step, linear regression was applied to OMI SO_2 data to estimate yearly SO_2 emission magnitude from AEPPs (Figure 6.8). Parameter *a* were obtained from OMI SO_2 Gaussian fit results and it was plotted with emission calculations for linear regression, according to the parameter *a* emission estimation can be applied for yearly emission of AEPPs.

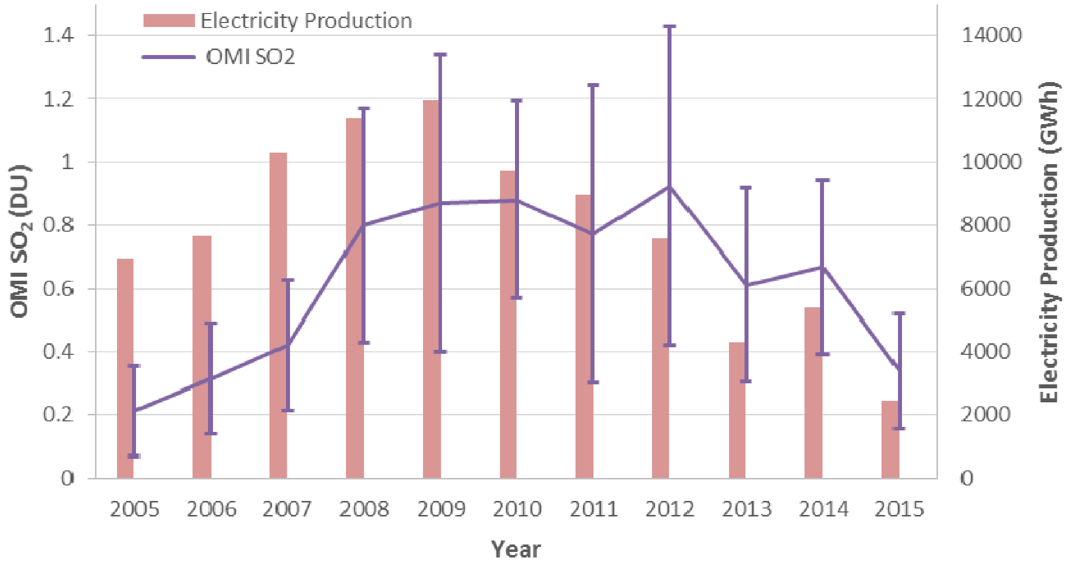

Figure 6.7 : Annual OMI SO_2 columns versus electricity production of AEPP

In linear regression (Figure 6.8) there were two clusters observed which are 2005-2007 and 2008-2015 possibly from the capacity increase in 2006. When 2005-2007 years were excluded from evaluation, correlation was significant (R^2=0.57). The correlation coefficient was calculated for theoretical emission calculations; however, it was similar for emission calculations using EPA and EMEP emission factors as well.

With this method, using *a* values, yearly emissions could be estimated for coal power plants with annual electricity production. This is important for estimating yearly emissions from older power plants such as AEPP with significant variation in their electricity production, maintenance and fuel quality.

This study estimated yearly SO_2 emissions from a large pollution source. Same method can be used for other large-scale coal power plants that were with significant OMI SO_2 signal. This study is different from the previous studies by applying linear regression for only one power plant to estimate yearly emissions. In previous studies, several power plants were investigated in a period to estimate emissions from different power plants (Fioletov et al., 2011; Lu et al., 2013). In the next section (6.2) similar methodology was applied for seven different coal power plants to estimate 11-year average emissions between 2005 and 2015.

Firstly, emissions were calculated using EMEP and EPA emission factors and theoretically using only S content and calorific value of coal. Electricity production data was also used while calculating emissions. There were no reported emissions for power plants, because of that reason emissions were calculated based on emission factors, S content and calorific values.

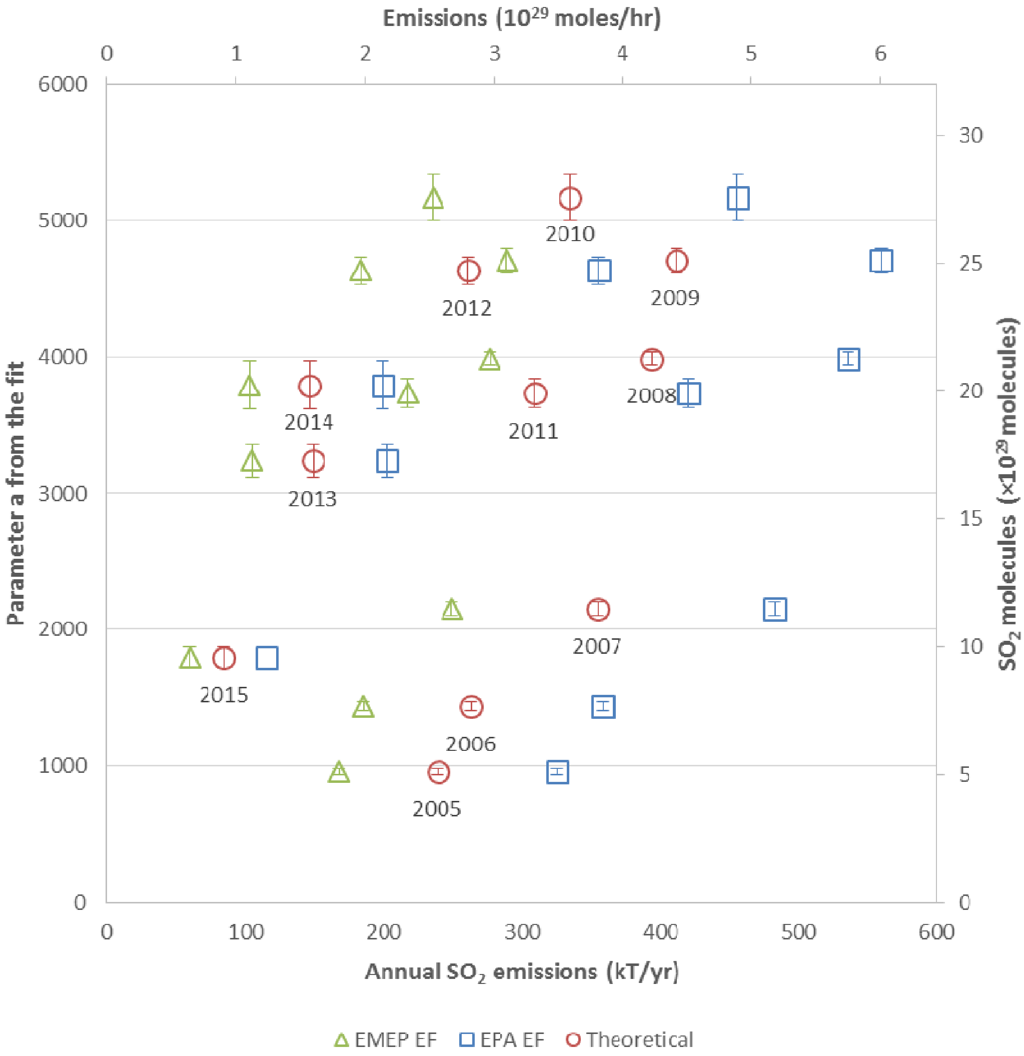

Figure 6.8 : Annual SO_2 emissions calculated versus estimated a values

6.1.2 Comparison with ground-based observations

There are two close ground-monitoring stations to Afşin Elbistan power plant. One is 24 kms south east of the plant which is Elbistan ground-monitoring station, the other one is Kahramanmaraş station which is 83 km south of the power plants. Location of the plants can be seen in Figure 6.6. The closer station was choosen to compare with OMI surface concentrations. (Figure 6.6).

Firstly, OMI SO_2 PBL retrievals were converted into µg/m^3 using equation (6.5). OMI SO_2 PBL product accounts for molecules number in planetary boundary layer (PBL). For initial calculation, all the molecules were assumed to be in surface layer although it was distributed to all PBL column. After getting Community Multi-Scale Air Quality (CMAQ) model results (Abdi, 2016), vertical profiles were used to calculate surface concentration of OMI SO_2 column.

$$SO_{OMI\ Derived}(\mu g/m^3) = SO_2OMI\ (ppm) \times P \times \frac{1}{R} \times \frac{1}{T} \times MW_{SO_2} \tag{6.5}$$

where ${SO_2}_{OMI\ Derived}$ states SO_2 concentration at surface. level, ${SO_2}_{OMI}$ states OMI SO_2 column, MW_{SO_2} states SO_2 molecular weight and P states pressure, T states temperature and R states gas constant.

Vertical profile for OMI mixing ratio for different height were obtained from CMAQ model results. The model was run for 2012 winter and summer seasons. January and July vertical profiles were drawn according to data from CMAQ model (Figure 6.9).

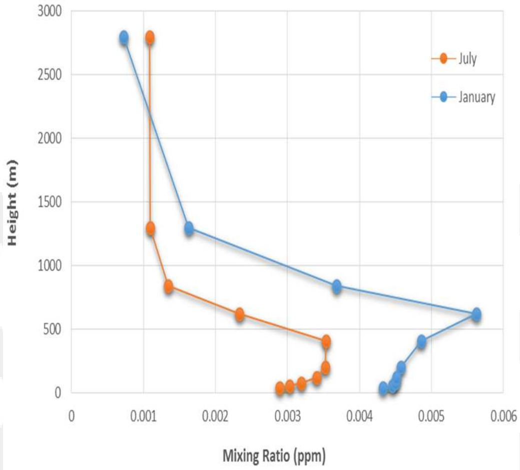

Figure 6.9 : Average monthly vertical profiles of SO_2 simulations for summer (July 2012) and winter (January 2012)

Vertical profiles for winter and summer are very similar to each other, and at surface layer (approximately the first 40 m) 11.13% and 11.37% of the column SO_2 was residing, respectively. For OMI (DU) to µg/m^3 concentration conversion, mean of these two contributions were used; 11.25%. Those are calculated according to previous studies as a ratio of Layer 1(surface layer) to sum of 10 layers where total height of those 10 layers close to PBL height (around 2.5 km). Previous studies were conducted for estimating surface layer mixing ratio from column for aerosols (Liu et al., 2004; van Donkelaar et al., 2006, 2010) and for NO_2 (Lamsal et al., 2008) and SO_2 (Lee et al, 2011). Basically the formula is multiplication of the ratio of first layer to the other layers in PBL obtained from simulations with OMI SO_2 column using equation (6.6).

$$S_{OMI} = \frac{S_{CMAQ}}{\Omega_{CMAQ}} \times \Omega_{OMI} \tag{6.6}$$

where subscripts indicate the source, while S is the SO_2 concentration (µg/m^3) and Ω is the SO_2 column (DU).

Yearly averages for OMI PBL SO_2 (DU) product were obtained for the grid where ground station take place. Those yearly averages (DU) were compared ground measurements. For all 11 years between 2005 and 2015 OMI SO_2 retrievals and ground measurements do not show any agreement to each other. OMI retreivals are in large amounts after beginning 2006 when Afşin Elbistan B power plant were installed (Figure 6.10). There is a decreasing trend for Afşin until 2009 but some decreases and increases were seen until 2015 due to some malfunctions among the years for the power plants.

After this, OMI SO_2 columns were converted to surface concentrations using CMAQ model vertical information and converted into $\mu g/m^3$. In the obtained results it was seen that, OMI derived results were in low amounts compare to ground measurements (Figure 6.11). This could be due to some reasons related to emission and meteorological input data to model or ground monitoring stations (Abdi, 2016).

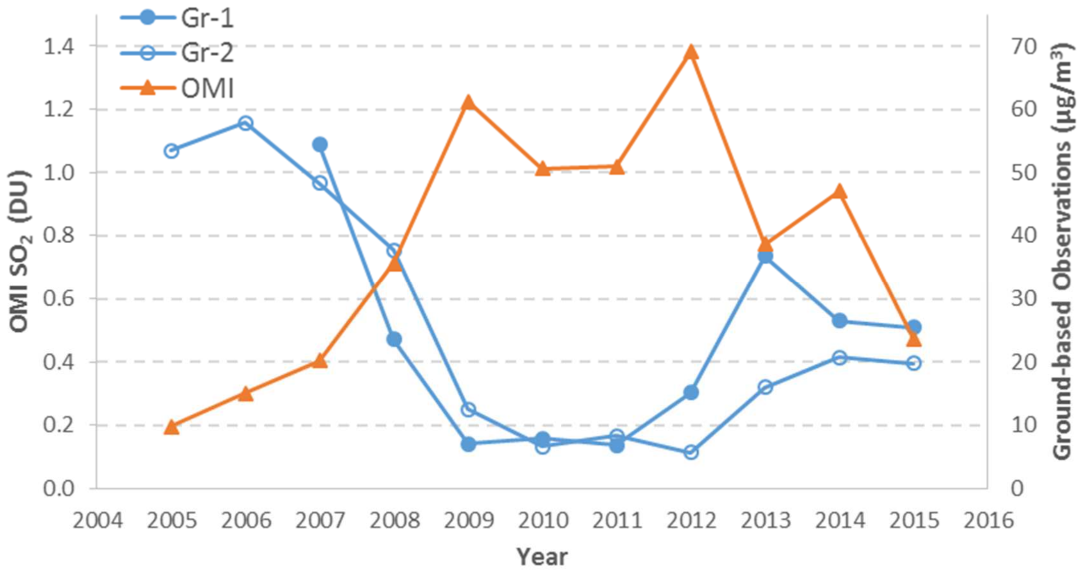

Figure 6.10 : OMI SO_2 retrievals and ground observation comparison for Afşin Elbistan power plant

Between OMI SO_2 column at ground level and ground monitoring measurements there is opposite trend for years 2005-2015. For OMI SO_2 column, there is an increasing trend for SO_2 concentrations until 2009 which also agrees with electricity production data, on the other hand, both of the ground monitoring stations indicate a decreasing from 2005 until 2009 which is completely opposite to electricity production amounts of AEPPs.

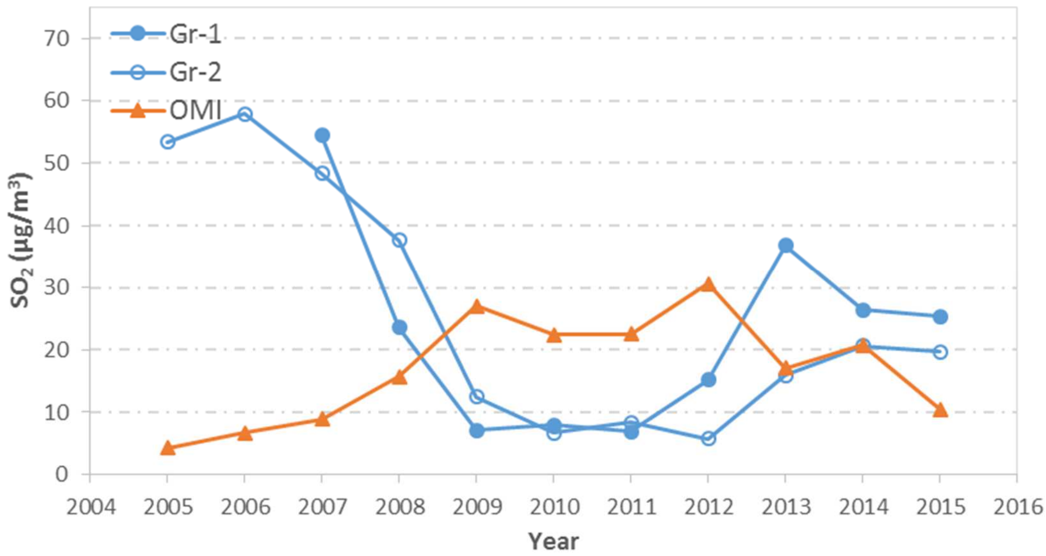

Figure 6.11 : OMI derived SO_2 surface concentrations and ground-based observations (µg/m^3)

6.2 Other Power Plants

Other than Afşin Elbistan, 14 large-scale coal power plants in Turkey were evaluated in this study. Similar methodology was applied for those power plants as it was performed for Afşin Elbistan power plant (Chapter 6). Eight other domains than Afşin Elbistan were selected for individual studies where important signals were visible in OMI SO_2 maps (Figure 6.12). Important pollution areas were detected as around Muğla, Ankara, Kütahya, Bursa, Şırnak, Manisa, Bursa provinces. Those pollution areas were related with large-scale power plants that are primarily S emitting sources in those cities.

Closest ground monitoring stations were also found to each selected power plants for ground level comparison with OMI SO_2 columns (Table 6.2). Çanakkale Çan and Zonguldak Çatalağzı power plant was not included in emission estimation study since there was not important visible pollution around those power plants.

Manisa Soma were included in the study although pollution signal was not so strong due to high emissions reported in emission inventories such as EMEP. It was one of the highest emission points in EMEP emission inventory of 2011, 2012 and 2013. Because of that reason, it was included in the emission estimation study.

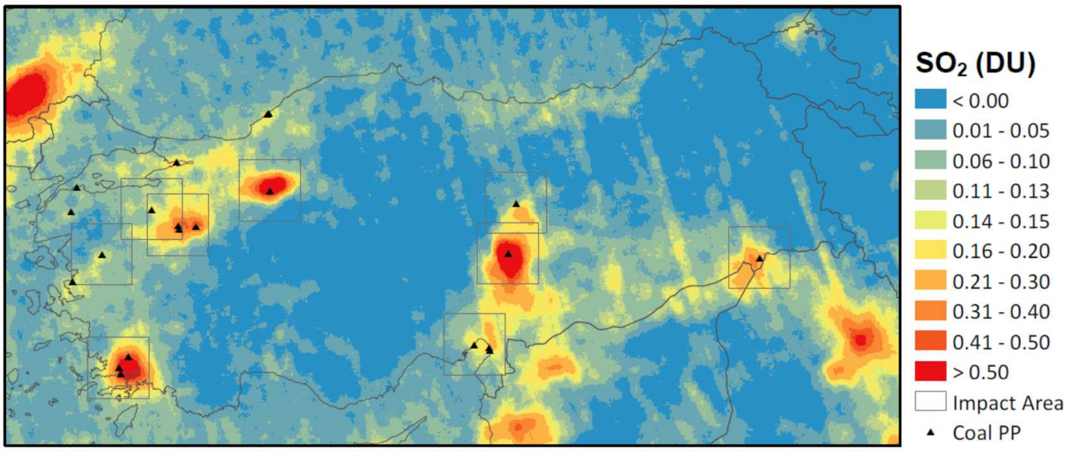

Figure 6.12 : Selected domains over pollution map of Turkey for the years between 2005 and 2015.

Table 6.2 : Selected power plants and closest ground monitoring stations

Power Plant	City	Coal Type	Closest Ground Monitoring Station (km)
Afşin Elbistan	Kahramanmaraş	Lignite	Elbistan (24), Kahramanmaraş (83)
Çan	Çanakkale	Lignite	Biga (52)
Kangal	Sivas	Lignite	Sivas Başöğretmen (63)
Orhaneli	Bursa	Lignite	Bursa Uludağ Ünv. (32)
Seyitömer	Kütahya	Lignite	Kütahya (25)
Tunçbilek	Kütahya	Lignite	Kütahya (62)
Kemerköy	Muğla	Lignite	Yatağan (50)
Yatağan	Muğla	Lignite	Yatağan (4)
Yeniköy	Muğla	Lignite	Yatağan (4)
Çatalağzı	Zonguldak	Hard Coal	Zonguldak (15)
Soma	Manisa	Lignite	Soma (3)
Çayırhan	Ankara	Lignite	Bolu (68), Sincan (75)
İsken Sugözü	Adana	Hard Coal	Osmaniye (42), Adana Doğankent (46)
İskenderun Demir	Hatay	Hard Coal	Osmaniye (35)
Şırnak Silopi	Şırnak	Asphaltite	Şırnak (23)

There are three large scale power plants in Muğla city of Turkey. Those power plants are considered as single source while applying gaussian fit and emission estimation.There is a considerable decrease for Muğla PP from 2005 to 2015. Especially for the years 2009 and 2010, SO_2 decreases remarkably. In 2009 and 2010, Yeniköy PP produces less electricty compared to other years, this change could be attributed to this (Figure 6.13).

Ankara Çayırhan power plant is not in EMEP emission inventory although it is a large scale power plant and it is also seen by OMI with a great signal. It is not in the Sozen's inventory neither. The power plant emission exists in TNO emission inventory. There is also limited data of electricity production for this power plant. There is a slightly decrease of SO_2 pollution area for the plant within the years until 2015. The SO_2 pollution area changes its direction to north in recent years while it has a eliptical shape between 2005 and 2008 (Figure 6.14).

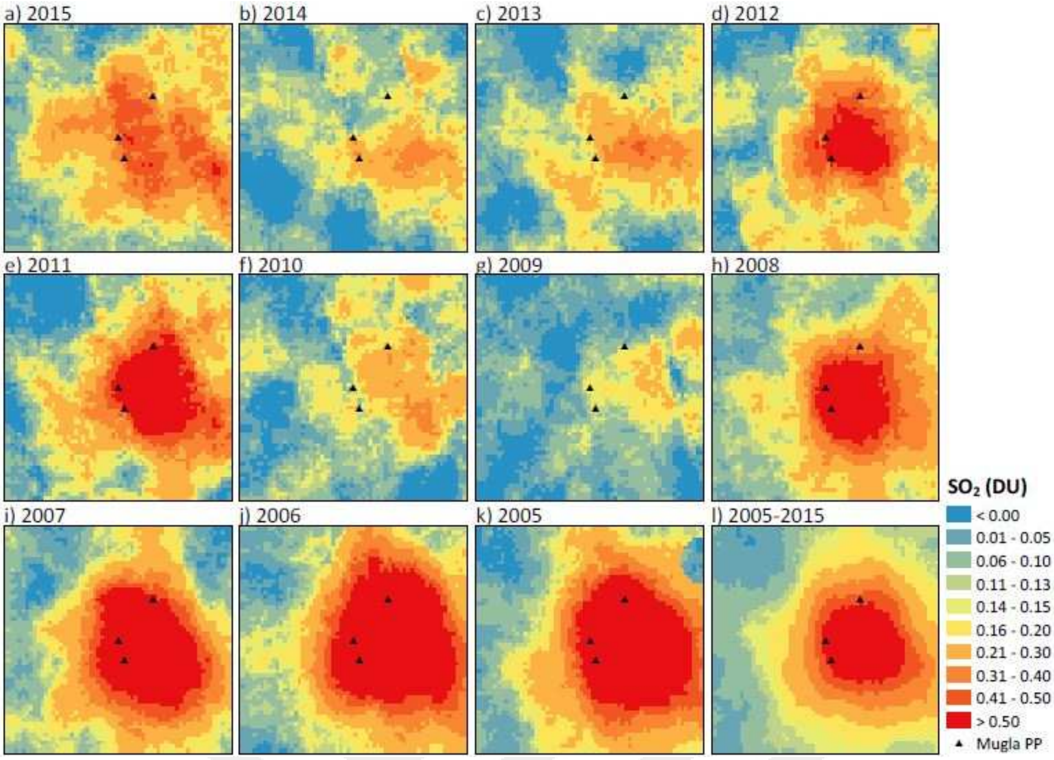

Figure 6.13 : Annual changes of SO_2 pollution around Muğla power plants.

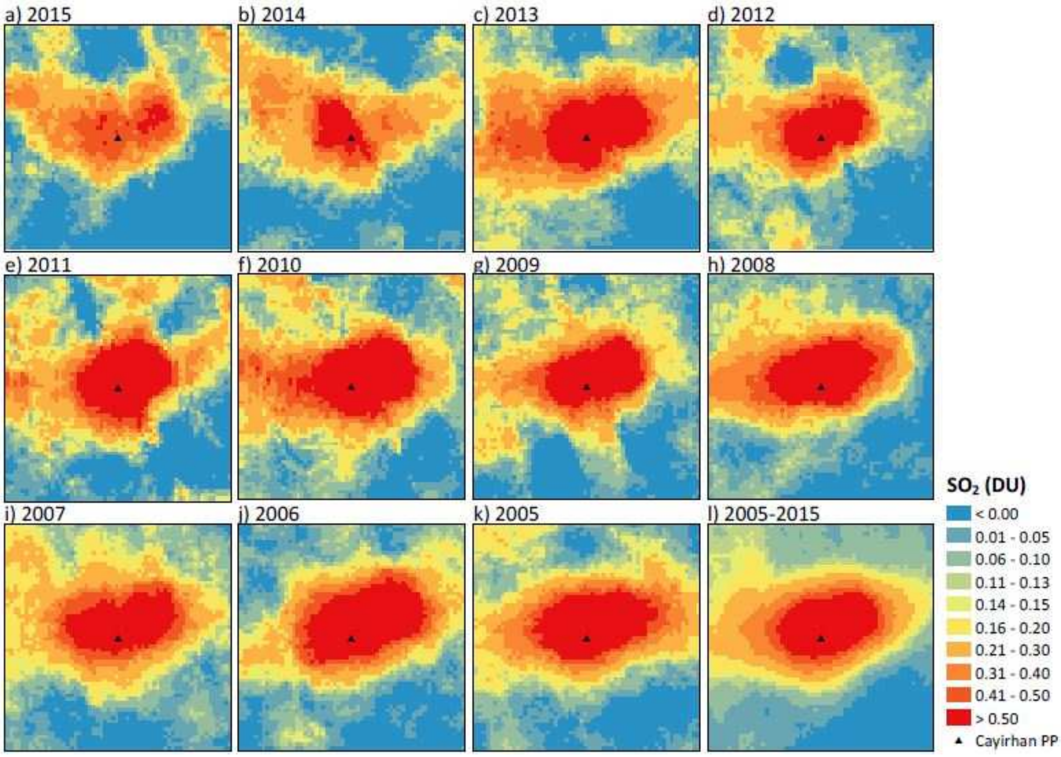

Figure 6.14 : Annual changes of SO_2 pollution around Ankara Çayırhan power plant

In Kütahya city of Turkey, there are three large scale power plants (>50 MWe). Those are Seyitömer, Tunçbilek and Polatlı power plants. Polatlı power plant seen in south of the map is established in 2014 with 51 MWe installed capacity. Tunçbilek and Seyitömer power plants are among the oldest power plants in Turkey. There is one other plant in the domain which is in Bursa Orhaneli power plant in the northwest of the domain. It is investigated in another domain for only itself. In Kutahya domain there is a high pollution seen by OMI, and it does not change dramatically year by year. In 2014, although Seyitömer and Tunçbilek electrical production are decreased, there is an increasing seen by OMI retrievals. This could be due to installation of Polatlı power plant in 2014 in the domain close to Tunçbilek and Seyitömer power plants (Figure 6.15).

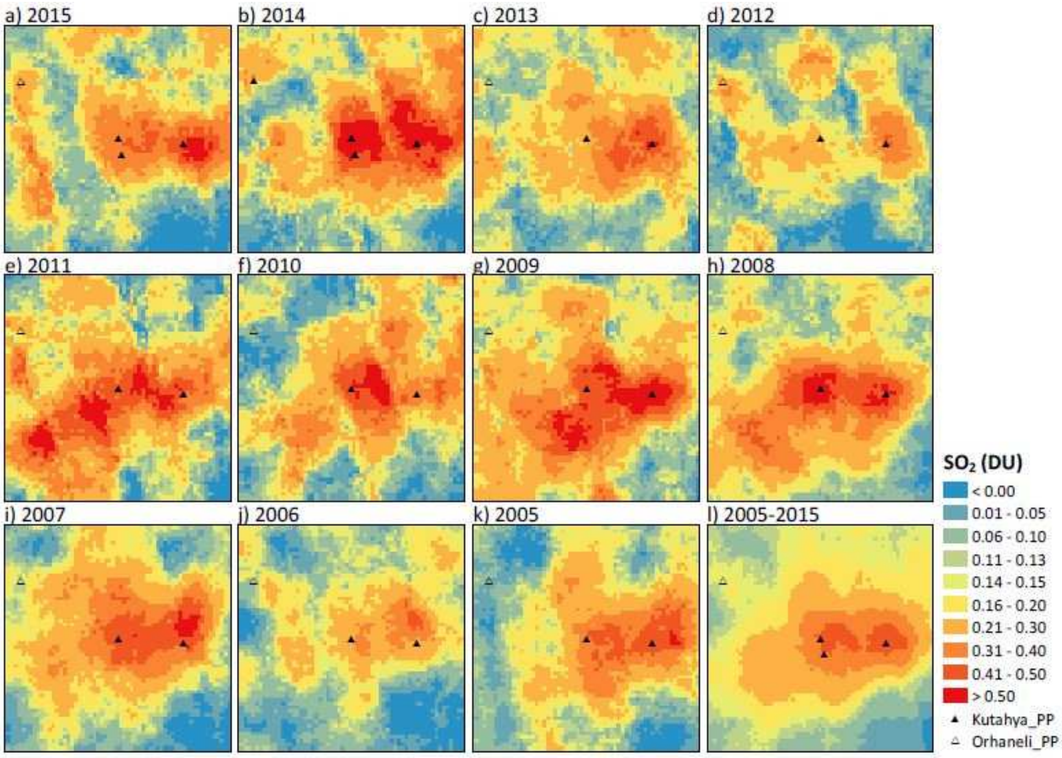

Figure 6.15 : Annual changes of SO_2 pollution around Kütahya power plants

Around Şırnak Silopi power plant, there is one of the most visible pollution in the study domain. Şırnak Silopi power plant was established in 2009, asphaltite is used in the plant, which is similar to coal but with higher S content and lower calorific value. Before that year there is still some SO_2 pollution seen by OMI, this could be due to another power plant opeared by fuel-oil which very close to the Silopi power plant or other industries. However, after installation of Şırnak Silopi power plant in 2009, there was a rapid increase at SO_2 pollution in the domain (Figure 6.16).

Manisa Soma power plant has one of the highest emission amounts according to TNO, EMEP and Sözen emission inventories, however the result from the fit for 60×60 km^2 domain indicates that pollution region is not gaussian shape for Manisa. There is moderate corelation for 30×30 km^2 domain with R^2 = 0.34 (Figure 6.17).

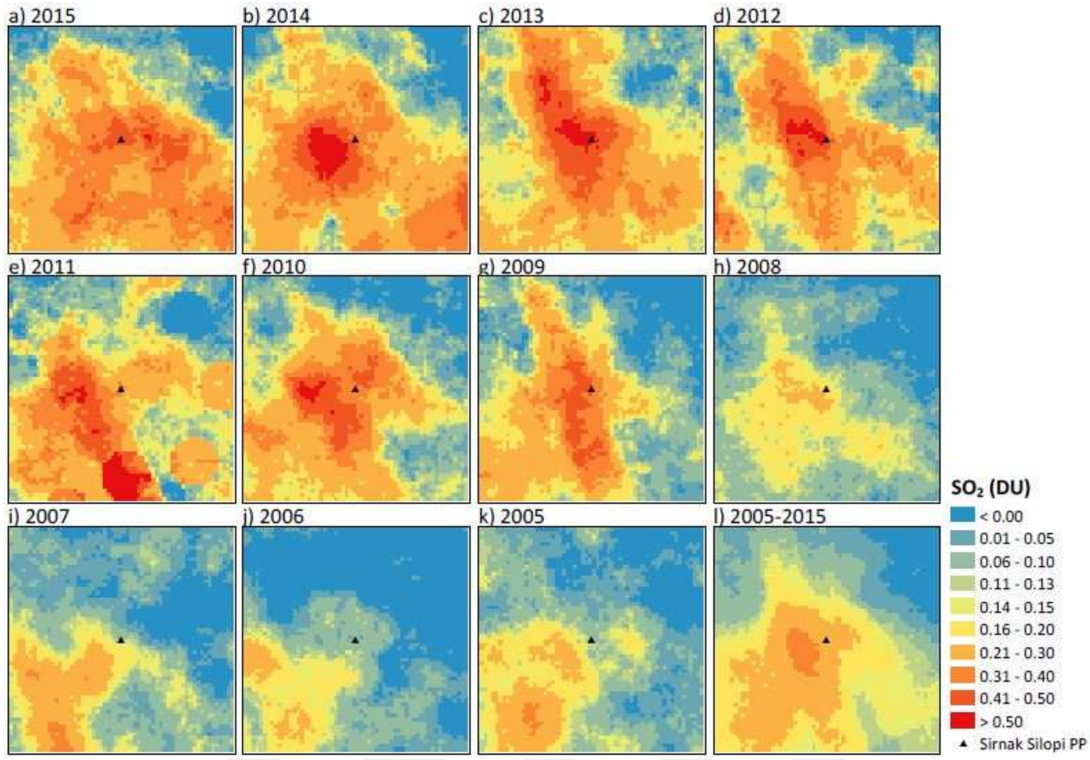

Figure 6.16 : Annual changes of SO_2 pollution around Şırnak Silopi power plant.

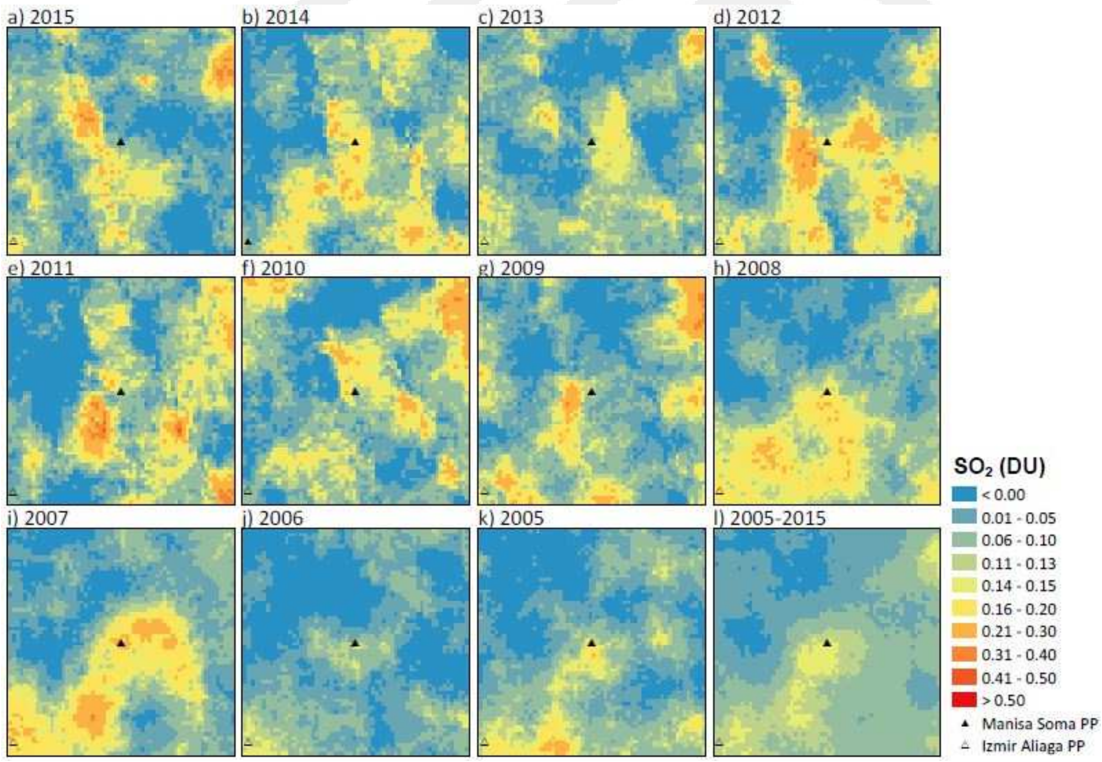

Figure 6.17 : Annual changes of SO_2 pollution around Manisa Soma power plant.

Annual electricity production, calorific value and S content of the coal for other 14 power plants were used in the studies (Table 6.3). Selected six power plants other than Afşin Elbistan were investigated in detail with electricity production and OMI SO_2

retrievals (Figure 6.19). Şırnak Silopi asphaltite power plant emission is not available (Table 6.2), but it was evaluated because of significantly high OMI SO_2 retrievals. Orhaneli power plant was not included in the emission estimation since there was not a distribution around the power plant that fits 2-D Gaussian function (Figure 6.18).

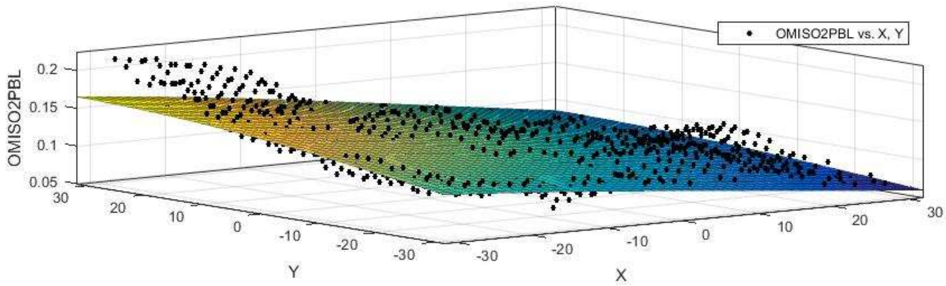

Figure 6.18 : 2-D gaussian function for Bursa Orhaneli power plant

Electricity production and OMI SO_2 retrievals for different power plant were investigated (Figure 6.19). In general for Seyitömer, Tunçbilek (Kütahya), Yeniköy, Kemerköy, Yatağan (Muğla) and Sivas Kangal power plants there was a good agreement between OMI SO_2 retrievals and annual electricity production. There was a good agreement as well for Ankara Çayırhan power plant but there were some missing electricity production data since in 2005, the power plant was privatized and only 5 years data of electricity production were found. OMI SO_2 retrievals were very low for Manisa Soma power plant while electricity production were high. There was no electricity production data for Şırnak Silopi since it is a private power plant. Only OMI SO_2 retrievals trend were shown. There was an increase in 2009 where Şırnak Silopi power plant were installed (Figure 6.19). For power plants in Muğla (Yeniköy, Kemerköy, Yatağan), electricity productions indicate high values for all 10 years, while OMI SO_2 retrievals show variaton among the years. The retrievals indicate high values for initial years, than it decreases significantly for the domain until 2009, there is a slight increase for the years 2010 and 2011, then it decreases again. Kütahya power plants (Seyitömer, Tunçbilek) trends for OMI SO_2 retrievals and electricity productions show good agreement to each other except for the last two years. In 2013 and 2014 OMI SO_2 retrievals decrease while electricity production increases. Sivas Kangal power plant electrical generation and OMI SO_2 retrievals complies to each other, they were both in low quanitity, and trends also have agreement for most of the years except a slight difference for 2007 and 2011. For Manisa Soma power plant, OMI SO_2 retrievals are very low and even minus for some years (2005, 2006, 2008, 2009) while electrical productions are in high amounts for all years with some minor changes.

Table 6.3 : Yearly electrical production (GWh) and calorific value and S content for selected large-scale coal power plants

POWER PLANT	CITY	YEARLY ELECTRICAL PRODUCTION (GWh)													Calorific Value (kcal/kg)		S content (%)	
		2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	Average	St Dev	St Dev (%)	1	2	1	2
Afşin Elbistan	Kahramanmaraş	4253	4325	7583	8984	9736	11957	11440	10306	7650	6944	8317.9	2681.9	32.24	1145	1000	2.1	1.4
Çan	Çanakkale	1917	2042	1450	2127	2141	1950	2192	2051	1261	824	1795.3	459.3	25.59	3000	2600	4.2	4.2
Kangal	Sivas		1276	1268	2491	2313	1658	1811	2745	2535	2050	2016.4	546.9	27.12	1282	1300	2.8	2
Orhaneli	Bursa	1299	154	941	1300	1174	1202	1332	1160	1085	634	1028.1	370.9	36.08	2279	2560	2.8	1.9
Seyitömer	Kütahya		1967	3384	3896	3623	4022	4051	3122	2986	3455	3389.6	653.0	19.26	2058	1500	1.2	2
Tunçbilek	Kütahya	2222	1436	1547	1791	1659	1606	1607	1478	1148	1210	1570.5	301.6	19.2	2560	2600	1.6	2
Kütahya Total		**2222**	**3403**	**4931**	**5687**	**5283**	**5628**	**5659**	**4600**	**4134**	**4666**	**4621.2**	**1117.6**	**24.18**	**2309**	**2050**	**1.4**	**2**
Kemerköy	Muğla	3399	2825	2826	4095	2720	3012	3411	2907	2945	1489	2962.7	662.3	22.36	2167	2600	3.1	3.2
Yatağan	Muğla	1722	2115	2982	4100	2599	3266	3981	3069	2895	3344	3007.2	742.1	24.68	2442	2100	2.7	2.7
Yeniköy	Muğla	2528	2633	2897	2730	1308	901	1929	2212	2012	1698	2084.8	647.4	31.05	2442	1750	2.7	4
Muğla Total		**7648**	**7573**	**8705**	**8388**	**6627**	**7179**	**9321**	**8188**	**7852**	**6531**	**7801.0**	**886.7**	**11.37**	**2350**	**2150**	**2.8**	**3.3**
Çatalağzı	Zonguldak	1511	1386	1479	2004	1883	1851	1882	2073	1909	1857	1783.5	236.3	13.25	2411	3200		0.8
Soma	Manisa	5535	3623	5063	5020	3897	4796	5482	4688	3514	3885	4550.1	760.5	16.71	2827	2400	1.2	1.5
Çayırhan [3]	Ankara	3521		3687	3823	3751					4058	3768.0	197.0	5.23	2592	2800	3.0	4.7
İsken Sugözü	Adana	9363	9507	9244	9076							9297.5	182.7	1.96		6150		0.9
İskenderun Demir	İskenderun										758	767.0						
Adana Total		**9363**	**9507**	**9244**	**9076**						**758**	**10064.5**	**3822.3**					

[1] Güler, 2010, [2] Say, 2006, [3] All electricity production statistics taken from TEIAS and only Çayırhan statistics were taken from enerjiatlasi.com

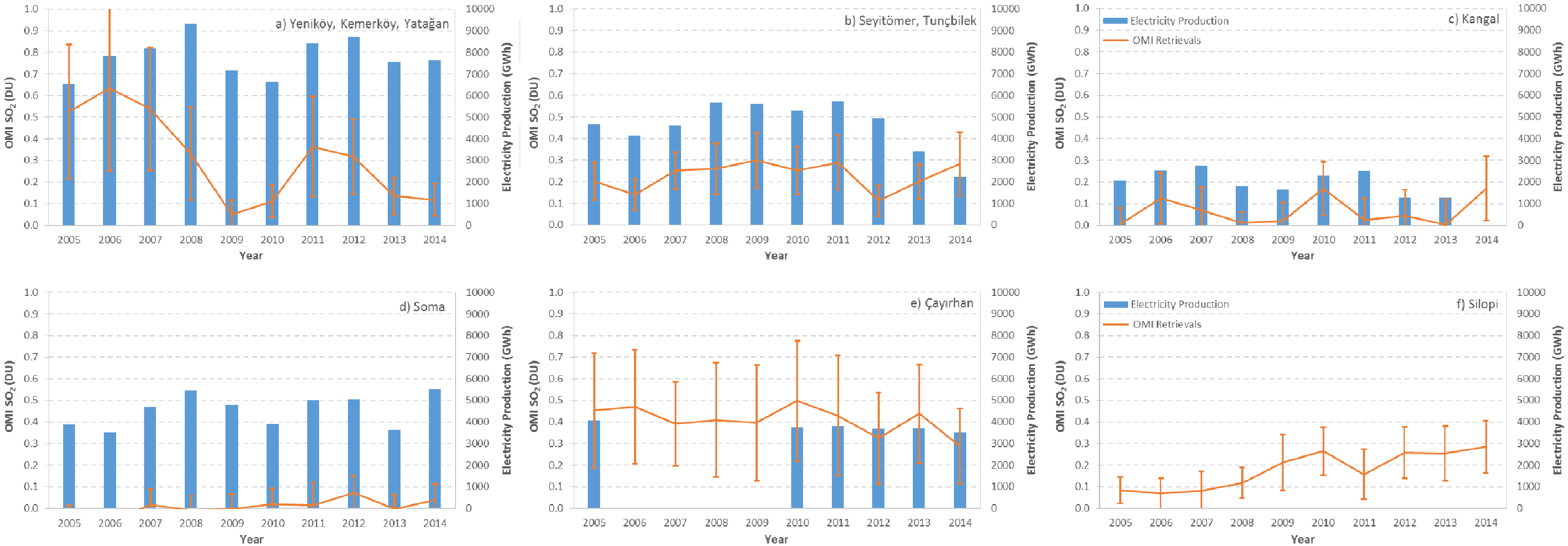

Figure 6.19 : Yearly electrical production and OMI SO_2 retrievals between 2005 and 2014 for a) Yeniköy, Kemerköy, Yatağan b) Seyitömer, Tunçbilek c) Kangal d) Soma e) Çayırhan f) Silopi power plants

Manisa Soma power plant emissions are also high in inventories, however, in OMI SO_2 retrievals there is not a significant pollution around the power plant, this could be due to meterological factors.

In pollution maps, there is not big difference for the pollution area, too. From 2005 up to 2015, Çayırhan was one of the biggest in the whole study area. For Şırnak Silopi power plant, electrical data is not available, however OMI SO_2 retrievals showed significant increase for the power plant for all years except only for 2010. The power plant was built in 2009, however there were some minor industries and a fuel oil power plant before that year. In 2009, there is a large increase in the domain probably due to installation of the Silopi power plant. After these studies, a better correlation were found between those different power plants emissions and emission estimation value ($R^2 = 0.70$) (Figure 6.20). Three different emissions were calculated since there was no reported emissions for the power plant. The emissions were calculcated using EPA and EMEP emission factors and mass balance calculation based only on S and calorific content of the coal. In addition, emission estimations from EMEP, TNO inventories and different studies were given for comparison (Table 6.4) (Alyuz, 2012; Sözen et al., 2010). For all three emission calculations, there is a similar correlation with parameter a from gaussian estimations (R^2=0.75). A better agreement were obtained with 11 year average data than yearly data in the case study for Afşin Elbistan. This is due to high yearly variation in SO_2 emission from point sources. Prevailing wind, wind direction and other meterological factors may effect the size of the pollution areas and emission estimations as well as S and calorific content of the coal. A new methodology could be developed for better emission estimation.

Individiual 2-D gaussian fittings and some statistical information were obtained for each selected domain (Table 6.4). A high correlation were found for each power plant ($R^2 > 0.87$) in Gaussian fitting method only without Manisa Soma power plant with lower correlation ($R^2 = 0.34$). Şırnak Silopi power plant were not taken into emission estimations since there was not a electricity production data for the power plant. In addition, no reported emission were found in the literature as well.

Therefore, using the regression line obtained from emission estimation study were used to estimate Şırnak Silopi power plant. According to the calculations using equation from linear regression line (Figure 6.20), emission for Silopi power plant were found 112,36 kton/yr.

Table 6.4 : 2-D Gaussian function method values and emissions for selected power plants

Power Plant	a	σ_x	σ_y	RMSE	R^2	$OMISO_2$ (DU)	SO_2 Emissions (Mg)						
							Theoretical	EPA EF	EMEP EF	EMEP^{2012}	TNO^{2009}	Sözen^{2010}	Alyüz^{2012}
Afşin Elbistan	3073 ± 47	19.1	23.2	0.01	0.95	0.37	333.50	453.82	251.53	280.10	122.191	193.253	455.60
Muğla	2298 ± 30	22.5	24.7	0.02	0.99	0.22	259.96	353.75	411.14	194.05	113.207	48.223	246.55
Ankara Çayırhan	2112 ± 24	26.3	16.1	0.03	0.98	0.17	131.84	179.40	249.84		55.705		
Sivas Kangal	535 ± 29	21.7	19.4	0.02	0.94	0.07	82.94	112.86	75.26	52.19	40.431	278.649	139.48
Kutahya	1611 ± 59	36.1	22.6	0.03	0.87	0.18	88.59	120.55	135.75	119.44	92.452	38.2	108.38
Manisa Soma	55.93 ± 8	12.4	11.6	0.03	0.34	0.06	57.77	78.61	106.15	119.95	92.901	72.761	56.38
Şırnak Silopi	1202 ± 42	26.8	25.5	0.03	0.88	0.13							

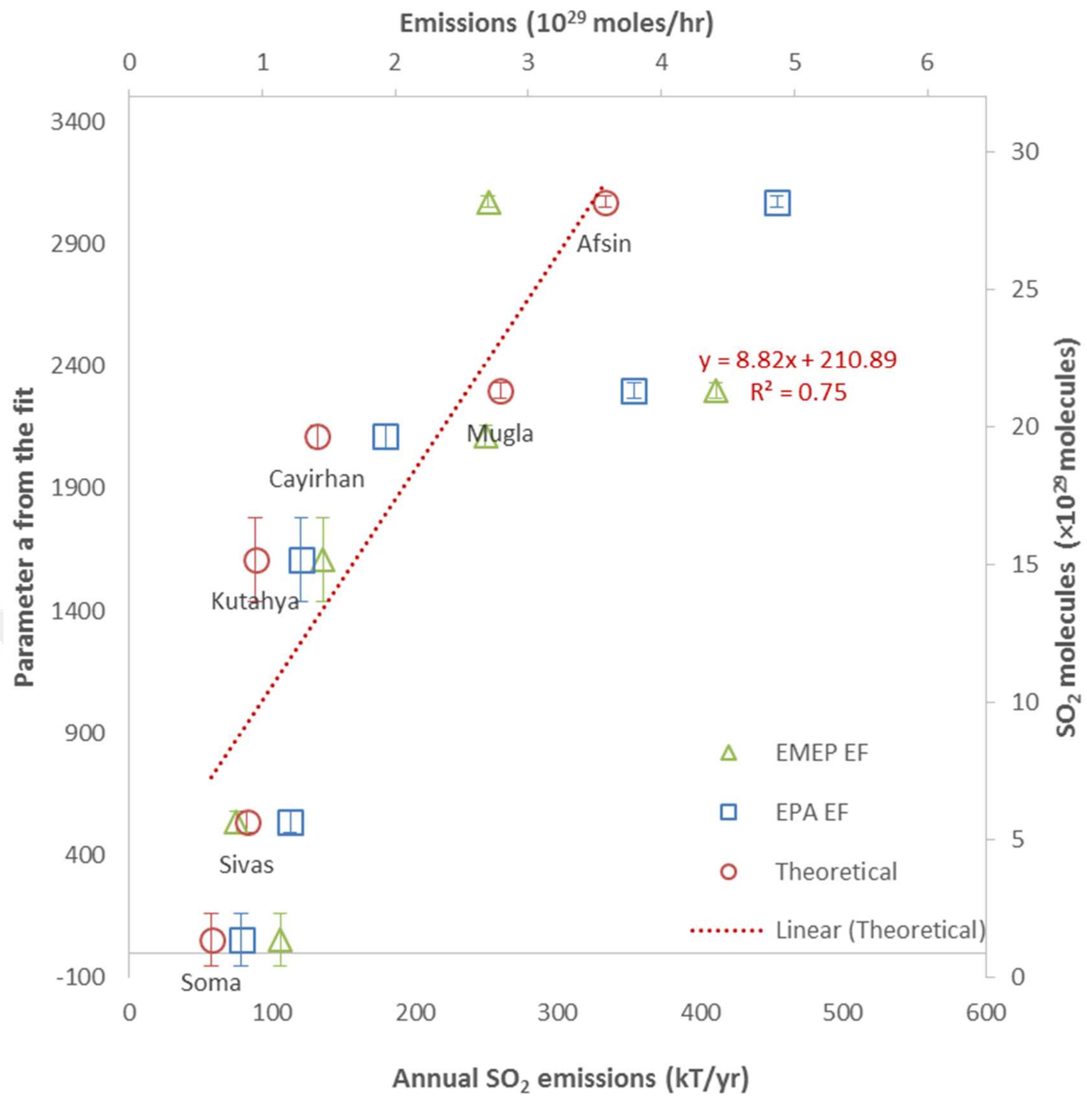

Figure 6.20 : Emission estimation value versus calculated emission (trendline is given for theoretical calculation)

In the previous yearly OMI SO_2 pollution distribution changes, it was also seen that OMI SO_2 signals were not strong around Manisa Soma power plant and there was not a gaussian shape distribution for the power plant SO_2 pollution. On the other hand, Manisa Soma emissions indicate one of the highest values in EMEP emission inventory with 119 kton SO_2 per year.

Emission inventories and studies, calculated emissions and OMI SO_2 retrievals indicate large variations among each other. For example, high emission (278 kton/yr) were reported for Sivas Kangal by an emission study (Sözen et al., 2010) however, EMEP and TNO emission inventories, and calculated emissions were too low compare to this value. In addition, the study reported low emissions for Muğla (Yeniköy, Kemerköy and Yatağan) and Kütahya (Tunçbilek and Seyitömer) power plants while inventories, and OMI signals were high for the power plants in the city.

In the emission calculation study, two different sources were used for S content and calorific value from the literature (Guler, 2010; Say, 2006). Averages of S content and calorific values of these two studies were used (Table 6.3).

According emission estimation paramter (a value) from Gaussian fit, highest emissions were for Afşin Elbistan power plant as also indicated in both TNO and EMEP emission inventories. For emission study by Sözen et al., Sivas Kangal were reported as highest emission for Turkey. In addition, Ankara Çayırhan were not reported in EMEP inventory and Sözen study, while Şırnak Silopi were not reported in any of the emission studies, since there was not a reported electricity production, calculations for emission were not conducted for this plant. Ankara Çayırhan and Şırnak Silopi were detected by OMI SO_2 retrievals in study area, as two of strongest signals. Especially Ankara Çayırhan pollution was very large as indicated before in yearly pollution maps (Figure 6.12).

OMI SO_2 retrievals and ground-based observations were compared for selected six power plants Firstly, OMI SO_2 in DU retrievals were compared with ground-based observations (Figure 6.21). Then OMI SO_2 retrievals were used to estimate ground concentrations (µg/m^3) using a vertical profile from CMAQ simulations as a preliminary study (Figure 6.22).

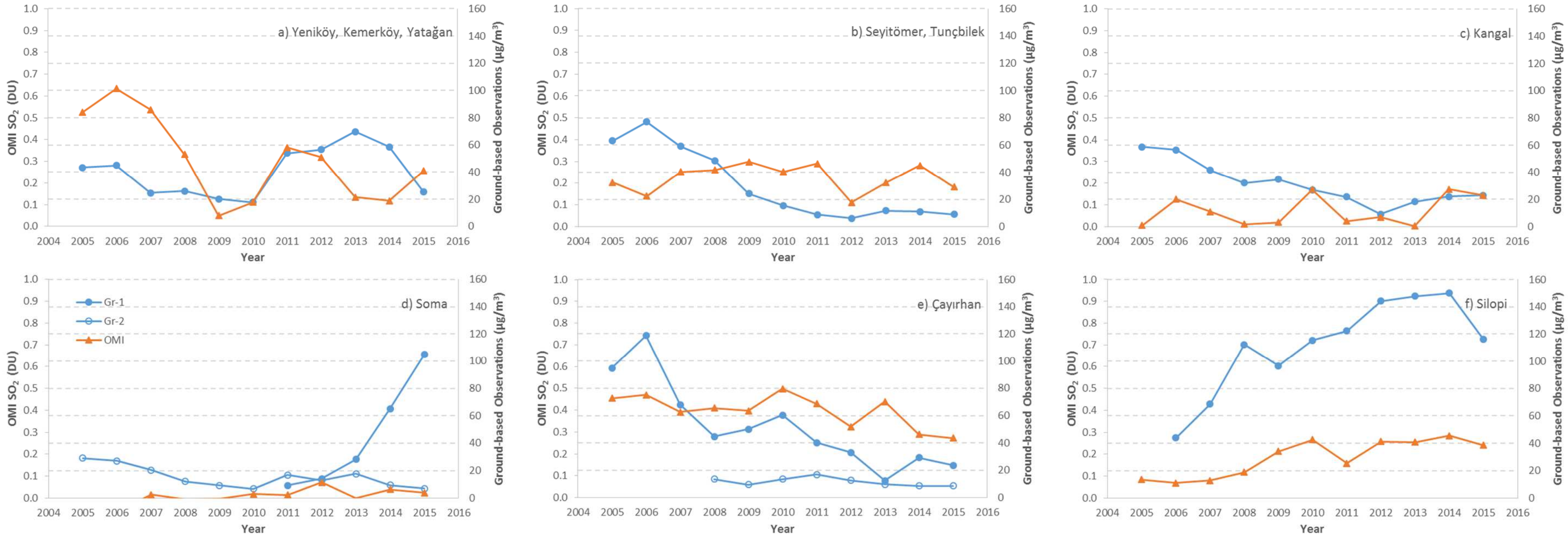

Figure 6.21 : Yearly ground-based observations (µg/m^3) and OMI SO_2 (DU) measurements for a) Yeniköy, Kemerköy, Yatağan b) Seyitömer, Tunçbilek c) Kangal d) Soma e) Çayırhan f) Silopi power plants

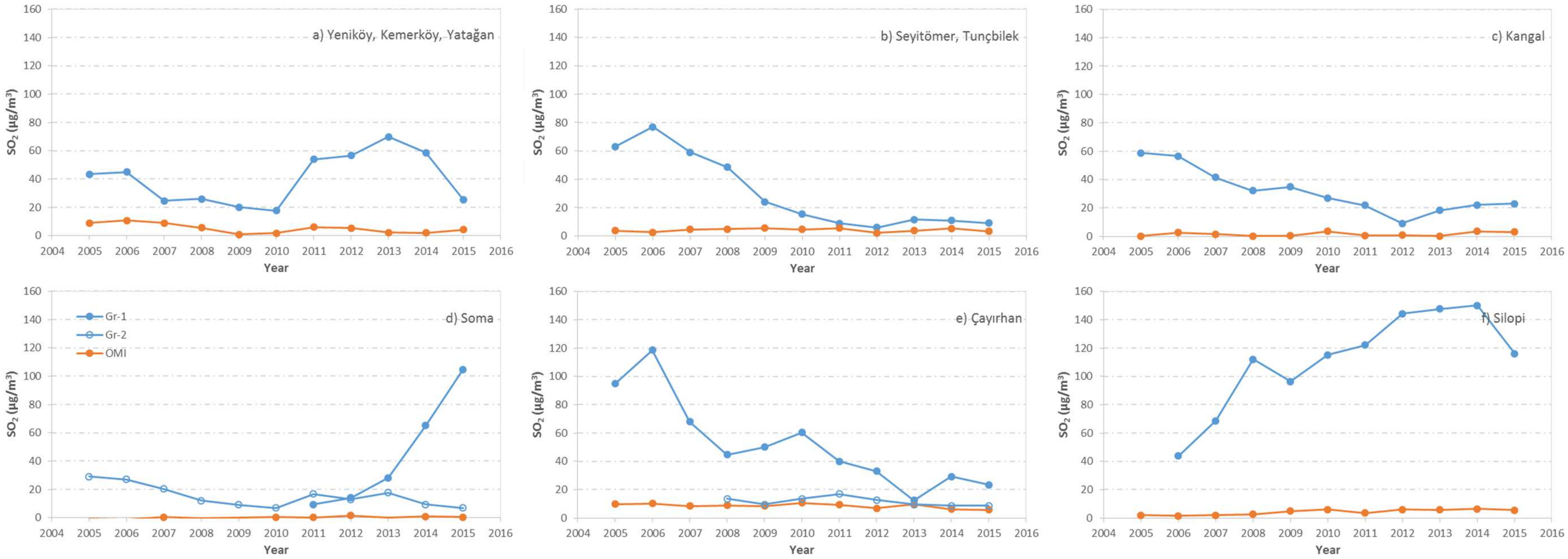

Figure 6.22 : Yearly ground-based observations (µg/m^3) and OMI SO_2 (µg/m^3) measurements derived from OMI retrievals for a) Yeniköy, Kemerköy, Yatağan b) Seyitömer, Tunçbilek c) Kangal d) Soma e) Çayırhan f) Silopi power plants

7. CONCLUSION AND DISCUSSIONS

In this thesis, 11 year of OMI SO_2 retrievals between 2005 and 2015 were analyzed for Turkey and surrounding. The retrievals were also compared with EMEP SO_2 emissions and ground monitoring observations.

OMI SO_2 retrievals show high signals primarily around large-scale point sources such as coal power plants and industrial regions those are emitting significant amount of SO_2. Large-scale coal power plants are investigated individually since they are the primary emission sources of SO_2 because of low calorific value and high S content of Turkish coal (lignite). This study showed that OMI SO_2 retreivals can be used to detect SO_2 pollution from large-scale power plants. In the study domain, some pollution from close neighborhood were also detected. Most visible signals in the domain were in the border of Bulgaria from Maritsa power plants. According to the prevailing wind, there may be a pollution transport from this country to Turkey. Transboundary pollutions can not be observed by ground monitoring but can be seen with satellite retrievals.

Emission estimation study were conducted in the thesis since there is no regular reporting system of large scale emission sources. Firstly, 60×60 km^2 grid was created with two steps around large-scale sources. Oversampling method were applied for yearly data of OMI PBL. Background noise were removed substracting 300 km average from each year data. After that, 2-D Gaussian fitting method were applied to OMI retrievals for estimatimg SO_2 emissions from the sources. As a case study, Afşin Elbistan power plant were analyzed for 11 year data of the source, and a moderate correlation (R^2 = 0.57) were found between estimatation values and calculated values for the source. After that, estimation study were conducted for eight selected power plants. A good correlation (R^2 = 0.75) were found between estimation parameter and calculated emissions. For Şırnak Silopi power plant, there is no electricity production data, therefore emission for the power plant were estimated using lineer regression line obtained from parameter *a* and calculated emissions for selected power plants. According to that calculation, emission of Şırnak Silopi power plant was estimated as around 112 kton/yr.

Large-scale SO_2 sources that were detected by OMI were compared with EMEP SO_2 emissions for the years of 2012 and 2013 with 0.1˚ × 0.1˚ resolution. In emission inventory, more than 50% of the national total emissions are due to public power emissions. Due to that reason, initial comparison was performed for power plants. As a result, there was not a good agreement between OMI and EMEP. For some large-scale sources such as Afşin Elbistan in Kahramanmaraş, Manisa Soma, Tunçbilek and Seyitömer in Kütahya, there were slightly agreement between EMEP and OMI. Around other large-scale power plants such as power plants in Muğla, Sivas Kangal, İsken Sugözü. Furthermore, EMEP does not contain some of the large sources of Turkey as Ankara Çayırhan that has one of the highest signals in study area by OMI. İsken Sugözü is another large-scale power plant that were not in the inventory. After that, city-based comparison was conducted between OMI and EMEP. OMI SO_2 retrievals in some cities where large-scale power plants are located have some agreement with EMEP emissions. However, OMI SO_2 retrievals for many cities do not agree with EMEP emissions. Most interesting cities are mainly Aydın, Bilecik, Düzce, Diyarbakır, Gaziantep, and Osmaniye. Many of those cities are close to large-scale emissions sources and majority of those cities are industrialized regions where SO_2 emissions could be high in the cities due to industrial processes. Another example of possible missing emission source is for Batman city. In the city, there is a large-scale oil processing industry that may lead high SO_2 emissions. However, the emission inventory does not indicate high SO_2 emissions for the city, while OMI retrievals indicate high SO_2 concentrations for the city.

As a result, it was seen that EMEP inventory do not have a complete emission inventory for Turkey and it has missing and dislocated point sources in Turkey. This study could give important feedback to improve the future emission inventories.

Second important comparison of this thesis is with ground monitoring observations. Ground monitoring stations close to large-scale emissions sources were selected and their observations were compared with OMI SO_2 retrievals. Firstly, the comparison were done with OMI SO_2 columns and ground based measurements. In the comparison, it was seen that there was no good agreement between OMI SO_2 retrievals and ground measurements. This could be due to reasons, such as some of the ground monitoring stations were far away from the power plants, and SO_2 retrievals indicate not only ground but also elevated pollution with columns. Therefore, OMI SO_2 retrievals were converted to surface concentrations to make a better comparison using vertical profile from model outputs. However, there was no good agreement in this comparison as well. OMI SO_2 concentrations in surface were seen very low compare to ground monitoring stations. Other than that, changing trends were also opposite

7.1 Future Works

In this thesis, SO_2 emissions were evaluated using OMI satellite retrievals. This work can be improved comparing different satellite instruments. There are many other instruments such as GOME-2, SCIAMACHY, in the evaluation period of this thesis.

Furthermore, there are different algorithms those applied on satellite data and as a result data products are different. Those different alogrithms and data products could be compared and discuss differences among them.

In this thesis, OMI retrievals were compared with ground monitoring stations close to large-scale emission soruces. In addition, a detail comparison may be done between OMI SO_2 retrievals and all ground monitoring stations.

Different pollution species such as PM, CO, NH_3, NO_x can be investigated as future works for 11 years using various of satellite instruments. Similar studies in this thesis may be applied to different pollution species. Pollution trends could be evaluated beginning from 2005 up to date.

In the near future, satellite instruments with better spatial resolution will be launched to space such as TROPOMI. This can be used for better evaluation of .tropospheric SO_2 pollution for the future studies.

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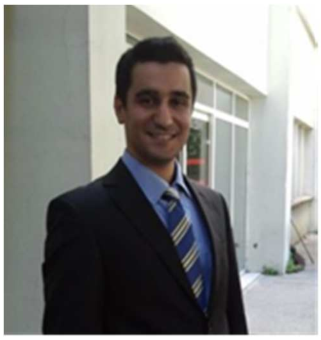
CURRICULUM VITAE



Name, Surname : Ertuğ FIRATLI

Place and Date of Birth : İstanbul – 15 August, 1989

E-mail : firatli@itu.edu.tr, ertugfiratli@hotmail.com

B.Sc. : İstanbul Technical University, Environmental Engineering, 2014

Professional Experience and Rewards:

Arasya Group of Companies (HUBER distributor)
(02.2014-10.2014)
Position : Environmental Engineer **(**Sludge treatment equipments)

SH+E Group Turkey
(06.2013-02.2014)
Position: Environmental Engineer (Wastewater treatment plant design)

StulzPlanaqua GmbH - Tuzla İDOSB WWTP Project
(01.2013-06.2013)
Position : Site Engineer (Renovation of Tuzla İDOSB WWTP)

Institution Building on Air Quality in The Marmara Region
(08.2012-09.2012)
Position : Intern at management (Air quality observation)

Ministry of Forestry and Water- İstanbul Directorate- Hasanpaşa Building
(08.2011-09.2011)
Position : Intern at air quality inspection (Air quality, wastewater)

List of Publications and Patents :

- Firatli E., Kaynak Tezel B., "Evaluation of SO_2 emissions from large scale power plants using OMI SO2 retrievals for Turkey", 23rd International Conference on Modelling, Monitoring and Management of Air Pollution, Valencia, Spain, 01-03 June 2015.
- Firatli E., Kaynak Tezel B., "Comparison of OMI SO_2 retrievals and ground monitoring observations for Turkey", 6th National Air Pollution and Control Symposium, Izmir, Turkey, 07-09 October 2015.
- Kaynak Tezel B., Firatli E., "Estimating SO_2 emissions from a large point source using 10 year OMI SO_2 observations: Afsin Elbistan Power Plant", European Geoscience Union General Assembly, Vienna, Austria, 17-22 April 2016.