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# The relationship between Carbon dioxide ($CO_2$) /derived/ from SCIAMACHY.ENVISAT-1, meteorological parameters, and vegetation indices – case study of Poland

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**Abstract**. The requirement for information concerning air quality with special attention to $CO_2$ concentration is increasing in different fields of research. Satellite observations could provide information on gases which for special areas could be provided with high temporal resolution. One of the sources of measurements of $CO_2$ was the *SCIAMACHY.ENVISAT-1* (the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) sensor. The study that has been introduced as part of the National Project (1600/B/T02/2011/40) of the Institute of Geodesy and Cartography: "Application of new generation satellite data for the assessment of the impact of soil moisture and biomass on carbon balance" relates to the application of $CO_2$ measurements by the SCIAMACHY sensor for the environment. The main objective of the Project was to use the satellite data as an input to the model of assessing carbon balance. Unfortunately it was not possible to obtain the data from the satellite at the time of carbon in-situ measurements. The paper presents the relationships performed between $CO_2$ values derived from SCIAMACHY data and meteorological parameters measured at ground stations throughout Poland. Also presented is the relationship between $CO_2$ and the vegetation index (NDVI) calculated from NOAA satellites, and between $CO_2$ concentration and the percentage of forest cover in NUTS2 regions in Poland. The correlation between $CO_2$ and air temperature $T$ has been found to be significant, as well as that between $CO_2$ and net radiation $R_n$. In the regional scale it was also concluded that the percentage of forest areas determines the concentration of $CO_2$ in the air. In addition the seasonal correlation of $CO_2$ and NDVI was determined. This research might be a contribution for the further analysis of air quality using the Sentinel – 4 and 5 of the COPERNICUS Programme.

**Keywords:** SCIAMACHY, $CO_2$, meteorological parameters, air temperature, NDVI, radiation, correlation

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## 1. Introduction

The study has been carried out as a part of the National Project (1600/B/T02/2011/40): „Application of new generation satellite data for the assessment of the impact of soil moisture and biomass on carbon balance". One of the Project's objectives was to use the satellite data as an input to the model of assessing carbon balance. The values of $CO_2$ and $CH_4$ content derived from data collected by the SCIAMACHY.ENVISAT-1 (the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) sensor were an important source of information both to estimate the carbon balance, and to verify data obtained from satellites by means of data measured at the ground; the data were used to present the spatial distribution of $CO_2$ over wetland and agriculture areas. Many studies have been con-

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ducted with the usage of SCIAMACHY datasets by a group of scientists from the University of Bremen, where they have developed the algorithms for SCIAMACHY measurements (Reuter et al., 2011). Throughout the research the calibration of the data from SCIAMACHY was done and compared with the ground measurements, for example atmospheric $CO_2$ from SCIAMACHY was compared to ground-based Fourier-transform infrared spectrometers (Dils et al., 2006; Barkley et al., 2006). For ecological studies, the researchers from the National Academy of Sciences of Ukraine, used the SCIAMACHY data for evaluation of vegetation cover change and estimated the contribution of vegetation to the greenhouse effect as a Case Study for Ukraine (Lyalko et al., 2009). They estimated the character of $CO_2$ changes in the atmosphere and the quantity of atmospheric $CO_2$. The behaviour of the terrestrial biosphere was examined by the exploration of the correlation between the spatial distribution of SCIAMACHY $CO_2$ and land vegetation cover over the USA (Barkley et al., 2007). Also, Wang et al. (2011) analysed the spatial and temporal distribution of carbon dioxide using SCIAMACHY observation in regard to land use and vegetation indices. The usage of data from the SCIAMACHY instrument, despite the not very high accuracy (Guo et al., 2012), might give a new look at climate change studies by examining their relationships with data from other sources. The goal of the following study was to assess the relationship between carbon dioxide ($CO_2$) and meteorological and vegetation parameters in Poland.

## 2. Data set

### 2.1. Satellite (imagery) data – SCIAMACHY.ENVISAT-1

The following description presents the results of computing mean $CO_2$ values. The task was performed for the ESA PECS CARBON and National Project (1600/B/T02/2011/40). The projects were carried out by the Institute of Geodesy and Cartography (IGiK); two test sites were chosen for the investigation of carbon balance. However, it was impossible to download the data from SCIAMACHY at a required time-window – during the years of field measurements (2010–2011) no points due to the location of SCIAMACHY registrations were found to compare at the test sites (just only 1 point was found at the Greater Poland Voivodeship's test site.) – see Figure 1. The authors decided to pick a data span over the area of Poland irrespective of the time requirement. The data were derived from SCIAMACHY.ENVISAT-1. The SCIAMACHY instrument was launched on board ENVISAT and was operational from March 2002 to April 2012. This passive remote sensing spectrometer was designed to investigate atmospheric composition and processes (Barkley et al., 2007) for measuring backscattered, reflected, and transmitted, or emitted radiation from the atmosphere and Earth's surface. The radiation values were recorded in the ultraviolet, visible, and NIR spectral regions (240–1750 nm, 1940–2040 nm, 2265–2380 nm) throughout 8 detector modules with moderate spectral resolution of 0.2–1.4 nm (Buchwitz et al., 2007). The objective of SCIAMACHY was the global measurement of various trace gases in the troposphere and stratosphere and the determination of aerosols and clouds. Additionally, the SCIAMACHY spectrometer allowed the detection of small optical absorptions; as small as $2E^{-4}$ in some regions of the spectrum (ESA, 2010). The measurements of a number of atmospheric constituents included:

- in the troposphere – $O_3$, $O_4$, $N_2O$, $NO_2$, $CH_4$, CO, $CO_2$, $H_2O$, HCHO and aerosols and, in polluted conditions, $SO_2$;
- in the stratosphere – $O_3$, $O_2$, $O_4$, NO, $NO_2$, BrO, $N_2O$, CO, $CO_2$, $H_2O$, $CH_4$ plus during a volcanic eruption $SO_2$, plus with ozone hole conditions OClO and ClO.

SCIAMACHY made spectral measurements in passive limb and nadir viewing in the following channels presented in Table 1.

Table 1. Spectral characteristics of the SCIAMACHY instrument

| Spectral bands | The wavelength range [μm] |
|---|---|
| 1–2 | 0.24–0.40 |
| 3 –5 | 0.40–1.00 |
| 6 | 1.00–1.70 |
| 7 | 1.94–2.04 |
| 8 | 2.265–2.38 |

The maximum swath width was 960 km and the typical single ground pixel was 30 km along track × 60 km across track. Also, polarization (Polarization Measurement Devices, PMD) was measured in several channels (ESA, 2010). The SCIAMACHY products are classified as Level 0, 1B or 2. For the study it was decided to choose the data concerning atmospheric $CO_2$ vertical columns ($XCO_2$) in the near infrared region retrieved through the Bremen Optimal Estimation Differential Optical Absorption Spectroscopy (BESD-DOAS) algorithm developed by the Institute of Environmental Physics (IUP), University of Bremen. BESD has been designed to analyse near-infrared nadir measurements of the SCIAMACHY instrument in the $CO_2$ absorption band at 1580 nm and in the O2-A absorption band at around 0.760 nm. The algorithm used measurements in the O2-A absorption band to gain scattering information of clouds and aerosols. This information was transferred to the $CO_2$ absorption band at 1580 nm by simultaneously fitting the spectra measured in both spectral regions. Therefore, by this approach, the explicit consideration of scattering reduces potential systematic biases due to clouds or aerosols (Reuter et al., 2013). $XCO_2$ is the column-average dry-air mole fraction of atmospheric $CO_2$ (Reuter et al., 2011), and was retrieved only if the pixel and the area of 40 km$^2$ in the vicinity were 100% cloud free. These data were downloaded for the years from 2006 to 2011, as is shown in Figure 1.

There is the significant lack of data during the satellite overpasses, and lack of data during the ground $CO_2$ measurements at the test sites.

## 2.2. Meteorological database

The meteorological database was acquired from the World Weather website *www.tutiempo.net/en*. This website is the world's largest archive of weather data, where meteorological data from stations around the world, including 116 stations in Poland, are available. The meteorological stations are distributed evenly (Fig. 2).

The following ten meteorological data parameters were downloaded:

1) daily average air temperature [°C],
2) daily maximum air temperature [°C],
3) daily minimum air temperature [°C],
4) mean sea level pressure [hPa],
5) mean of relative humidity [%],
6) quantity of precipitation [mm],
7) mean visibility [km],
8) mean wind speed [km/h],
9) maximum sustained wind speed [km/h],
10) maximum wind gust [km/h]).

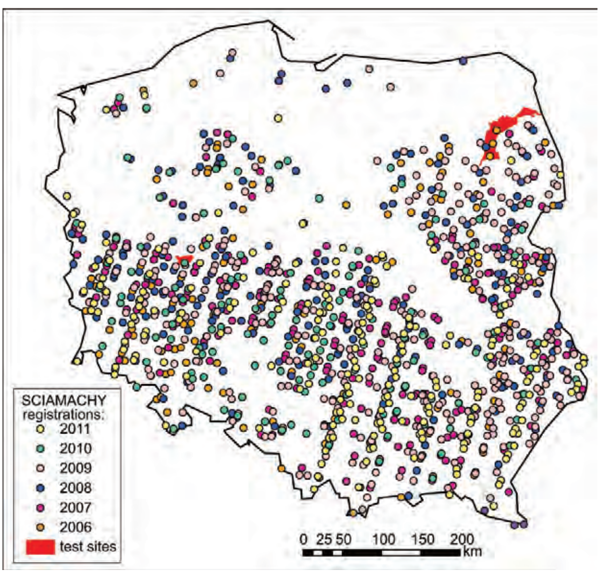


Fig. 1. Spatial distribution of SCIAMACHY $XCO_2$ measurements for Poland for the years 2006 to 2011

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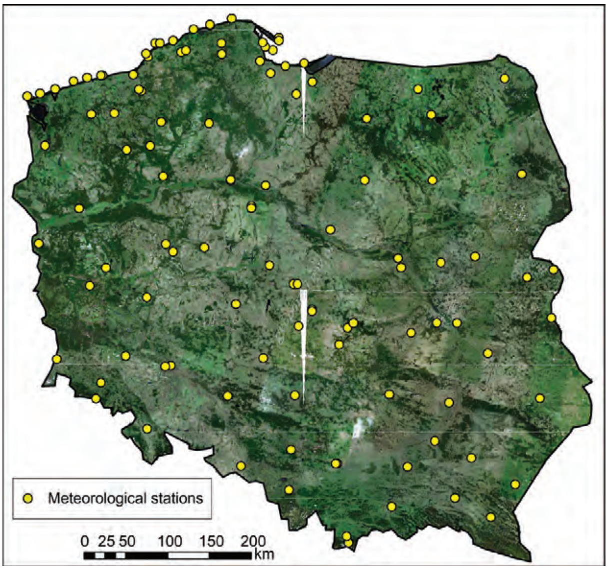


Fig. 2. Spatial distribution of Polish meteorological stations

Also, the indicators of rain, drizzle, snow/ice pellets, or thunder and fog occurrence were collected. The World Weather website includes additionally monthly and yearly means of meteorological data. Furthermore, the information about the height above sea level of meteorological stations and coordinates of station locations are specified.

### 2.3. Vegetation database

For this investigation information about vegetation as forest cover and the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974) were used. Forest cover is the indicator of woodiness at a specified area, expressed as a percentage value. The specified area (total area) refers to the Polish administration units NUTS2 (voivodeships). Data were gathered by the Polish Central Statistical Office. The Normalized Difference Vegetation Index (NDVI), that could be calculated from satellite data, describes the condition of plants, and is related to photosynthetic activity. The NDVI (the range is between –1.0 and 1.0) is calculated by dividing the difference in the near-infrared (NIR) and red band (RED) by the sum of the NIR and RED for each pixel.

## 3. Methodology

### 3.1. Processing of the SCIAMACHY data

After downloading, the data were processed into a different file format. The original files contain information, besides $XCO_2$, about the Solar and Viewing Zenith Angle, coordinates of measurements, surface elevation and pressure levels, and also the value of the profile of dry-air mole fraction of atmospheric $CO_2$ (VMR). The abundance of the original files' content forced the authors to select and extract necessary information to other datasets. To create the new database, the script written beforehand in *Visual Basic* for Applications (VBA) was used. This script selected information as $XCO_2$ values, and the coordinates and time of measurement. The original file format, NetCDF, was changed into text file format.

The time range of available data was from April until October and depended on the year. The number of measurements from all days is listed in Appendix 1. For daily data, the SCIAMACHY instrument gathered measurements through the swath over Poland. All possible SCIAMACHY acquisitions for the given years (Table 2) have been collected.

The daily data were computed into monthly average values. The monthly values were exported into the spatial shapefile format in ArcGIS Software (Fig. 1). Following these procedures, the $XCO_2$ database retrieved from SCIAMACHY.ENVISAT-1 was prepared.

Table 2. The quantity of SCIAMACHY $XCO_2$ measurements in 2006–2011

| Number of measurements | Quantity of days with measurements | Year |
|---|---|---|
| 137 | 21 | 2006 |
| 226 | 26 | 2007 |
| 195 | 23 | 2008 |
| 346 | 29 | 2009 |
| 141 | 11 | 2010 |
| 200 | 24 | 2011 |

## 3.2. Processing of meteorological parameters

The meteorological parameters (1–10, listed above in subsection 2.2) were downloaded and prepared at two time-resolutions. The first database included all daily data from the years 2006 to 2011; the second one consisted of the dates with respect to the $XCO_2$ SCIAMACHY acquisitions. From the daily meteorological data, the monthly averages were calculated.

Daily meteorological parameters for Polish stations were downloaded from *www.tutiempo.net/en* website and converted to Data Base Files with the use of Python scripts.

On the basis of the gathered data extraterrestrial radiation $R_a$, solar radiation $R_s$, net radiation $R_n$, and water pressure deficit $e_s - e_a$ were calculated (Allen et al., 1998) using Python scripts.

Extraterrestrial radiation $R_a$ is the solar radiation received at the top of the Earth's atmosphere on a horizontal surface. $R_a$ could be calculated by the following equation:

$$R_a = \frac{24\,(60)}{\pi} G_{so} d_r \left[\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s\right] \quad (1)$$

where

$G_{so}$ – solar constant = 0.0820 [MJm$^{-2}$min$^{-1}$],

$d_r$ – inverse relative distance Earth-Sun:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} J\right),$$

$\omega_s$ – sunset hour angle: $\omega_s = \arccos(-\tan\varphi \tan\delta)$,

$\varphi$ – latitude [rad]: radian $= \frac{\pi}{180}$,

$\delta$ – solar decimation [rad]: $\delta = 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right)$,

$J$ – the number of the day in the year between 1 and 365 or 366.

Solar radiation $R_s$ is the amount of radiation reaching the horizontal plane. The value of $R_s$ can be derived from air temperature differences by the Hargreaves' radiation formula (Allen et al., 1998)

$$R_s = 0.16\sqrt{(T_{\max} - T_{\min})}R_a \quad (2)$$

where 0.16 is the adjustment coefficient [°C$^{-0.5}$] for interior locations.

Net radiation $R_n$ is the difference between incoming and outgoing short and long wave radiation (Allen et al. 1998):

$$R_n = R_{ns} - R_{nl} \quad (3)$$

with

$$R_{ns} = (1 - 0.23)R_s \quad (4)$$

$$R_{nl} = \sigma\left[\frac{T^4_{\max K} + T^4_{\min K}}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\cdot \left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad (5)$$

$$R_{so} = (0.75 + 2 \times 10^{-5} z)R_a \quad (6)$$

where

$\sigma = 4.903^{-9}$ [MJ K$^{-4}$m$^{-2}$day$^{-1}$] – Stefan-Boltzmann constant,

$T_{\max K}$ – maximum absolute temperature during the 24-hour period (K = °C + 273.16°),

$T_{\min K}$ – minimum absolute temperature during the 24-hour period (K = °C + 273.16°),

$e_a$ – actual vapour pressure [kPa],

$R_{so}$ – calculated clear-sky radiation [MJ m$^{-2}$ day$^{-1}$],

$z$ – station elevation above sea level [m].

The water pressure deficit is the difference between the saturation $e_s$ and actual vapour pressure $e_a$. It is dependent on the saturation vapour pressure at the maximum $e°(T_{\max})$ and minimum $e°(T_{\min})$ temperature as well as humidity $H$ (Allen et al., 1998):

$$e_s = \frac{e°(T_{\max}) + e°(T_{\min})}{2} \tag{7}$$

$$e_a = \frac{H_{\text{mean}}}{100}\left[\frac{e°(T_{\max}) + e°(T_{\min})}{2}\right] \tag{8}$$

where

$$e°\,(T) = 0.6108\exp\left[\frac{17.27T}{T + 237.3}\right] \tag{9}$$

is saturation vapour pressure at the air temperature.

There are differences between the location of meteorological stations and the areas of SCIAMACHY registration, so the investigation was done at the country and at the regional scale. The values were averaged for the whole country, as well as for Polish NUTS2 (voivodeships).

### 3.3. Processing of vegetation parameters

The forest cover for the year 2010 was acquired from the Polish Central Statistical Office (Statistical Yearbook, 2011). The NDVI was calculated on the basis of NOAA/AVHRR images collected at the Institute of Geodesy and Cartography. The IGiK's system produces every ten days a raster map with 1000 m ground resolution. The aggregated values of NDVI were done for the Polish administrative units NUTS2. These ten days' data were recalculated and averaged to mean monthly values.

## 4. Results

Daily means of SCIAMACHY values of $XCO_2$ were calculated and compared with daily values of downloaded and calculated meteorological parameters. The Pearson correlation coefficient was calculated for each of the relationships between $XCO_2$ and a given meteorological parameter. These processes were done for the whole of Poland (NUTS0) and also for NUTS2.

Table 3 shows the results of the relationships between daily $XCO_2$ values (1074 samples) and particular meteorological parameters for the whole country.

Table 3 presents the correlation coefficients and the levels of significance for the relationships between daily $CO_2$ values and particular meteorological variables. The best relationship is found between $CO_2$ and air temperature $T$ and between $CO_2$ and net radiation $R_n$. A less significant correlation is found between $CO_2$ and water pressure deficit $e_s - e_a$ values.

The correlation between carbon dioxide $CO_2$ measured by the SCIAMACHY spectrometer and daily mean air temperature measured at the meteorological stations is negative (the correlation coefficient is –0.400), which means that with the increase in the air temperature the values of $CO_2$ are decreasing (Fig. 3). The air temperature oscillated between 5°C and 25°C.

Figure 4 presents the monthly averaged distribution of carbon dioxide concentration over Poland from 2006 to 2011. It should be noted that the seasonal variability of $CO_2$ measured by SCIAMACHY exists.

The peak values of $CO_2$ were found in April and May in each considered year and the lowest values were obtained in August and September also in each considered year.

The correlation between carbon dioxide and net radiation is positive, which means that with the increasing values of carbon dioxide, values of net radiation also increase. In these cases net radiation is related to the solar radiation so in consequence to the amount of radiation used for photosynthesis and biomass production. In general it could be stated that high biomass may absorb more $CO_2$. The relationship is presented in Figure 5.

Table 3. Results of the relationship between daily $CO_2$ values and particular meteorological parameters for Poland

| Variable | | Correlation coefficients $r$ and significance level $p$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | $T_{\text{mean}}$ [°C] | $H_{\text{mean}}$ [%] | $R_{a\ \text{mean}}$ [MJ/m²/day] | $R_{s\ \text{mean}}$ [MJ/m²/day] | $e_s - e_{a\ \text{mean}}$ [kPh] | $R_{n\ \text{mean}}$ [MJ/m²/day] |
| $XCO_2$ [molecules/cm²] | $r$ | –0.4003 | –0.2282 | 0.1961 | 0.0800 | –0.0569 | 0.5523 |
| | $p$ | 0.000 | 0.000 | 0.000 | 0.009 | 0.062 | 0.000 |

The relationship between carbon dioxide and water pressure deficit $e_s - e_a$ is the weakest. The correlation coefficient oscillates around 0, which means no relationship (Fig. 6). Probably it results from the different time of the data collection – data from SCIAMACHY were collected for a particular time (10:00 a.m. local time) while $e_s - e_a$ calculations were performed for the maximum (about noon) and minimum (early morning) temperature.

The same statistical analyses were performed for each of the administrative divisions of NUTS2 (voivodeships) separately (Table 4).

The higher correlation coefficient is when there is a larger quantity of the measurements. It should be stated that the type of land use has a substantial influence on $CO_2$ sequestration (Wang et al. 2011). Especially forest areas determine the amount of $CO_2$ in the atmosphere, because trees are one of the largest

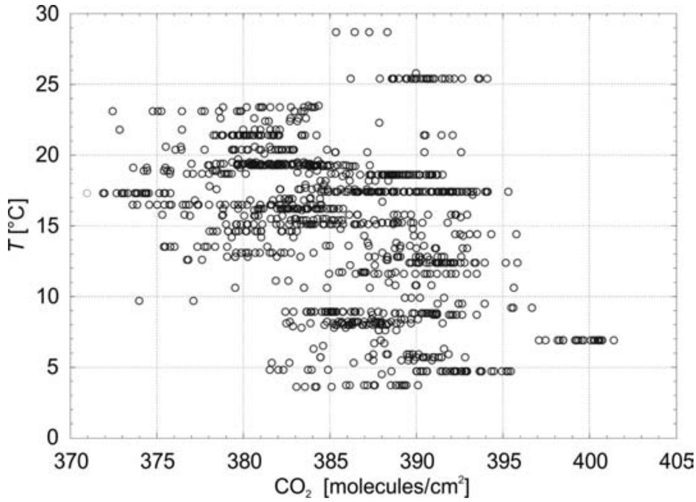


Fig. 3. Relationship between daily SCIAMACHY registration of $CO_2$ and daily air temperature for Poland

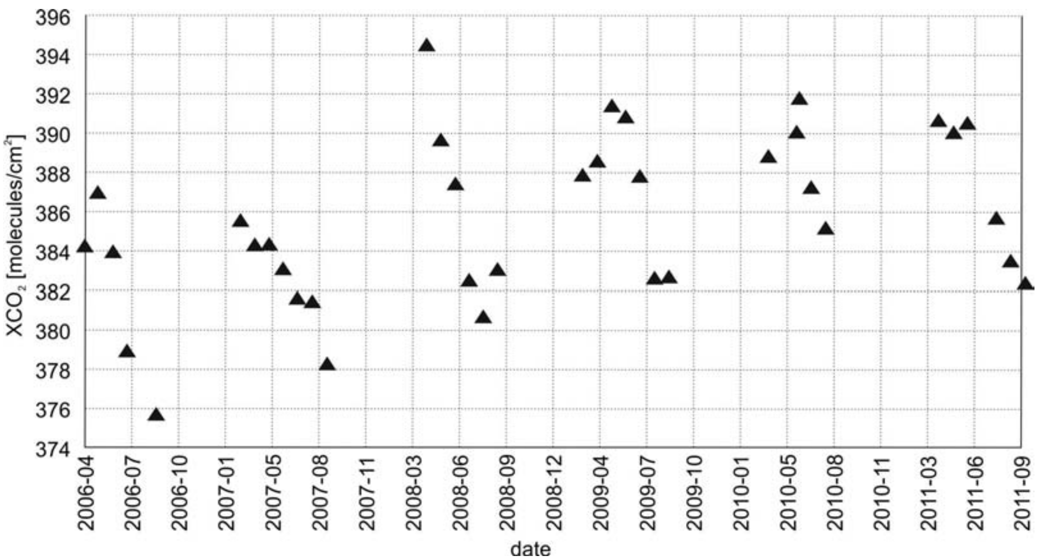


Fig. 4. The variability of monthly averaged $XCO_2$ concentration in Poland during 2006–2011

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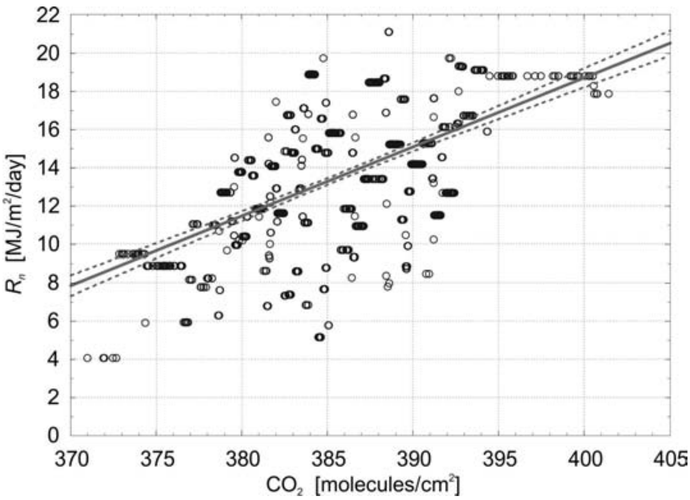


Fig. 5. Relationship between daily SCIAMACHY registration of $CO_2$ and computed daily net radiation $R_n$ for Poland

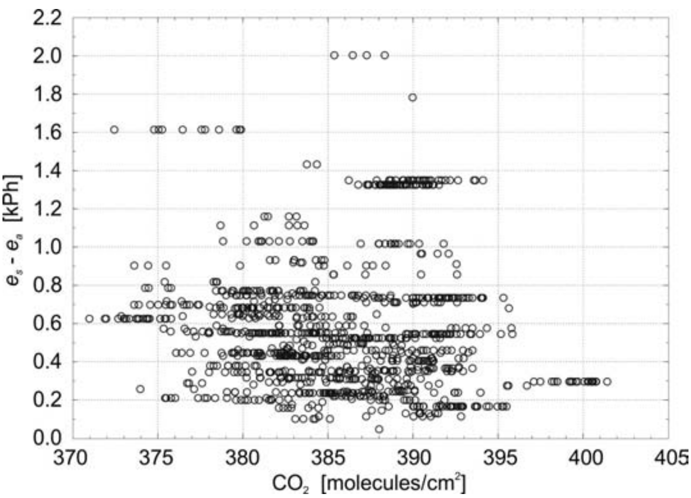


Fig. 6. Relationship between daily SCIAMACHY registration of $CO_2$ and computed water pressure deficit for Poland

absorbers of $CO_2$ from the air. Figure 6 presents the $CO_2$ values in two Polish voivodeships. Lodzkie voivodeship has the lowest percentage of forests (21.1%) in Poland, and Lubuskie voivodeship has the highest percentage of forest (49%) in Poland (the Polish Central Statistical Office).

It should be stated that in Lubuskie voivodeship the concentration of $CO_2$ obtained from SCIAMACHY is lower than in Lodzkie voivodeship. It is noted in both regions that the concentration of $CO_2$ is lowering in July–August in all years.

In less forested voivodeships, like Lodzkie, the correlation between $CO_2$ and net radiation is poorer. In the voivodeships where the percentage of forest is higher (Lubuskie), the values of $CO_2$ are lower, which indicates better $CO_2$ sequestration.

The seasonal relationship between $CO_2$ concentration (SCIAMACHY measurements) and vegeta-

Table 4. Correlation coefficients between daily $CO_2$ values and particular meteorological parameters for voivodeships; $N$ – number of measurements

| $XCO_2$ [molecules/cm²] | | $N$ | $T$ [°C] | $H$ [%] | $R_a$ [MJ/m²/day] | $R_s$ [MJ/m²/day] | $e_s - e_a$ [kPh] | $R_n$ [MJ/m²/day] |
|---|---|---|---|---|---|---|---|---|
| Voivodeships | Dolnoslaskie | 105 | –0.453 | 0.222 | 0.571 | 0.190 | –0.454 | 0.575 |
| | Kujawsko-pomorskie | 27 | –0.584 | –0.113 | –0.072 | –0.424 | –0.314 | 0.667 |
| | Lubelskie | 153 | –0.467 | –0.184 | 0.267 | 0.167 | –0.183 | 0.536 |
| | Lubuskie | 68 | –0.238 | –0.184 | 0.429 | 0.272 | –0.032 | 0.478 |
| | Lodzkie | 108 | –0.454 | –0.369 | –0.236 | –0.084 | 0.028 | 0.327 |
| | Malopolskie | 69 | –0.222 | –0.428 | 0.499 | 0.330 | 0.222 | 0.623 |
| | Mazowieckie | 110 | –0.457 | –0.136 | –0.062 | –0.084 | –0.129 | 0.584 |
| | Opolskie | 15 | –0.301 | 0.448 | 0.522 | 0.215 | –0.529 | 0.524 |
| | Podkarpackie | 88 | –0.450 | –0.334 | –0.041 | 0.052 | –0.055 | 0.510 |
| | Podlaskie | 54 | –0.435 | –0.058 | 0.215 | 0.013 | –0.147 | 0.609 |
| | Pomorskie | 9 | –0.509 | 0.302 | –0.057 | –0.244 | –0.615 | 0.116 |
| | Slaskie | 53 | –0.209 | –0.227 | 0.346 | 0.140 | 0.063 | 0.472 |
| | Swietokrzyskie | 69 | –0.275 | –0.451 | 0.120 | 0.028 | 0.112 | 0.652 |
| | Warminsko-mazurskie | 6 | –0.606 | –0.557 | –0.284 | 0.520 | –0.074 | 0.775 |
| | Wielkopolskie | 127 | –0.458 | –0.140 | 0.187 | 0.093 | –0.213 | 0.515 |
| | Zachodnio-pomorskie | 13 | 0.075 | –0.382 | 0.636 | 0.415 | 0.280 | 0.400 |

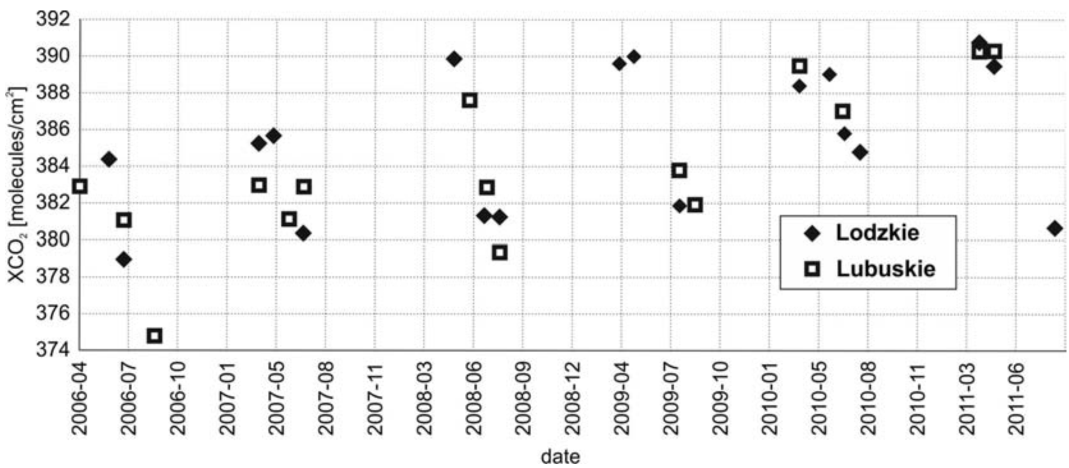


Fig. 7. Monthly variability of $XCO_2$ values in Lodzkie and Lubuskie Voivodeships

tion could be verified by the comparison of $CO_2$ values with values of NDVI.

Figure 8 presents the seasonal variability of $XCO_2$ concentration and NDVI values for Wielkopolskie and Dolnoslaskie voivodeships.

Both atmospheric $CO_2$ concentration and NDVI are time-dependent variables, which can be seen in Figure 7. In Dolnoslaskie, NDVI values are lower in July 2007, in August 2008 and in July 2010. In Wielkopolskie NDVI lowered in July in all considered years. It is noted that at the same dates the $CO_2$ in both regions also followed NDVI. In the case of two Polish voivodeships the highest values of $CO_2$ as well as NDVI values are in spring and the lowest in autumn, which indicates the seasonality of $CO_2$ concentration. The visible correlation

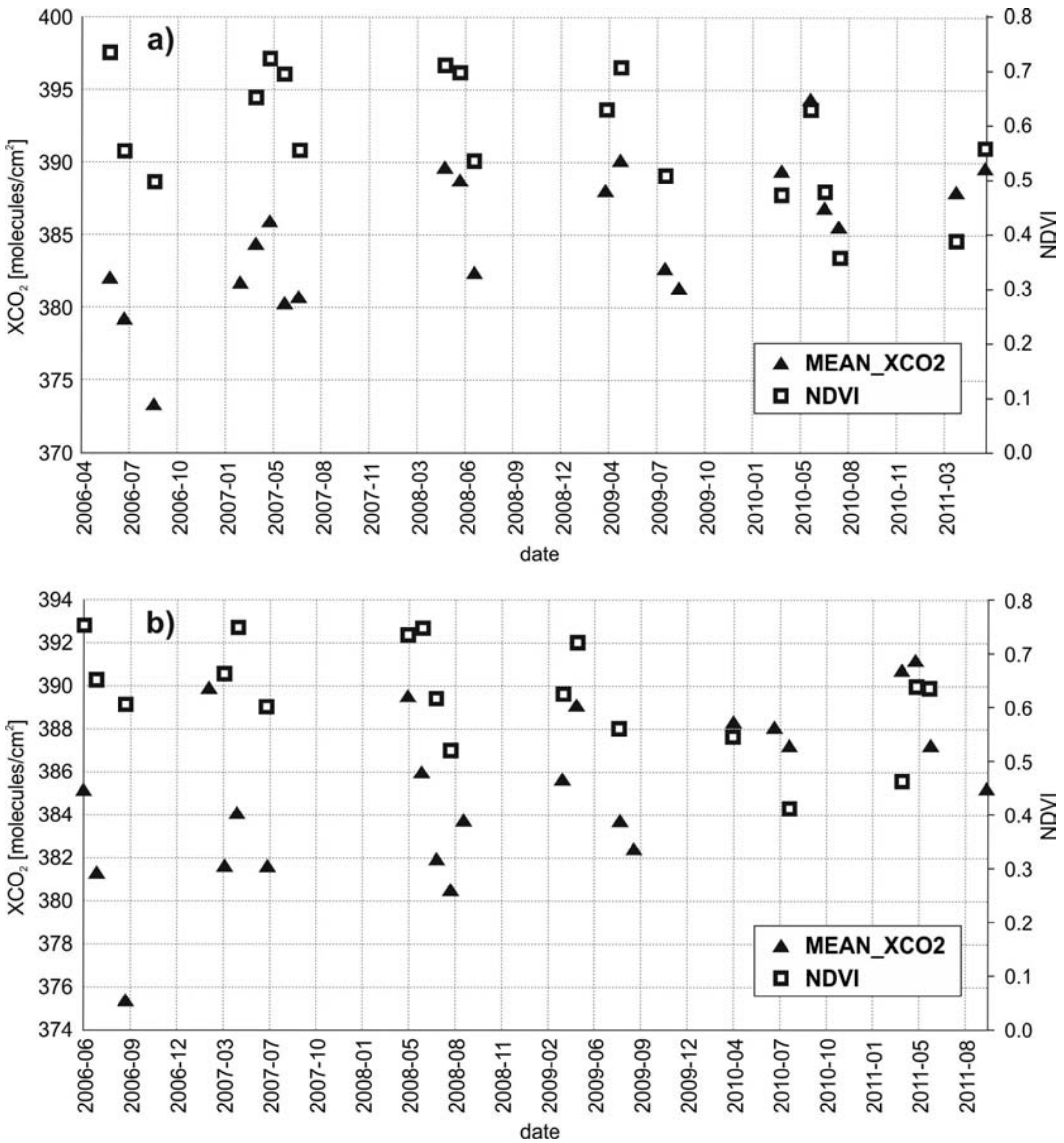


Fig. 8. Monthly variability of $XCO_2$ values from SCIAMACHY and NDVI from NOAA AVHRR in Wielkopolskie (a) and Dolnoslaskie Voivodeships (b)

is explained by the fact that the vegetation for development needs to absorb a high amount of $CO_2$ for the process of photosynthesis.

In the literature it may be found that the positive correlation between $CO_2$ and biomass proves the effect of fertilization (Lim et al., 2004). The results of many studies show that the high concentration of $CO_2$ affects the fertilization of plants (Bazzaz and Sombroek, 1996).

## 5. Discussion

The paper presents the relationships performed between $CO_2$ values derived from SCIAMACHY data and meteorological parameters measured at ground stations. It also presents the relationship between $CO_2$ and the vegetation index (NDVI) calculated from NOAA satellites, and between $CO_2$ concentration and the percentage of forest cover (the Polish Central Statistical Office).

It was observed that the $CO_2$ recorded by the SCIAMACHY radiometer is a time-dependent parameter. The investigation over Poland showed that, as well as over China (Wang et. al, 2011), the highest values of carbon dioxide occurred in April and May. Wang (2011) explained the short-term atmospheric $CO_2$ concentration variations are affected by the regional terrestrial ecosystem, human activities and local meteorological conditions. Some significant correlations were found between $CO_2$ and air temperature $T$ (correlation is negative), and between $CO_2$ and net radiation $R_n$ (correlation is positive). In the regional scale it was also concluded that the percentage of forest areas determines the amount of $CO_2$ in the air, and the correlation between $CO_2$ values and NDVI is positive. However a larger number of data collected from a wider area, such as the whole of Europe, could improve the correlation results. The data from SCIAMACHY have low spatial and temporal resolution. They are compared to the meteorological parameters at the level of 2 m, which could result in the large error in the correlation. SCIAMACHY was a satellite spectrometer designed to measure Earth's atmosphere, and the parameters observed at the ground at 2 m could not correlate well with the atmosphere $CO_2$. This research gives an overview on SCIAMACHY data and the possibilities to link these data to ground observations. In the nearest future the Sentinel-4 and Sentinel-5 of the COPERNICUS Programme will provide information on atmospheric variables in support of European policies. The services will include monitoring of air quality.

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APPENDIX 1. Number of measurements (No) derived from SCIAMACHY.ENVISAT-1 at particular date

| Date | No | Date | No | Date | No | Date | No | Date | No | Date | No |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2006-04-23 | 3 | 2007-03-25 | 1 | 2008-04-08 | 1 | 2009-03-31 | 1 | 2010-04-18 | 2 | 2011-04-10 | 5 |
| 2006-04-25 | 1 | 2007-03-28 | 2 | 2008-04-23 | 2 | 2009-04-02 | 5 | 2010-06-18 | 2 | 2011-04-19 | 10 |
| 2006-05-09 | 13 | 2007-03-29 | 2 | 2008-04-24 | 22 | 2009-04-03 | 3 | 2010-07-04 | 5 | 2011-04-21 | 1 |
| 2006-05-11 | 1 | 2007-03-30 | 5 | 2008-05-07 | 2 | 2009-04-06 | 8 | 2010-07-10 | 38 | 2011-04-22 | 31 |
| 2006-06-12 | 12 | 2007-04-01 | 2 | 2008-05-09 | 4 | 2009-04-11 | 1 | 2010-07-11 | 4 | 2011-04-27 | 5 |
| 2006-06-13 | 2 | 2007-04-04 | 6 | 2008-05-12 | 3 | 2009-04-14 | 7 | 2010-07-16 | 3 | 2011-05-07 | 4 |
| 2006-06-25 | 5 | 2007-04-14 | 32 | 2008-05-28 | 3 | 2009-04-19 | 15 | | | 2011-05-08 | 2 |
| 2006-07-07 | 1 | 2007-04-16 | 3 | 2008-05-29 | 15 | 2009-04-21 | 8 | | | 2011-05-10 | 7 |
| 2006-07-11 | 8 | 2007-04-17 | 3 | 2008-06-03 | 8 | 2009-04-22 | 15 | | | 2011-05-11 | 43 |
| 2006-07-17 | 11 | 2007-04-20 | 3 | 2008-06-09 | 2 | 2009-04-24 | 16 | | | 2011-05-24 | 6 |
| 2006-07-18 | 4 | 2007-04-26 | 7 | 2008-06-10 | 4 | 2009-04-25 | 13 | | | 2011-05-26 | 1 |
| 2006-07-20 | 2 | 2007-04-27 | 3 | 2008-06-22 | 6 | 2009-04-28 | 50 | | | 2011-05-30 | 33 |
| 2006-07-27 | 12 | 2007-04-29 | 1 | 2008-07-02 | 44 | 2009-04-30 | 1 | | | 2011-06-04 | 9 |
| 2006-07-28 | 11 | 2007-05-03 | 13 | 2008-07-03 | 5 | 2009-05-01 | 3 | | | 2011-06-05 | 4 |
| 2006-09-12 | 20 | 2007-05-04 | 3 | 2008-07-12 | 1 | 2009-05-03 | 17 | | | 2011-06-06 | 1 |
| 2006-09-15 | 4 | 2007-05-19 | 31 | 2008-07-25 | 2 | 2009-05-26 | 30 | | | 2011-06-13 | 3 |
| 2006-09-16 | 4 | 2007-05-24 | 1 | 2008-07-31 | 20 | 2009-06-14 | 3 | | | 2011-06-28 | 1 |
| 2006-09-22 | 13 | 2007-05-25 | 4 | 2008-08-07 | 2 | 2009-07-23 | 1 | | | 2011-08-22 | 1 |
| 2006-09-23 | 3 | 2007-06-10 | 10 | 2008-08-19 | 26 | 2009-08-01 | 4 | | | 2011-09-05 | 1 |
| 2006-09-25 | 4 | 2007-07-15 | 36 | 2008-08-20 | 5 | 2009-08-16 | 4 | | | 2011-09-27 | 11 |
| 2006-09-26 | 1 | 2007-07-16 | 12 | 2008-08-31 | 11 | 2009-08-17 | 4 | | | 2011-09-29 | 2 |
| | | 2007-08-16 | 24 | 2008-09-07 | 6 | 2009-08-20 | 52 | | | | |
| | | 2007-08-23 | 1 | 2008-09-10 | 1 | 2009-08-21 | 11 | | | | |
| | | 2007-09-14 | 3 | | | 2009-09-11 | 1 | | | | |
| | | 2007-09-17 | 7 | | | 2009-09-21 | 8 | | | | |
| | | 2007-09-23 | 10 | | | 2009-09-27 | 7 | | | | |

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# Badanie zależności między wartościami dwutlenku węgla w atmosferze pozyskanymi z SCIAMACHY.ENVISAT-1 a parametrami meteorologicznymi oraz wskaźnikami roślinnymi – opracowanie dla obszaru Polski

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**Streszczenie** Przeważająca ilość metod badających jakość powietrza oraz szacowania strumienia węgla opiera się na pomiarach naziemnych. W celu poszerzenia zakresu tych metod, dane pozyskane poprzez instrument *SCIAMACHY* znajdujący się na pokładzie satelity ENVISAT (działającego w latach 2002–2012) zostały wykorzystane do opracowania niniejszego artykułu. Badania zostały przeprowadzone w ramach realizowanego w Instytucie Geodezji i Kartografii przez Zakład Teledetekcji grantu naukowego (1600/B/T02/2011/40) o tytule: „Zastosowanie danych satelitarnych nowej generacji do szacowania wpływu wilgotności gleby i roślinności na bilans węgla". Jednym z głównych założeń projektu jest wykorzystanie danych satelitarnych do szacowania bilansu węgla. Artykuł przedstawia uzyskane relacje między wartością dwutlenku węgla (pozyskaną za pomocą SCIAMACHY) oraz danymi meteorologicznymi zebranymi ze stacji pomiarowych zlokalizowanych na obszarze całej Polski. Dodatkowo przeprowadzono badanie dotyczące relacji pomiędzy poziomem zawartego w powietrzu $CO_2$ a wartością Znormalizowanego Wskaźnika Roślinnego (NDVI) obliczonego na podstawie danych rejestrowanych przez satelitę NOAA, oraz wskaźnikiem lesistości dla obszarów województw. Najbardziej znaczące wyniki uzyskano dla relacji pomiędzy dwutlenkiem węgla a temperaturą powietrza $T$, jak również pomiędzy $CO_2$ a gęstością strumienia różnicowego radiacji $R_n$. Stwierdzono, że poziom lesistości jest związany z ilością $CO_2$ w powietrzu, a korelacja między $CO_2$ a NDVI związana jest z sezonowością i rozwojem roślinności. Autorzy uważają, że badanie będzie kontynuowane wraz z umieszczeniem na orbicie satelity z misji Sentinel, przeznaczonego między innymi do badania atmosfery ziemskiej. Ponieważ konstelacja satelitów Sentinel została zaprojektowana w ramach Europejskiego Programu Obserwacji Ziemi: COPERNICUS, dane przeznaczone do badań naukowych będą bezpłatne.

**Słowa kluczowe:** SCIAMACHY, $CO_2$, parametry meteorologiczne, temperatura powietrza, NDVI, radiacja, korelacja