Economic crisis detected from space: Air quality observations over Athens/Greece

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[1] Using both satellite observations of tropospheric NO_2 columns and a number of economic metrics, we investigate the impact of the economic crisis (from 2008 onward) on air quality over Greece, and Athens in particular. The multiannual analysis shows that NO_2 columns over Athens have been significantly reduced in the range 30–40%. This decline is further supported by surface measurements of atmospheric NO_2 mixing ratios. Additionally, the declining local concentrations of NO, CO, and SO_2 are associated with an increase in ozone due to reduced titration by NO. In particular, regression analysis revealed that the reduction of NO_2 (0.3 ± 0.2 ppbv y^{-1}) and SO_2 (0.2 ± 0.1 ppbv y^{-1}) during the period 2000–2007, significantly accelerated during the economic crisis period (from 2008 onward), reaching 2.3 ± 0.2 ppbv y^{-1} and 0.7 ± 0.1 ppbv y^{-1}, respectively. The strong correlations between pollutant concentrations and economic indicators show that the economic recession has resulted in proportionally lower levels of pollutants in large parts of Greece. **Citation:** Vrekoussis, M., A. Richter, A. Hilboll, J. P. Burrows, E. Gerasopoulos, J. Lelieveld, L. Barrie, C. Zerefos, and N. Mihalopoulos (2013), Economic crisis detected from space: Air quality observations over Athens/Greece, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50118.

1. Introduction

[2] Nitrogen oxides ($NO_x = NO + NO_2$) and sulphur dioxide (SO_2) are among the most important contributors to air quality degradation. NO_x species affect tropospheric chemistry by: (i) controlling the photochemical production of ozone [*Seinfeld and Pandis*, 2006 and references therein], (ii) contributing to nitric acid (HNO_3) formation [e.g., *Vrekoussis et al.*, 2004, 2006; *Monks*, 2005; *Seinfeld and Pandis*, 2006] thus leading to acidification, (iii) controlling the nighttime oxidizing capacity of the atmosphere through nitrate radical formation [*Wayne et al.*, 1991; *Vrekoussis et al.*, 2007], and (iv) affecting the radiative forcing of the atmosphere [*Solomon et al.*, 1999], either directly, when high levels of NO_2 are reached, or indirectly, through ozone formation and by changing the lifetime of several reactive greenhouse gases. When emitted into the atmosphere, SO_2 is rapidly oxidized leading to aerosol formation thus affecting climate [*Ramanathan et al.*, 2001]. High levels of these pollutants may lead to adverse human health effects. According to the World Health Organization (WHO), exposure of the public to high concentrations of air pollutants is related to various health problems including irritated eyes, headaches, asthma, and chronic diseases eventually leading to increased morbidity and mortality [*Solomon et al.*, 2011].

[3] Athens, the capital of Greece, is a heavily polluted capital in the region [*Im and Kanakidou*, 2012] owing to: (i) the extensive number of registered vehicles (2.7 M private cars, 0.7 M motorcycles, and 0.3 M trucks; Hellenic Statistical Authority (El-stat): http://www.statistics.gr), (ii) the presence of industrial regions close to the city and (iii) the complex topography of the area, favoring pollutant accumulation in the atmospheric boundary layer [*Kalabokas et al.*, 1999], (iv) the intense photochemical processes, favored by high temperature and insolation [*Lelieveld et al.*, 2002], and (v) the reception of transboundary pollution [e.g., *Gerasopoulos et al.*, 2011]. As a result, this densely populated area (up to 16 thousand citizens per square kilometer, http://www.statistics.gr) suffers from high levels of air pollutants emanating mainly from anthropogenic sources.

[4] Enhanced levels of air pollution over the East Mediterranean (including Athens) have been already recorded by satellite [e.g., *Ladstätter-Weißenmayer et al.*, 2007; *Zyrichidou et al.*, 2009; *Kanakidou et al.*, 2011] and in-situ observations [e.g., *Kouvarakis et al.*, 2002; *Gerasopoulos et al.*, 2006]. Complementary to in-situ observations, satellite data are used to reveal the spatial and temporal distribution of pollutants on regional and global scales to infer their impact on atmospheric chemistry. For example, satellite observations have been used to identify the increasing NO_2 trends over China due to the rapid economic and industrial development [*Richter et al.*, 2005] or the decline in NO_x emissions during the Beijing summer Olympic Games due to abatement measures by the local authorities [*Mijling et al.*, 2009]. More recently, *Castellanos and Boersma* [2012] reported large reductions of at least 20% throughout Europe for the period 2005–2010, attributed to the economic recession period and the applied environmental emission controls. Similarly, large reductions in NO_2 concentrations have been detected across the US during the respective US economic recession period [2007–2009] and over urban areas and power plants [*Russell et al.*, 2012].

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[5] In this paper, we report the drastic and significant reduction of primary gaseous pollutants in the form of NO_2 columnar densities observed over Athens during the economic recession that started in 2008 indicating large reductions in pollutant emissions. The reported reduction is supported for the first time to our knowledge for this area by several independent measurements including in situ measurements and economic metrics. More specifically, data from three satellite spectrometers have been analyzed: (a) the SCanning Imaging Absorption SpectroMeter for Atmospheric CartograpHY (SCIAMACHY), (b) the Global Ozone Monitoring Experiment-2 (GOME-2), and (c) the Ozone Monitoring Instrument (OMI). The observed, significant reduction was evaluated via in-situ observations of NO_2, NO, SO_2, CO, and O_3 and further compared to several economic metrics used as proxies of activities that contribute to air pollution.

2. Methods and Data Sources

2.1. Satellite Data

[6] For this study, we used spaced-based data from three satellite instruments, the SCIAMACHY, GOME-2, and OMI measuring the transmitted, reflected, and scattered light upwelling at the top of the atmosphere from the Earth's atmosphere and surface. The SCIAMACHY spectrometer, onboard ENVISAT satellite [2002–2012], had a local equator crossing time of 10:00 LT in the descending node and the ground pixel is $30 \times 60\,km^2$ [*Burrows et al.*, 1995; *Gottwald et al.*, 2006]. The GOME-2 spectrometer, on board the MetopA satellite (launched in October 2006) flies in a sun-synchronous orbit with an equator crossing time of 09:30 LT with a nominal ground-pixel of $40 \times 80\,km^2$ [*Callies et al.*, 2000]. The OMI instrument, on board the Aura Satellite (launched in July 2004) has an equator crossing time of 13:30 LT in the ascending node and a spatial footprint of $13 \times 24\,km^2$ at nadir with daily global coverage [*Levelt et al.*, 2006].

[7] Satellite retrieval of NO_2 vertical column loading involves three basic steps: (a) the spectral fitting using the Differential Optical Absorption Spectroscopy technique [*Platt*, 1994] to estimate the optical density of NO_2 along the optical path, (b) the separation of stratospheric from tropospheric content, and (c) the conversion of the obtained slant columns to tropospheric vertical column densities of NO_2 after applying an air mass factor based on the Radiative Transfer Model SCIATRAN [*Rozanov et al.*, 2005]. The SCIAMACHY and GOME-2 NO_2 vertical column computation was based on the retrievals algorithms of the University of Bremen (UB) [e.g., *Richter et al.*, 2005, 2011]. For the OMI NO_2 vertical column, the slant column provided by the operational NASA OMI product (collection 3) was converted to vertical column density following steps 2 and 3 of the UB algorithms [e.g., *Kim et al.*, 2009]. Uncertainties in satellite observations of tropospheric NO_2 columns are large for individual measurements and over polluted regions are dominated by uncertainties in cloud effects, surface reflectance, and NO_2 vertical distribution [*Richter et al.*, 2005]. However, in the analysis of NO_2 changes, many of the systematic errors cancel and the relative uncertainty of annual averages accounting for this effect can be estimated to be about 15% [*Richter et al.*, 2005].

2.2. In-situ Surface Observations

[8] We used data collected at 10 air quality monitoring stations operated by the Greek Ministry of Environment Energy and Climate Change (http://www.ypeka.gr/). These stations are located at both urban-traffic and suburban regions (see supplementary material, Figure S1). Continuous, hourly concentrations of NO, NO_2, O_3, SO_2, and CO have been recorded by commercial instruments with the use of the chemiluminescence, UV-absorption, UV-fluorescence, and IR absorption techniques, respectively, and have been averaged over months and years to investigate the interannual variability. The NO, NO_2, SO_2, and CO instruments were dynamically calibrated using standard gases while for O_3 the primary UV calibration method has been applied (www.ypeka.gr). It should be noted that for instruments using Molybdenum catalysts without a photolytic or a blue light converter, the recorded NO_2 concentrations actually reflect an upper limit of the real NO_2 measurements. In the absence of such converters, other odd nitrogen reactive species (e.g., peroxyacetyl nitrate-PAN, nitric acid-HNO_3, nitrates-NO_3^-) are catalyzed together with the ambient NO_2 by the Molybdenum catalyst commercial instrument [*Dunlea et al.*, 2007]. This could lead to significant errors, up to 100%, especially in remote areas [e.g., *Steinbacher et al.*, 2007], while in urban sites the overestimation is in the order of 50% [*Dunlea et al.*, 2007].

3. Results and Discussion

[9] Changes in the annual averages of the tropospheric GOME-2 NO_2 vertical columns (VCD_{NO2}) over Greece, including parts of the neighbouring countries, during the economic recession period were analyzed first. Figure 1a illustrates the spatial distribution of the linear regression coefficient computed for the period 2007–2011, based on the GOME-2 VCD_{NO2} at 9:30LT for each grid cell (0.125° 0.125°). The computed slopes of the regression point to an overall reduction of VCD_{NO2} over Greece. Particularly over Athens [37°58′N, 23°43′E], the reduction during the economic recession period was found to be as high as $8 \cdot 10^{14}$ molec $cm^{-2}\,y^{-1}$, equivalent to an annual reduction of about 8%. In absolute terms (Figure S2), large negative differences greater than $2.5 \cdot 10^{15}$ molec cm^{-2} are observed above Athens [37°58′N, 23°43′E] and Thessaloniki [40.65°N, 22.9°E], the two largest cities of Greece (populations of the metropolitan areas about 3.7 M and 1.0 M, respectively). Given the short chemical lifetime of NO_2, of the order of few hours, these changes should reflect reductions in local rather than regional NO_x emissions; in Athens, more than 50% of these emissions are related to road traffic [*Markakis et al.*, 2010]. Pearson Probability analysis of significance of non-zero slope (Figure 1b) showed that at 95% confidence limit ($a < 0.05$; dark red in Figure 1b) there was a significant linear regression mostly over Athens over the 5 years of the analysis.

[10] To further investigate the temporal variability of NO_2 over Athens, monthly averages of the VCD_{NO2} derived from SCIAMACHY (2003–2011) and OMI measurements (2004–2011) have been analyzed (Figure 1c). Overall, SCIAMACHY VCD_{NO2} at 10:00 are higher than the OMI ones (at 1:30 pm). This could be due to two factors: (a) higher NO_x emissions at 10 am than at mid-afternoon related to the morning rush hour and (b) the stronger photochemical NO_2 loss during midday [*Boersma et al.*, 2008]. Despite differences in absolute values, both SCIAMACHY and OMI confirm the significant reduction in NO_2 levels depicted by GOME-2 data (Figure 1a).

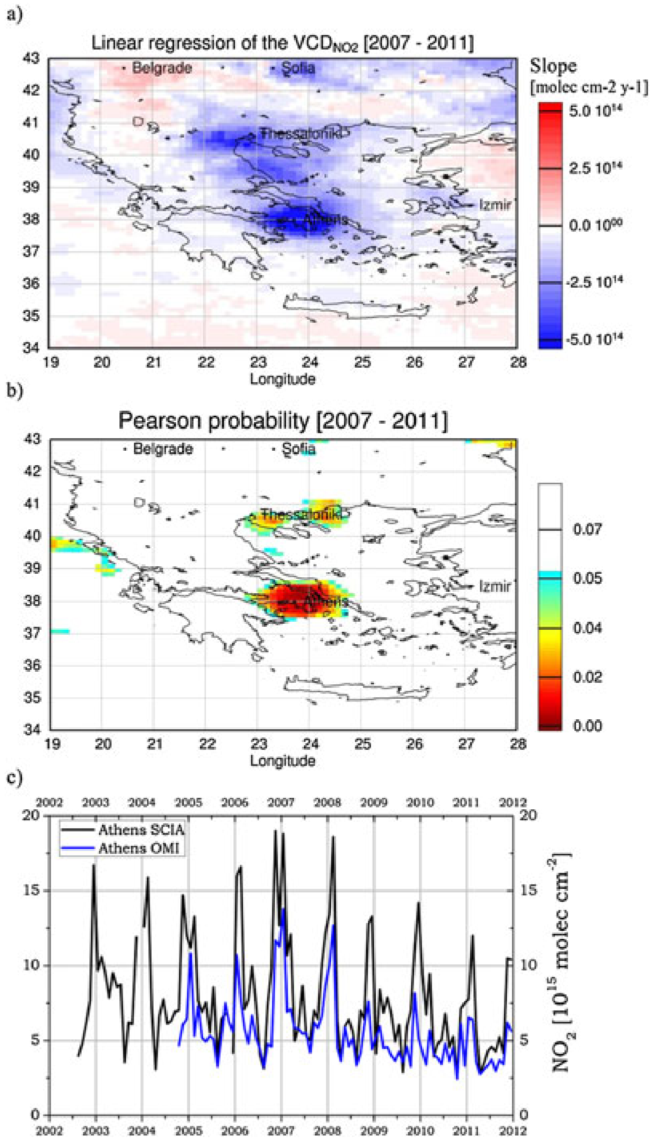

Figure 1. (top row) Linear regression of the annual averages of the nitrogen dioxide vertical columns retrieved for the period 2007–2011. Red color denotes an increase and blue a decrease in VCD_{NO2} values. Middle row presents the Pearson probability of the linear regression; dark red color denotes statistical significant linear correlations ($a < 0.05$). Bottom row depicts the monthly mean averages of the NO_2 vertical column densities over Athens [23.750 ± 0.125E, 38.000 ± 0.125N] derived using the SCIAMACHY (black line) and the OMI (blue line) data.

[11] Since 2008, the overall tropospheric VCD_{NO2} decrease over Athens, derived from the three independent satellites, was calculated to be in the range 30%–40%. Reductions of 20%–30% have previously been reported throughout Europe for the year 2010 compared to the reference year 2005 [*Castellanos and Boersma*, 2012] and were mainly attributed to the reduction prompted by the economic crisis and European emission controls. However, contrary to the Greece case, the authors reported that the reductions slowed down in 2010 possibly due to the economic recovery. Similarly, accelerated reductions have been also reported for the US during the economic crisis (2007–2009) which have slowed down or even, in some cases, reverted during the economic recovery [*Russell et al*., 2012].

[12] In addition to the observed decrease of VCD_{NO2} over Athens, the temporal variability of surface concentrations of key pollutants in Athens was investigated. Depending on their location, two categories of monitoring stations were distinguished: urban and suburban (Figure S1: supplementary material). Monthly and annual arithmetic average mixing rations of NO, NO_2, O_3, SO_2, and CO were calculated from hourly values during the 2004–2011 period. This includes three additional years (2004–2006) to test the representativeness of the results which were found in the first place but with the starting year 2007 for the linear analysis. Figure 2a–e illustrates the mean temporal tendency of these pollutants computed from the two categories of monitoring stations for the whole period of study (2004 to 2011). Overall, two distinct periods were identified: the first period was before the economic downturn (2004–2007) when small decreases were detected in the main gaseous pollutants (Figure 2a–d). This first period marks the effects of pollution abatement efforts which started about two decades ago. The second period (2008 and onwards) contains most of the long term economic crisis period for Greece when sharp decreases in all primary pollutant levels were observed. On the average, during the economic crisis period, a $32 \pm 5\%$ reduction of surface NO_2 levels is recorded at the urban-traffic sites, equivalent to a decrease of the ambient NO_2 by 13 ppb_v. Similarly, in suburban areas, the corresponding figures were $35 \pm 6\%$, and 5 ppb_v NO_2, respectively. NO_2 is not the only pollutant that declined significantly; the average concentrations of both site types revealed consistent decreases in carbon monoxide, CO (by $25 \pm 14\%$), and sulfur dioxide, SO_2 (by $48 \pm 8\%$). The concentration of those three key pollutants has been directly compared with the officially reported EMEP emissions (European Monitoring and Evaluation Programme, http://www.emep.int/) (Figure 2f). Excellent agreement was found between the reported reduction in NO_x, SO_x, and CO emissions (2008–2010), equal to 23%, 51%, and 23%, respectively, and the average reduction of the NO_2 (25%), SO_2 (49%), and CO (21%) concentrations computed with the same temporal resolution.

[13] In contrast, an average increase in surface ozone levels by $25 \pm 15\%$ is recorded, most likely owing to the decreased titration by nitrogen monoxide as NO mixing ratios decreased by $25 \pm 16\%$. Application of the Mann-Kendall statistical trend analysis [*Gilbert*, 1987] revealed a significant reduction ($a < 0.05$) in NO_2 and SO_2 during the economic downturn period reaching 2.3 ± 0.2 ppb_v y^{-1} and 0.7 ± 0.1 ppb_v y^{-1}, respectively. For the same period, a significant ($a < 0.10$) decrease has been computed for NO (2.2 ± 0.5 ppb_v y^{-1}) and CO (0.08 ± 0.02 ppm_v y^{-1}); in contrast, for ozone an increase equal to 1.4 ± 0.3 ppb_v y^{-1} was calculated ($a < 0.10$). For comparison, before the economic crisis period (2000–2007) a significant ($a < 0.10$) decrease was observed only for NO_2 (0.3 ± 0.2 ppbv y^{-1}) and SO_2 (0.2 ± 0.1 ppb_v y^{-1}) attributed to the air pollution abatement strategies following the European emission controls; from the above, it is concluded that (a) the annual reduction in NO_2 and SO_2 concentrations has been accelerated by 7.5 and 3.5 times during the period 2008–2011, compared to the most recent period prior the economic crisis and (b) the reported accelerated annual reduction in both NO_2 and SO_2 concentrations and EMEP emissions (Figure 2f) should be due to the economic recession effects since no additional

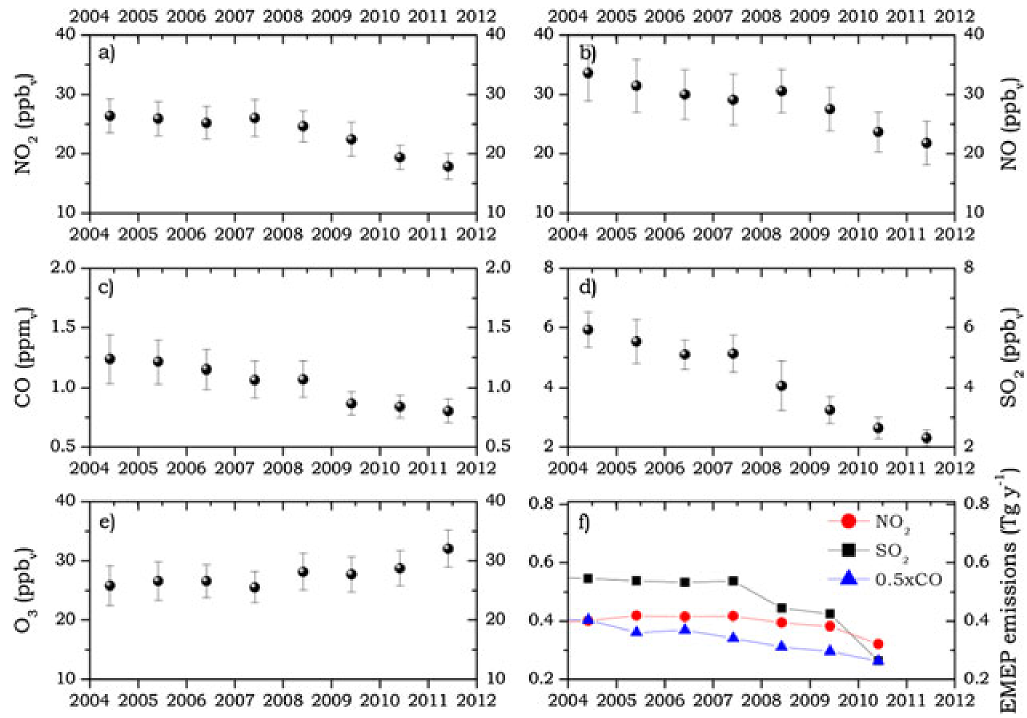

Figure 2. Annual means of air pollutants in Athens. First, second, third, fourth, and fifth panel depict the annual averages of the ground-based measurements of NO_2, NO, CO, SO_2, O_3, respectively. Black thin lines denote the annual standard deviations. Sixth panel presents the official EMEP emissions of NO_x (as NO_2 emissions, red circles), SO_x (as SO_2 emissions, black squares) and CO (blue triangles) over Greece.

mitigation strategies have been introduced after 2008. Quantitatively, an additional annual reduction equal to 2 ppbv y^{-1} and 0.5 ppbv y^{-1} in the observed NO_2 and SO_2 concentrations (2008–2011) topped up the above mentioned reductions attributed to the mitigation control strategies of the period 2000–2007.

[14] The computed accelerated negative slope in NO_2 and SO_2 is in good agreement with various economic metrics of anthropogenic activity. Figures 3a and 3b illustrate the annual variability of the oil consumption per day (source: Statistical Review of World Energy, http://www.bp.com), the Industrial Production Index (IPI, El-stat) and the Gross Domestic Product (GDP, source: European Commission Statistics, Eurostat, http://epp.eurostat.ec.europa.eu/) for Greece, together with the average in-situ NO_2 and SO_2 concentrations and the space-based VCD_{NO2} observations presented before. The sharp decrease in oil consumption (~100 kbarrels d^{-1}) in the economic downturn period is related to the continuous increase of oil price (not shown here) and the subsequent reduction of private car use. The GDP is a measure of the economic activity, defined as the value of all goods and services produced minus the value of any goods or services used in their creation, while IPI measures the real production output of manufacturing, mining, and utilities including the energy sector. The economic recession is reflected in the accelerated downward slope of all indicators (Figures 3a and 3b and Table ST1). It has to be noted that almost half of the population of Greece is concentrated in the capital of Athens, and thus, the majority of traffic and other economic activities related to emissions are spread in and around Athens basin.

[15] Interestingly, during the recession period, the annual averages of the in-situ observations of NO_2 significantly correlate (Table ST2) with IPI ($R^2 = 0.94$) and oil consumption ($R^2 = 0.96$) while the respective correlation with GDP is somewhat lower but still significant ($R^2 = 0.86$). Furthermore, a good correlation is also computed for the surface NO_2 measurements and the satellite tropospheric VCD_{NO2} observations ($R^2 = 0.91$); the latter is indicative of the good temporal agreement between the local emissions, tracked via the ambient in situ measurements, and the space-based observations. From the above, it is concluded that the observed decrease in ambient NO_2 levels is explained by lower NO_x emissions attributed to reductions in: (a) on-road traffic due to increased oil prices, economic factors, and the subsequent drop in oil consumption and (b) industrial activities and energy use. In fact, a large number (up to 30%) of small-scale industries and enterprises around Athens ceased their activities adding both directly, via reduced industrial emissions and indirectly, via reduced on-road traffic, to the reduction in NO_x emissions. Similarly, significant correlations were also observed between SO_2 concentrations and IPI ($R^2 = 0.95$), GDP ($R^2 = 0.95$), and oil consumption ($R^2 = 0.83$). *Markakis et al*. [2010] showed that more than 70% of the SO_2 in Athens emanates from industrial processes including energy use and residential combustion. In addition, since the beginning of the economic downturn, an increase in natural gas consumption (+25%: Eurostat) associated with a decrease in oil consumption (−15%: Eurostat) occurred. All the above clearly indicate, that the drastic reduction (50%) in SO_2 levels in Athens is closely related to the economic recession.

4. Conclusions

[16] The economic crisis in Greece (from 2008 and onward) resulted in a reduction of anthropogenic activities emitting

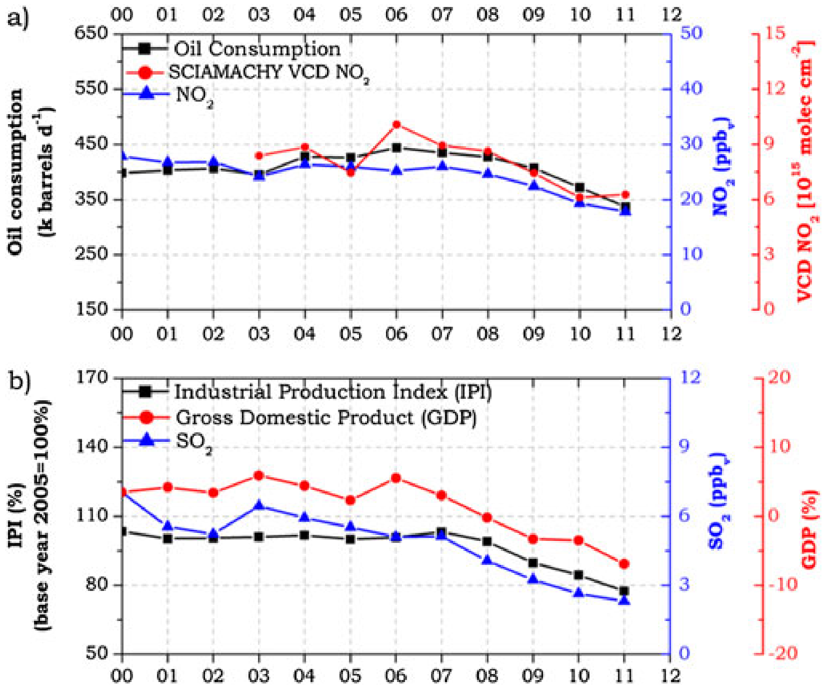

Figure 3. The top row (a) presents the annual means of nitrogen dioxide levels (NO_2) over Athens (blue) compared to the tropospheric SCIAMACHY VCD_{NO2} (red) and the oil consumption per day (black). The bottom row (b) depicts the annual means of sulfur dioxide (SO_2) levels in Athens (blue), the Gross Domestic Product of Greece (red) and the Industrial Production Index, IPI (black).

gaseous pollutants to the atmosphere. Observations derived from three different satellite instruments (SCIAMACHY, GOME-2, and OMI) revealed a large reduction (about 30–40%) in the tropospheric NO_2 vertical columns observed over Athens as well as decreases over other densely populated regions of Greece (e.g. Thessaloniki). Surface in-situ observations of nitrogen dioxide corroborate the above findings. On average, during this period of economic downturn, NO_2 concentrations dropped by 31% equivalent to a decrease of the ambient NO_2 levels by 13 ppb_v. SO_2 levels have also been reduced by 48%, from 13.5 ppb_v to 7 ppb_v.

[17] The strong correlations between pollutants measured by satellite and ground-based instruments and several indicators of economic activity (Gross Domestic Product, Industrial Production Index and Oil Consumption) that may serve as proxies of emissions to the atmosphere, may corroborate that the economic recession has resulted in proportionally reduced levels of pollutants over large areas of Greece.

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