"Paper submitted and under evaluation"

Comparison between economic growth and satellite-based measurements of NO_2 pollution over northern Italy

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INTRODUCTION

Since 1955, with the development of the Environmental Kuznets Curve (EKC) the effects of economic activity on environmental degradation has been an issue and gained attention especially in the context of climate change. In particular, the COVID-19 pandemic impressively showed how economic activity can affect the environment.

An established indicator of economic activity is the concentration of nitrogen dioxide, NO_2, in the lower atmosphere, as it is produced during combustion processes. This study investigates the variability of NO_2 from 1996 to 2021 over northern Italy and compares it with that of the gross domestic product (GDP).

Data

Monthly mean NO_2 tropospheric column densities are used based on the TEMIS data product for the successive satellite missions: ERS-2 (GOME), Envisat (SCIAMACHY), MetOp-A (GOME-2A), and MetOp-B (GOME-2B). The overpass times for these satellites are all in the range of about 09:30h to 10:30h (CET). As a result the time series of NO_2 covers the period from 1996 to 2021 (see Figure 1).

The information about the economic development in Italy are described by the gross domestic product (GDP) provided by the OECD. GDP data is provided as quarterly data.

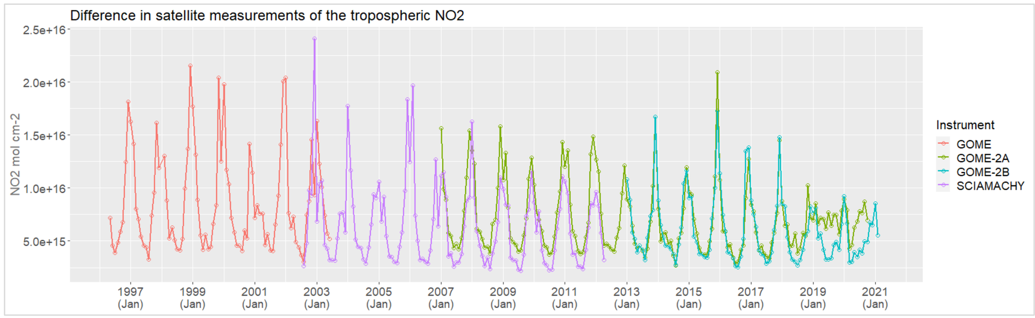

Figure 1: Tropospheric NO_2 column density measurements from ERS-2 (GOME), Envisat (SCIAMACHY), MetOp-A (GOME-2A) and MetOp-B (GOME-2B) from 1996 to 2021 for northern Italy (Po valley).

Area of Interest (AOI)

The AOI in this study is northern Italy because of the orographic characteristics (enclosed by mountains acting as kind of a barrier for air flows frequently leading to an accumulation of NO_2 in the Po valley) and its dominating share of Italy's GDP. As a typical example for such a situation, the Figure 2 shows the spatial distribution of NO_2 column density as a monthly average for January 2020 over this area, measured by the GOME-2B instrument. The AOI is highlighted with a red rectangle. The NO_2 pollution around the cities such as Milan and Turin or the area around Bergamo, Brescia, Verona, and Venice are clearly visible as they are mostly located in the higher polluted (red and orange) regions.

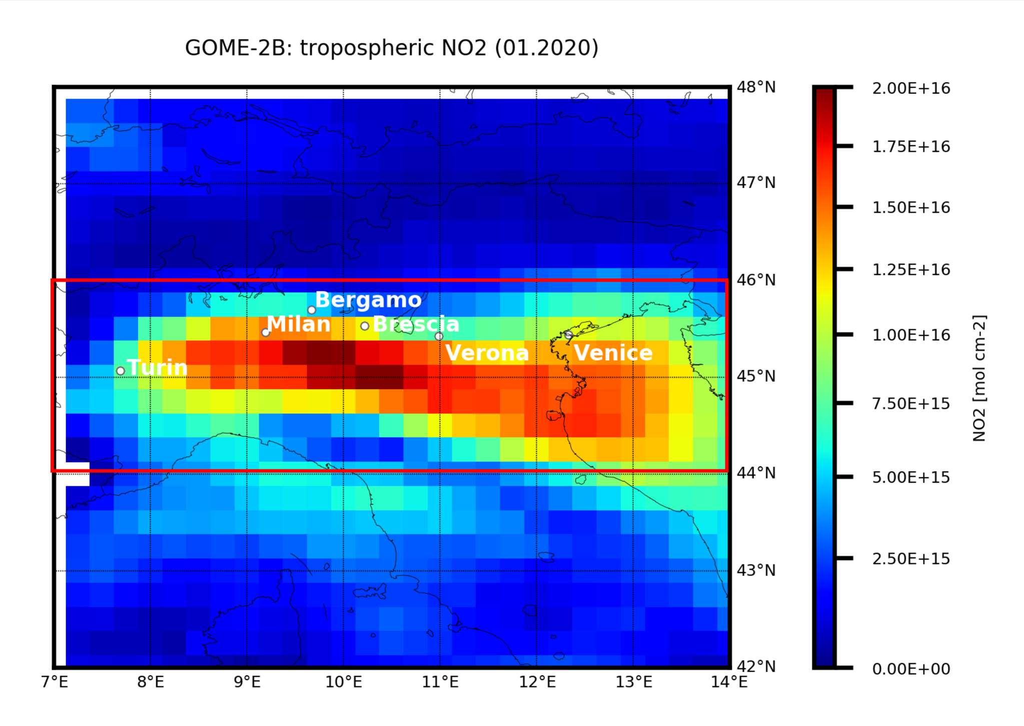

Figure 2: Tropospheric column NO_2 density for northern Italy measured by the GOME-2B instrument on board of MetOp-B (January mean, 2020).

METHODS

The focus of this study is on the identification of characteristic temporal variations that are simultaneously present in the time series of the tropospheric NO_2 column density as well as in the time series of the gross domestic product. We use the following spectral analysis methods for this purpose:

Harmonic Analysis (HA)

HA is a well-established spectral method. According to equation (1), e.g. the NO_2 time series can be broken down into a linear combination consisting of sine and cosine functions. The oscillation parameters are adjusted according to the least squares principle. The method is used to remove seasonal variations (annual and semi-annual) from the NO_2 data. This is done separately for each year, since in particular the amplitudes vary from year to year.

$$[NO_2](t) = \sum_{i=1}^{n} A_i \cdot sin\left(\frac{2\pi}{\tau_i}\, t + \varphi_i\right) \quad (1)$$

A_i is the amplitude of the *i-th* oscillation, τ_i is the period and φ_i is the phase.

Wavelet Analysis (WA)

WA is a powerful tool for examining a time series for possible periodic or quasi-periodic signals and is given in equation (2). The advantage of this method compared to a classic Fourier transformation or the HA described above is that the time series under study can also be "non-stationary" from a statistical point of view. In fact, the time series of NO_2 distribution and GDP examined in this study prove to be – to some degree - non-stationary, since their statistical moments (mean, variance, skewness) can change over time. The wavelet analysis has often proven to be a robust and suitable tool in such cases. It delivers a quasi-time-resolved spectrogram and does not average the spectral properties of the entire data series.

$$S(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\, h\left[\frac{t-b}{a}\right] dt \quad (2)$$

$f(t)$ is the time series, h is the basic wavelet with a the dilation-scale factor and b the translation in time.

Within this analysis we used a Morlet wavelet.

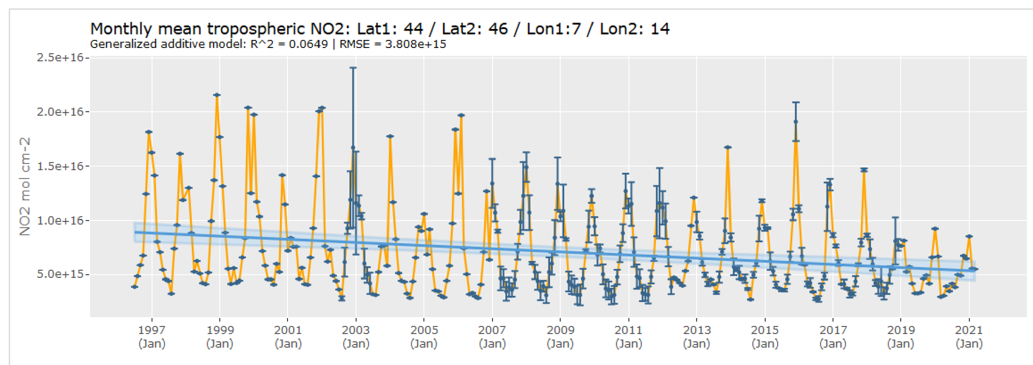

Figure 3: Tropospheric NO_2 column density time series (monthly means) from 1996 to 2021 based on satellite measurements from GOME, SCIAMACHY, GOME-2A and GOME-2B; The blue line presents a cubic spline; bars show the deviations of the different satellite measurements.

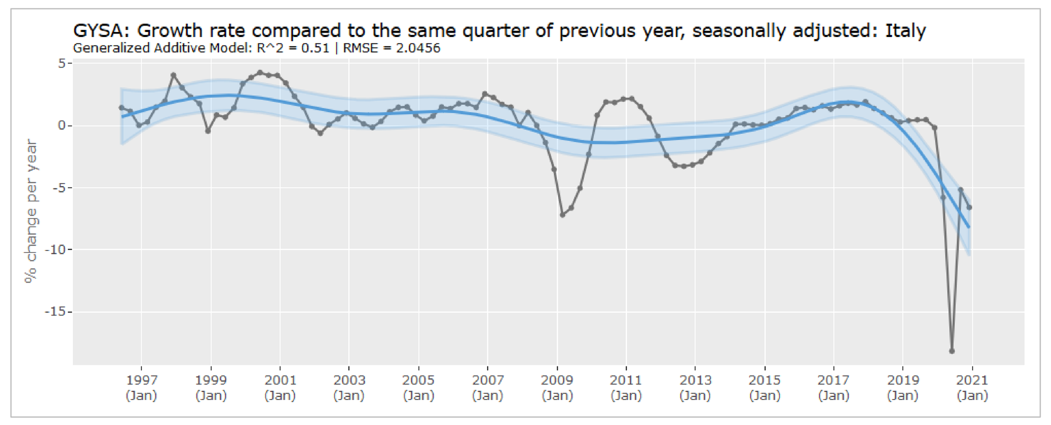

Figure 4: Quarterly change of the economic growth rate for Italy from 1996 to 2021

RESULTS I

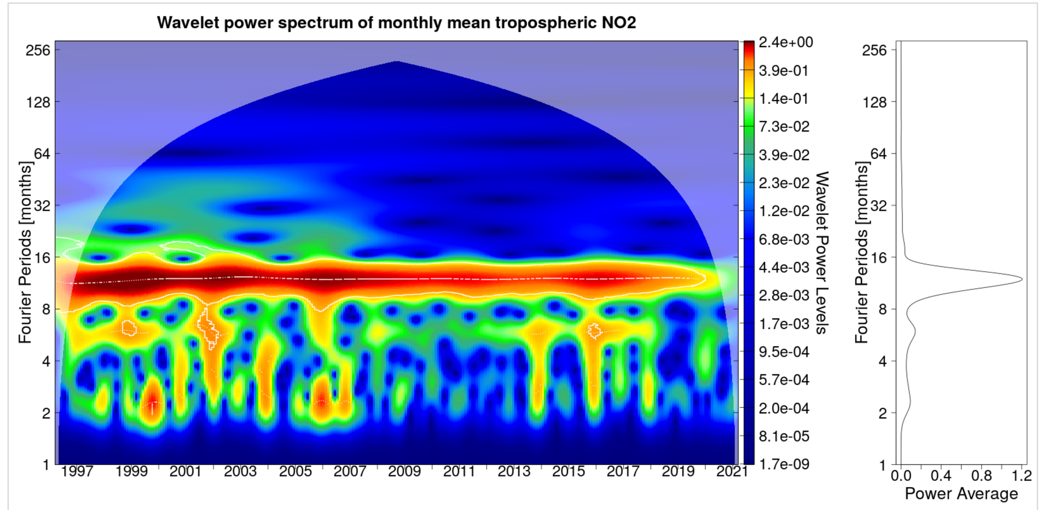

Figure 5: left - Wavelet spectrogram for the monthly mean NO_2 column density time series; red/blue colors indicate high/low spectral densities; right – integrated wavelet power density over the course of the time series

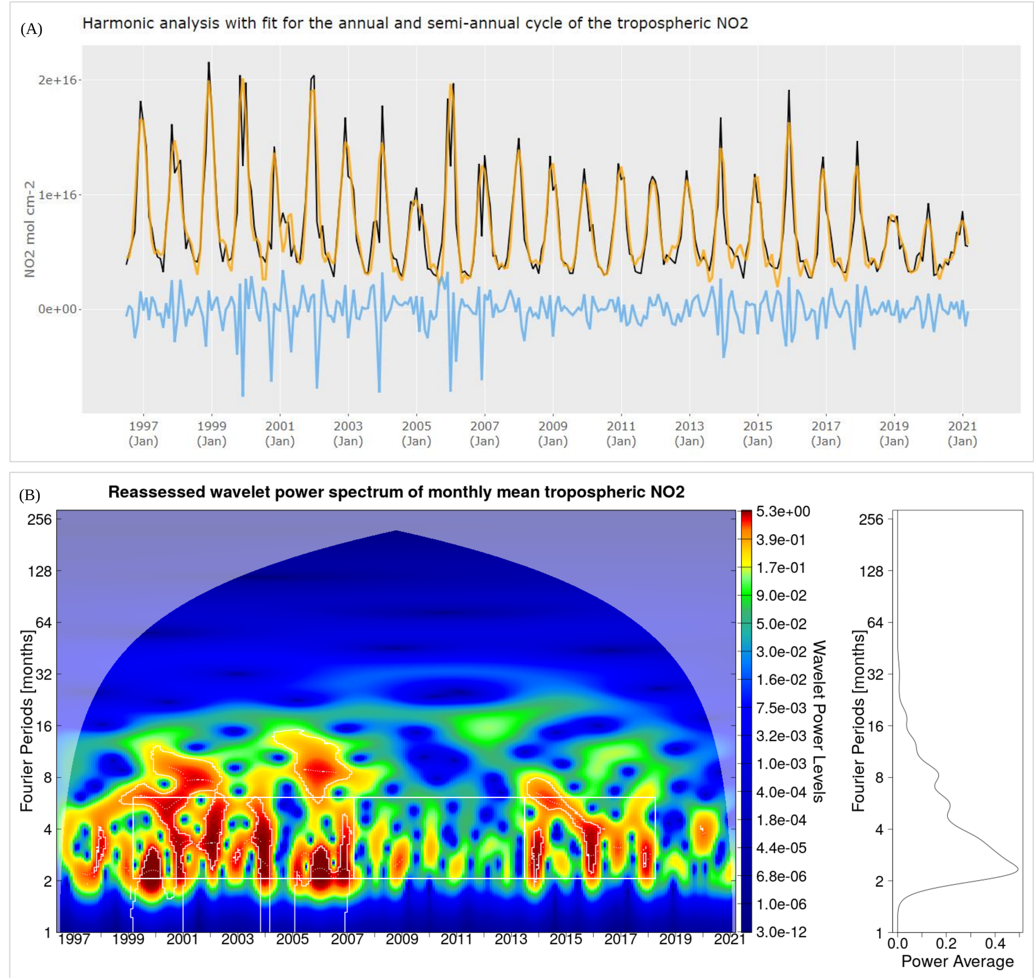

Figure 6: (A) Orange line presents the annual and semi-annual fit of the harmonic analysis; blue line represent the residuals; (B) Wavelet power spectrum of the monthly mean NO_2 column densities without the annual and semi-annual cycle (residuals)

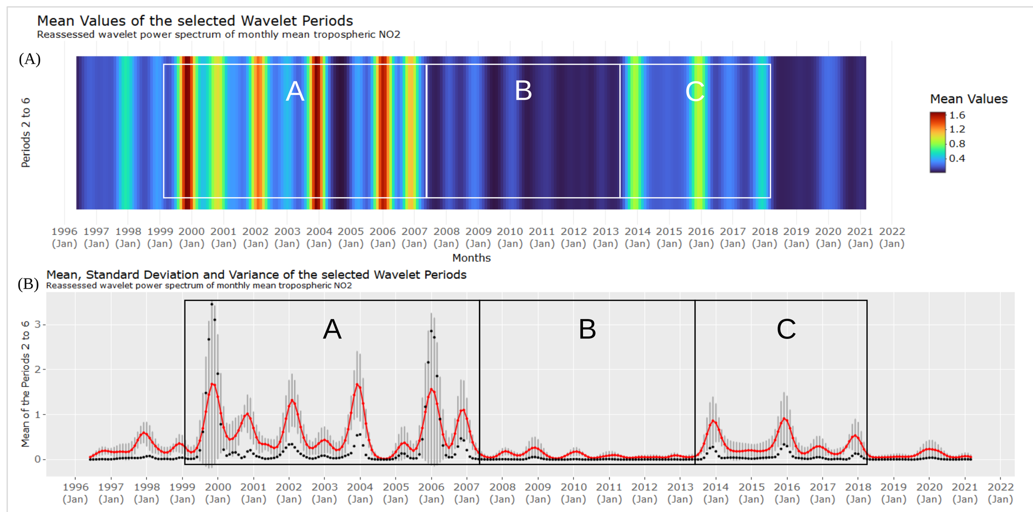

Figure 7: (A) Calculated mean values of the wavelet analysis (Fig. 6B) for the periods two to six; (B) red line presents the mean values of the wavelet analysis (Fig. 6B) for the periods between two to six; gray bars represent the standard deviation based on the mean values; black dots show the variation

Findings between a periodicity from 2 to 6 months

Preceding time interval – **A**
(beginning 1999 to mid-2007)

Crisis time interval – **B**
(mid-2007 to mid-2013)

Succeeding time interval – **C**
(mid-2013 to almost mid-2018)

- ➢Reduction* from A to B = **84,90%**
- ➢Reduction* from C to B = **72,25%**

*reduction in integrated spectral intensity of the fluctuations of the tropospheric NO_2 column density

RESULTS II

The temporal development of the tropospheric NO_2 column density is characterized by a long-term decrease of about 40% since 1996 which is in good agreement with ground-based station measurements (not shown here). A clear annual cycle is superimposed on this (Figures 3, 5). In order to study the fluctuations in the NO_2 time series and to exclude possible effects of seasonal variation on the analysis the annual and semi-annual cycles were removed by means of the HA (Figures 6A). The resulting spectrogram (Figures 6B) exhibit remarkably low spectral densities between about 2008 and 2014 for periods in the range below of about six months. To ensure that systematically increased cloud cover did not mask the NO_2 measurements during this period, cloud cover was analyzed for the entire period of the data series on the basis of ERA-5 reanalysis data. No systematic influences were found. We therefore take the finding seriously. The comparison with the temporal course of the gross domestic product shows that the period of systematically reduced spectral intensity in NO_2 coincides strikingly well with the period of the global financial crisis in 2008 which was then followed by a decline in foreign investment until about 2014 (Figure 4). At that time (2007-2009), the economic growth decreased by almost 8% in comparison to the same quarter of the previous year.

CONCLUSIONS

We tentatively conclude that the spectral analysis of fluctuations in NO_2 is an apparently very sensitive indicator of fluctuations in economic activity. The use of globally available NO_2 data sets should thus in principle allow changes in economic activity to be recorded in any region of the Earth. Such an indicator could help to monitor not only global economic development, but possibly also the transition in regions between different levels of economic development (primary, secondary and tertiary economic sector).

The strength of satellite-based observations lies on the one hand in the global coverage and on the other hand in the self-consistency of the measurements (uniform standard). However, they only give us information about the tropospheric NO_2 column density; information on ground-level air quality is not available and transport effects are masked to a certain extent. Furthermore, satellite overpasses usually occur only at a specific time of the day. The daily cycle of NO_2 (including the effect of traffic rush hours etc.) for instance can therefore not be analyzed by using satellite data only.

The synergistic use of satellite-based and ground-based measurements is therefore a way to further improve the analyses presented here.

ACKNOWLEDGEMENTS

We acknowledge the free use of tropospheric NO_2 column data from the GOME, SCIAMACHY, GOME-2A and GOME-2B sensor from www.temis.nl

This work has been supported by the DLR/DAAD Research Fellowship – Doctoral Studies in Germany funded by the German Academic Exchange Service (DAAD, No. 57478193).

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