Measuring CO_2 emissions - implications for spatial development

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1. Introduction

The effects of climate change can be felt in all spheres of contemporary life, often exacerbating existing challenges. Extreme weather requires that we reconsider risk management, with the development both of immediate responses and long-term strategies. Steps to mitigate the effects of climate change are being taken at the local, national and global levels. However, they are widely considered insufficient (Solomon et al. 2009). Only one of the four scenarios presented in a 2014 Report by the IPCC (RCP2.6) assumes a moderate increase in global surface temperature (1.5°C) by the end of the century (2100), compared to before the industrial revolution (1850-1900). Even this scenario predicts that many regions of the world will be vulnerable to extreme atmospheric events. The other scenarios, especially the continuation of business-as-usual, project much higher levels of uncertainty and risk.
This paper summarises the results of measurements of CO2 emissions on the campus of Lodz University of Technology in Poland between March and April in 2012, 2014 and 2016. The concentrations of CO2 were measured as a function of temperature, air pressure and wind speed. The measurements also considered the season and the time of day. This data was combined with an analysis of urban development, enabling assessment of the actual emissions relative to the architectural surroundings. These included tall, isolated buildings and denser, lower structures, parking lots and streets, greenery (neighbourhood parks and lawns), a nearby power plant and an electrical power and heating plant. In the next section, the rationale for measuring CO2 will be explained and the precedents for doing so internationally and in Poland will be examined. The case study of Lodz University of Technology campus B will then be presented. The measurement methods and the results will be discussed, followed by conclusions which will also point to avenues for future research.

2. Green House Gasses emissions - research rationale and precedents

Over 97% of scientists recognise that human activities are an important cause of climate change, through the emission of greenhouse gases (GHG). International accords such as the Paris UNFCCC Agreement of December 2015 reflect the widespread consensus that the current and predicted consequences of global warming should not be ignored. Research relating to GHG emissions, including systems for monitoring and protecting air quality, has therefore gathered pace worldwide.

2.1. *Role of GHG emissions*

According to an IPCC Report (2014, p.10), in order to limit human-induced warming to 2°C relative to 1861-1880 the cumulative CO2 emissions from all anthropogenic sources since 1870 should remain less than 2900 Gt CO2. Since 1900 Gt CO2 had already been released by 2011, the probability of achieving this goal has been estimated at around 66%. Global climate change has been strongly associated with the emission of GHGs, of which CO2 is the most important (IPCC 2014). Analysis shows that the most common coal isotope in the atmosphere has an atomic weight of 12 (12C). Carbon-12 can be absorbed by plants during photosynthesis and is also released when fossil fuels (which consist of organic matter) are burnt. The observable decrease in 13C atoms in the atmosphere is seen by some as proof that human activity has had an impact on CO2 concentrations (Burch, Harris 2014, pp. 134-135).

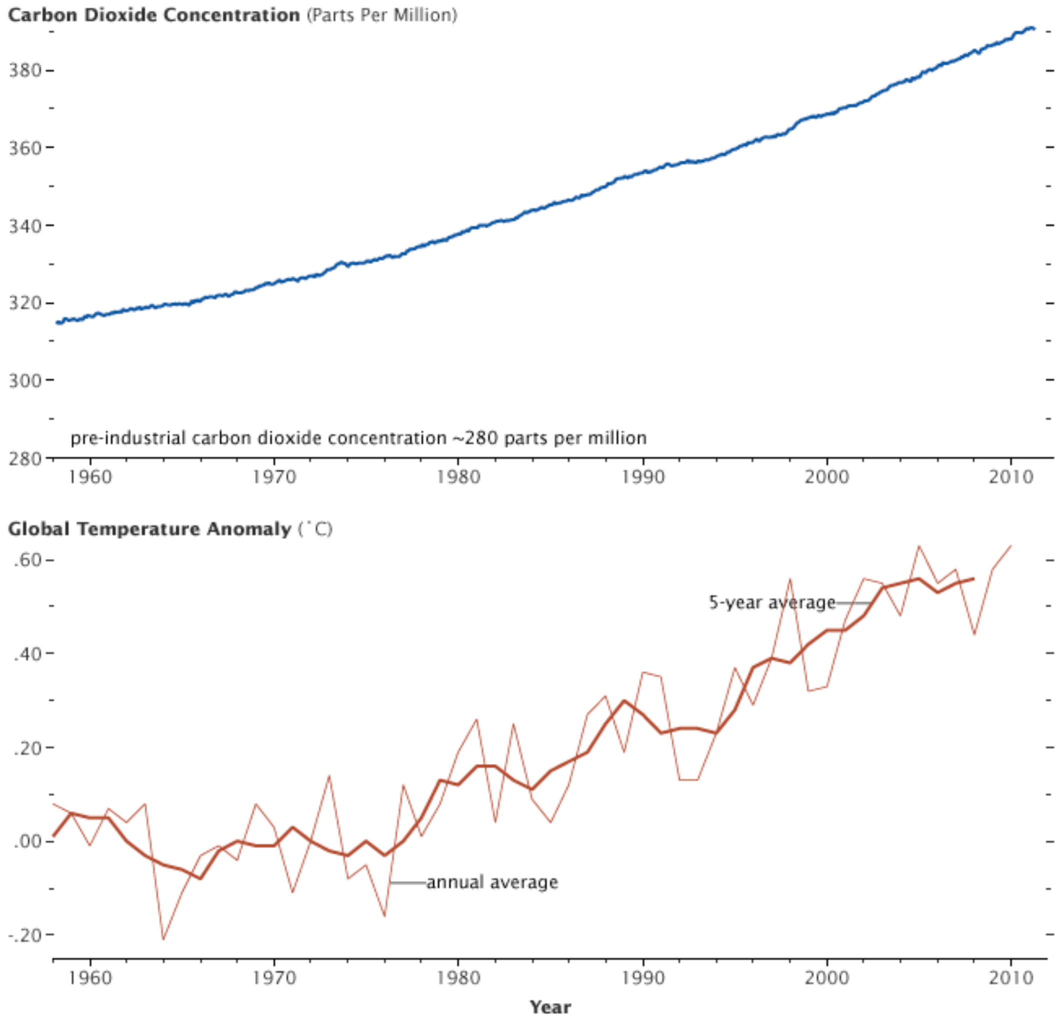

Figure 1.Changes in the concentration of carbon dioxide and Global Temperature Anomalies (source: https://earthobservatory.nasa.gov/Features/CarbonCycle/page5.php, data 2011, access 12.07.2018).

The United Nations Framework Convention on Climate Change (UNFCCC) in 1992 was the first global agreement regarding the reduction of GHG emissions. In the Kyoto Protocol of 1997, signatory governments agreed to comply with rules constraining the emission of GHG, including carbon dioxide. In 2016, the United Nations Framework Convention on Climate Change adopted the Paris agreement, which aims to mitigate the effects of GHG emissions, assist adaptation to climate change and finance the transformation process starting from 2020. The signatories of the agreement aim to keep 'the global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.'
In Poland, the Environment Protection Law regulates issues relating to air quality, such as the conditions of energy production and the release of substances into the atmosphere. The principal regulation defines limits for NO2, SO2, O3, CO and particulate matter PM10. The law does not require measurements of CO2. Protection of air is defined as keeping the emission of pollutants below the defined limits and reducing them to levels considered not to be harmful to human health. Since the law does not recognise carbon dioxide as having a direct negative impact on human health, it is not covered by State Environmental Monitoring. In the environment protection law approved before EU accession in 1999-2001, the Polish parliament adopted the regulations of the European Union. This law has since been considerably updated, including adjustments in line with the regulations of Directive 2008/50/ EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. The law defines emissions as *'substances or energy such as heat,*

noise, vibrations or electromagnetic fields introduced directly or indirectly into the atmosphere, water, soil or earth as a result of human activity.'

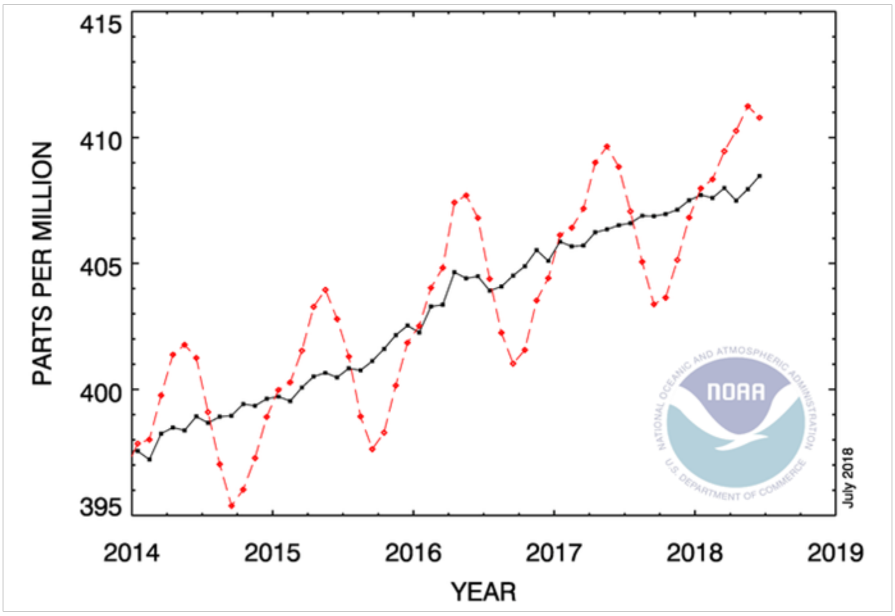

Figure 2. Recent monthly mean $C0_2$ at Manua Loa, June 2018: 410.79 ppm, June 2017: 408.84 ppm, source https://www.esrl.noaa.gov/gmd/ccgg/trends/index.html accessed 12.07.2018

2.2. CO_2 measurements

The Mauna Loa observatory in Hawaii has performed systematic measurements of atmospheric CO2 concentrations since 1955. A yearly rise has been recorded from around 315 particles ppm in 1958 to over 380 ppm in 2006 (after the data of SCRIPPS Institution of Oceanography: https://scripps.ucsd.edu, accessed 12.07.2018) up to around 408 ppm in 2017 (Fig. 2). Systematic measurements of CO2 concentrations in the atmosphere in Poland began in September 1994, at the KASLAB laboratory located in the IMGW meteorological observatory of Kasprowy Wierch in the Tatra Mountains. This is the only station to have kept such a long record of GHG concentrations in Central and Eastern Europe. Until 1996 it analysed air samples on a weekly basis. Since then, an automatic gas chromatograph (HP 5890) has been used (Chmura et al 2008).

3. Emissions and ambient concentration

Another indicator used to quantify levels of pollution is *'immission'* (Cichowicz et al. 2017) or ambient concentration, defined as a 'measure of environmental quality indicating the amount of pollutants found per unit volume in different environmental media' (https://unstats.un.org/unsd/environmentgl/gesform.asp?getitem=106…). It requires taking into account multiple emissions from diverse sources and comparing them with the permissible levels (Cichowicz et al. 2017).

Heating systems are a commonly recognised source of air pollution and GHGs. Smaller facilities, which serve individual households, buildings or close neighbourhoods, emit pollutants exclusively during the heating season. They are usually privately-owned are often called 'low emission' heat sources due to the actual height of the facilities (Adamczyk et al. 2017). The lack of compulsory emission controls constrains the measurement of emissions from these facilities. Moreover, the actual emissions depend on weather conditions and the availability of local fuel. For district facilities, which emit all year round, estimates of emissions are possible based on the amount of fuel used.

Transportation is another major source of pollutants and GHGs. particularly in the centres of large cities, leads to lower air quality. Measurements by the Central Statistical Office show that CO2 emissions from transportation in Poland increased from 26,403.76 thousand Mg in 2000 to 46,465.74 thousand Mg in 2010 (CSO 2012).

Ambient concentrations of CO2 show daily, seasonal and annual cycles depending on the use of local heating sources and road transportation. The location of emission sources does not influence concentrations at the district scale.

Figure 3. Measurement points in campus B

4. Case study

Measurements of ambient concentrations of CO2 were taken on campus B of Lodz University of Technology. This area is located in the southern part of the university, adjacent to Archbishop Klepacz park. Wólczanska Street, Wróblewskiego Street and Politechniki Avenue surround it on the remaining sides (Fig. 3). The municipal power plant EC2 stands to the south-west of the campus site. The 16 ha plot includes the historical nineteenth-century textile factory of Schweikert, complemented by several newer structures. In total, there are 19 buildings in this part of the campus.

While most of the site is paved and used as access roads and parking lots, there are also green areas, in the form of expansive lawns with some trees and bushes. The most densely built-up zone is in the eastern part of the site, and contains the most significant post-industrial development – a building home to three faculties: the Centre of Diagnostics and Laser Therapy of Lodz University of Technology, the Institute of Turbomachinery and the Faculty of Process and Environmental Engineering. The Dean's Office of the latter faculty features the lowest density of development in its surroundings and the highest share of pervious surfaces and vegetation. The construction of a huge sport centre next to Politechniki Avenue took place in 2017, after the measurements had been taken and so did not affect the results (Fig. 4).

Measurements were carried out at points located at the corners of each of the buildings in March and April of 2012, 2014 and 2016. The much smaller and more irregular structures on the eastern side of the site meant that more measurement points were used (Fig. 3). In March of both 2012, 2014 and in 2016, 83 measurement points were used. In April of both years, three more locations were included: two points along Politechniki Avenue and one in Wróblewskiego Street.

Figure 4: Changes to the physical development of Campus B in years 2011, 2013, 2015 and 2017. source http://mapa.lodz.pl*, accessed 01.07.2018*

5. Measurement methods

Measurements were taken using a VEGA-GC micro chromatograph (Pollution S.p.A., Italy), according to the method developed by Cichowicz (Cichowicz and Wielgosiński 2015a, Cichowicz and Wielgosiński 2015b). The VEGA-GC micro chromatograph is suitable for analyses in the field. It consists of a computer module, a tank with a carrier gas (helium), a pump for samples and two batteries. Two parallel columns can be used. A thermal conductivity detector (TCD) enables sample analysis at a minimum concentration of 500 ppb (0.005 ppm) for 6 to 300 s, depending on the type of gas. Measurements of carbon dioxide concentrations were performed at 90 s intervals on a PPQ-packed column, installed in the VEGA-GC micro chromatograph. Before the actual measurements, the chromatograph was calibrated using a test gas. Fig. 5 presents the calibration curve.

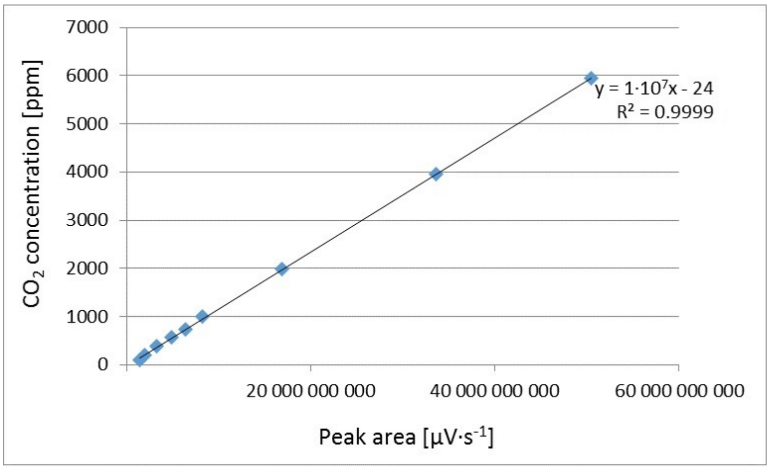

Figure 5: Plot of the calibration curve for carbon dioxide.

Once the batteries had been charged and inserted, a portable bottle with the carrier gas (helium) was installed. The operator then started the system and connected the MC2 and MC-Plan to tune the device. The operator launched the program for CO_2 measurement and headed to point number 1. While the measurements were being performed, the device was directed towards open space (the pavement).

Table 1: Weather data. Source: http://freemeteo.com/, accessed 12.07.2018

Date / Feature	**20.03.12**	**02.04.12**	**23.04.12**	**25.04.12**	**20.03.14**	**03.04.14**	**24.04.14**	**28.04.14**	**21.03.16**	**04.04.16**	**22.04.16**	**25.04.16**
Temperature [°C]	9-13	7	9-13	15	11-15	8-19	8-19	13-16	6	20-21	8-9	6-8
Cloudiness	slightly overcast	partly overcast	partly overcast	cloudless	slightly overcast	cloudless	cloudless	partly overcast	partly overcast	Cloudless	partly overcast	slightly overcast
Wind flow velocity [km/h]	22-31	26-30	9-15	13-19	17-33	6-13	17-21	6-17	17-26	19-20	22-26	11-13
Wind direction	W	W	SW	SW	W	W	W	SW	E	W	E	E
Pressure [hPa]	1031.2	1005.1	1008.1	1005.8	1018.5	1005.1	1019.8	1009.1	1011.0	1009.0	1013.5	1006.2
Relative humidity [%]	53-70	49-53	51-81	44-82	55-72	40-57	46-64	72-94	71-76	31-37	47-57	42-61

An external GPS device was used to record the date, time and coordinates of all points. The carbon dioxide measurements were compared with a map showing the Floor Area Ratio (FAR) and Building Coverage Ratio (BCR). The relationships between the measurements and the FAR and BCR values were examined. The FAR and BCR values were defined for units associated with each specific zone of the campus, including overhang on the ground floor in the external perimeter.
Data from the weather station in the Władyslaw Reymont airport in Lodz were used to determine the meteorological conditions when the measurements were taken [21]. The station is approximately 5 km in a straight line from campus B. Table 1 summarises the meteorological data recorded at the Lodz-Lublinek station when the measurements were taken.
ArcGIS 10.3 was used to visualise the results. A TNT surface was generated based on the recorded points, with the Z parameter describing the CO_2 concentration (Fig. 7). Due to the

irregular distribution of measurement points the surface is distorted, which influences the quality of the visualisation. Moreover, the resulting image does not take into account the volume of the buildings. The same symbology has been assigned to all six images, using equal intervals and the most extreme data spectrum, from April 2012. The background base map was provided by the Municipal Surveying Office and shows the site in 2012.

6. Carbon dioxide ambient concentrations - results and discussion

The ambient concentrations of carbon dioxide were measured in relation to two collector streets: Politechniki Avenue and Wólczańska Street (Fig. 6). The distance from these two linear emitters was assumed to impact the levels of CO2 in the air. In order to verify this assumption, the values associated with the measurement points were aggregated in four buffer zones: 0-50, 50-100, 100-150 and 150-200. Arithmetic means of the carbon dioxide concentrations were calculated for each of these zones. As a result, the impact of transport emissions on GHG levels could be observed.

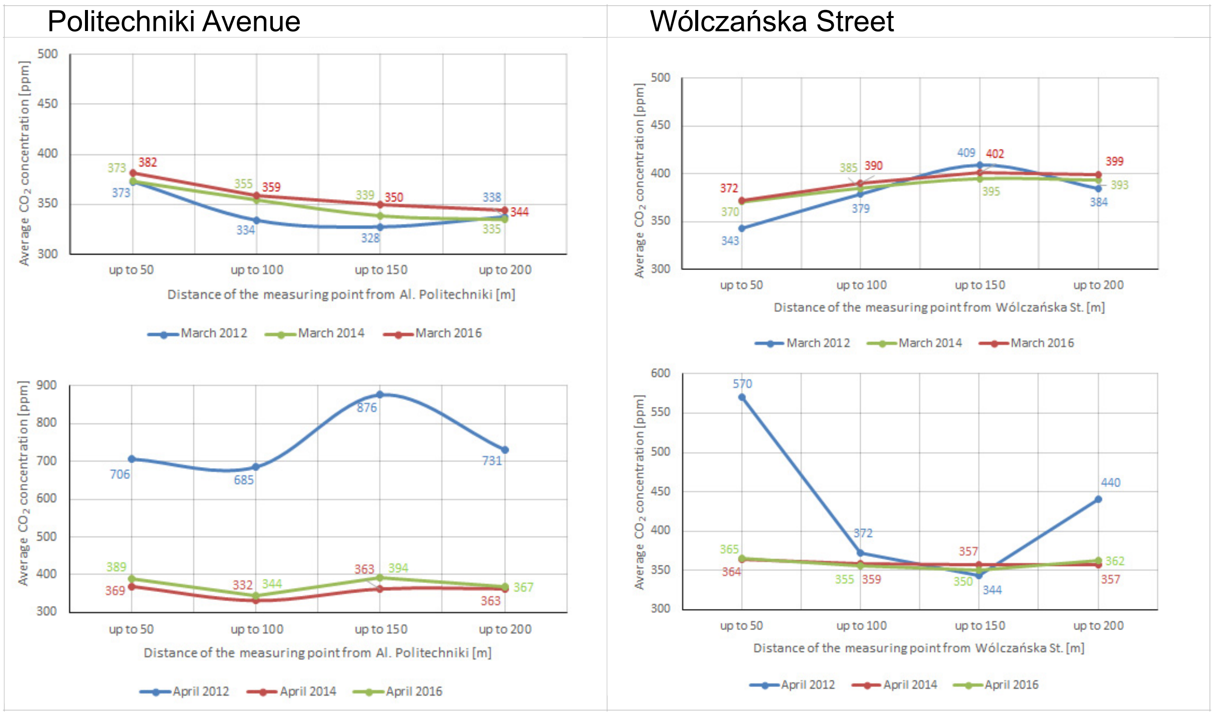

Figure 6: Average CO₂ concentration [ppm] in March and April 2012, 2014 and 2016 in relation to Politechniki Avenue and Wólczańska Street

The structures of the buildings in the vicinity of Politechniki Avenue required fewer measurement points than those next to Wólczańska Street. The average concentration of CO2 in the buffer zone adjacent to Politechniki Avenue in March 2012 and 2014 was 373 ppm. In April 2012 it rose to 706 ppm and in 2014 it was 369 ppm. In March 2012 and 2014 the values decreased with further distances from Politechniki Avenue. In March 2012 and 2014 the levels of CO2 rose as the distance of the measuring point from Wólczańska Street increased. In April 2012, the ambient concentration of CO2 grew with the distance from Politechniki Avenue and decreased with greater distances from Wólczańska Street. In April 2014, the average levels of carbon dioxide varied irrespective of the distance from Politechniki Avenue. The range of values remained the same. In April 2014, the levels lowered with increasing distances from Wólczańska Street (Cichowicz and Wielgosiński 2015b). The measurements were repeated in the same months of 2016.

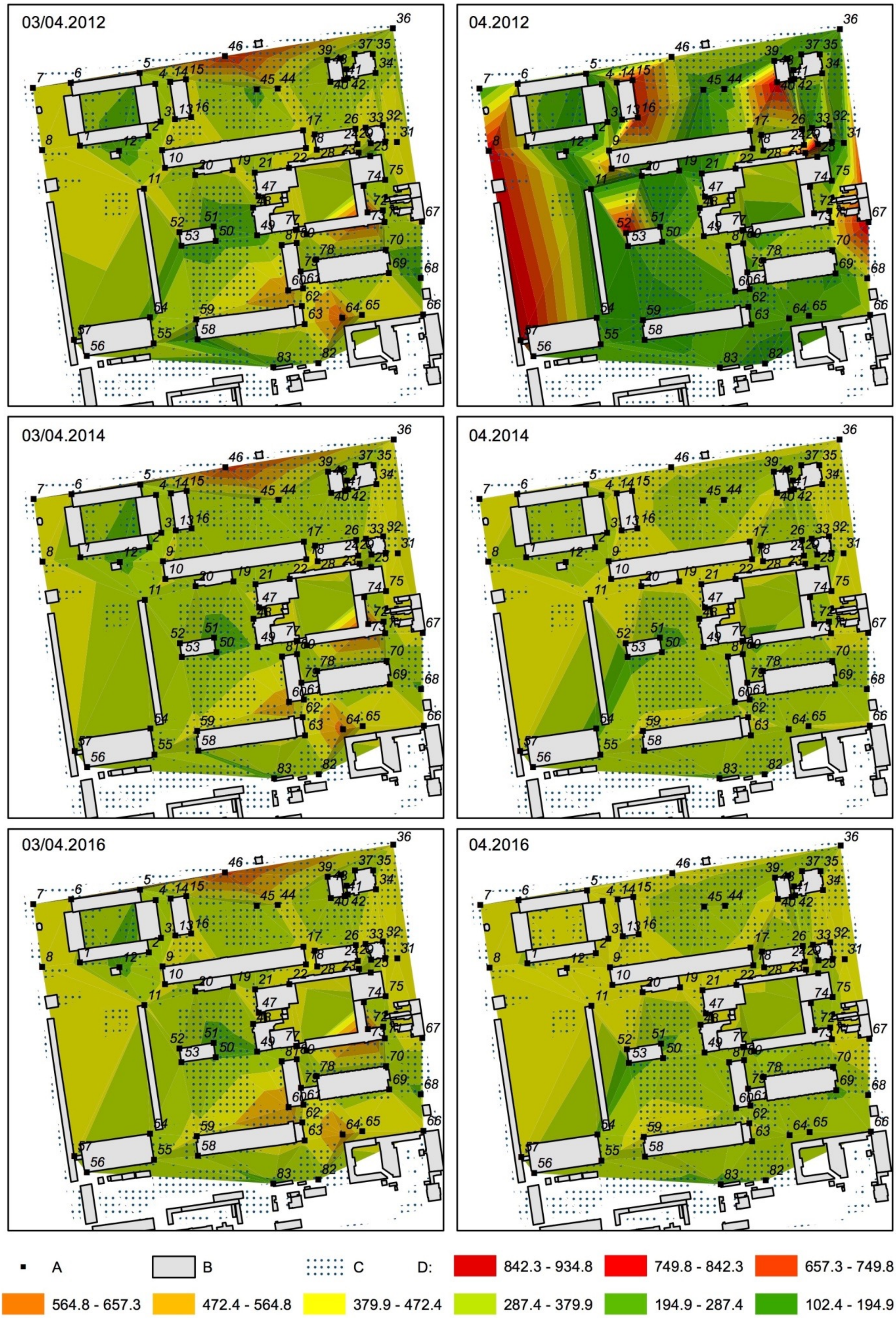

Figure 7: CO_2 concentration [ppm] in March and April 2012, 2014 and 2016

The variations in the levels of carbon dioxide observed in this study (Fig. 7) may result from a combination of several factors. Firstly, there is the obvious impact of street traffic both on Politechniki Avenue and on Wólczańska Street. In March, before the growing season, the impact of street traffic is more linear. In April, due to the appearance of vegetation and photosynthesis, large amounts of CO2 are absorbed (Allen 1990). This lowers the overall levels of this gas in the air. Another factor influencing emissions inside the campus is the circulation of cars within the campus, especially in the student and staff parking lots (Figs. 3 and 4). The direction of the wind, which during the measurements was mostly West and South West, may have carried some CO2 from the parking lots next to the old sports hall and the crossing of Politechniki Avenue and Radwańska Street nearby. This is probably the reason for the higher levels of CO2 in the Northern part of the campus. During the vegetation period, this difference does not occur because CO2 is absorbed by trees in Klepacza Park, north of the campus. A third element which could have affected CO2 levels is building density (Cichowicz and Wielgosiński 2015a). In general, the highest CO2 concentrations overlapped with the impermeable surfaces of the parking lots and pavements. This correlation was shifted due to the wind. The greatest differences in the CO2 levels in April 2012 may have resulted from the fact that the highest wind velocity and the lowest temperatures were recorded during this period. Our measurements demonstrate the impact of transportation emissions and of internal traffic circulation within the site and confirm the results of parallel research (Idso, Idso, Balling 2013, Nemitz et al. 2002, Gurney et al. 2012, Vogt et al. 2006). Other factors which may have had an influence the ambient concentrations of CO2 include the arrangement of the built structures, the amount of vegetation in surrounding areas and the distances between the buildings. Empty spaces form corridors which increase the displacement of air and therefore of pollutants (Chang et al. 2003). Emissions from the power plant and the electrical power and heating plant did not directly influence the results (Cichowicz 2018, Wielgosiński et al. 2018).

7. Conclusions and future research perspectives

The results of this study confirm a spatial correlation between the ambient concentrations of CO2 and the distribution of pavements and vegetation. This information could be used not only to improve the organisation of Campus B of Lodz University of Technology, but also to inform wider efforts to reduce greenhouse gas emissions in urban areas. Our results confirm empirically the influence of transportation arrangements on ambient CO2 concentrations. Transportation is estimated to contribute around 13 percent of total GHG emissions (Metz et al. 2007, p.52). The influence of corridors between buildings and of empty pathways between vegetation areas was also noted. In order to reduce emissions, transportation habits should first be changed, by encouraging the use of public transport and soft modes, such as walking and cycling, instead of individual vehicles. This would also require fewer on-surface parking lots. The hard surfaces should be rearranged and pavements replaced with more permeable solutions. The impact of the arrangement of various forms of built structure and the distribution of voids should be further analysed.

The gas micro-chromatograph provides exact records of carbon dioxide levels. Analyses of ambient concentrations of CO2 should be continued and improved by adding more measurement points distributed more regularly, in the form of a grid. This would eliminate visualisation distortions and improve the legibility of the outcomes.

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