Insights and Policy Implications from a Harmonized Earth Observation Approach to Urban Air Quality

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Abstract

Earth observation (EO) offers a promising and necessary approach to addressing environmental issues and sustainable development from the city to the global scale. The full potential is currently untapped, as global harmonization is necessary for comparability and scalability, as well as streamlining EO integration into informed and efficient decision-making. Focusing specifically on city needs, local and national authorities regulate urban air pollution, while the UN SDG 11 indicator 11.6.2 explicitly targets air pollution accounting for population in "cities" and aggregating to the national level. EO brings forth novel monitoring methods to achieve this alongside more traditional ones. However, how a city is spatially defined is an ongoing area of research and policy activity where the definitions differ, which can greatly impact the estimation of exposure to air pollution. To address the varying definitions and move toward a harmonized global approach, the H2020 SMURBS/ERA-PLANET project has created a workflow and tool that adopts two well established definitions of cities to assess population-weighted particulate matter (PM) pollution for approximately 800 European cities. The workflow utilizes the Copernicus Atmospheric Monitoring Service (CAMS – regional ensemble reanalysis) data for PM2.5, an open and free European-wide source of air pollution data, overlaid with two European Commission acknowledged city boundary definitions: the Functional Urban Area and the JRC's Degree of Urbanisation Urban Centre. These two approaches yield different results allowing stakeholders to comprehend the city boundary sensitivity. Statistical analysis on the results will highlight cases throughout Europe to showcase how important and potentially policy relevant the differences can be based on a city's definition, especially if there is a divergence when aggregated to the national level. The GKH will disseminate the knowledge-based workflow and give prominence to the its global relevance, providing a much needed resource for developing countries and giving decision-makers an EO-based consistent tool to help meet societal challenges that are intertwined with urban growth.

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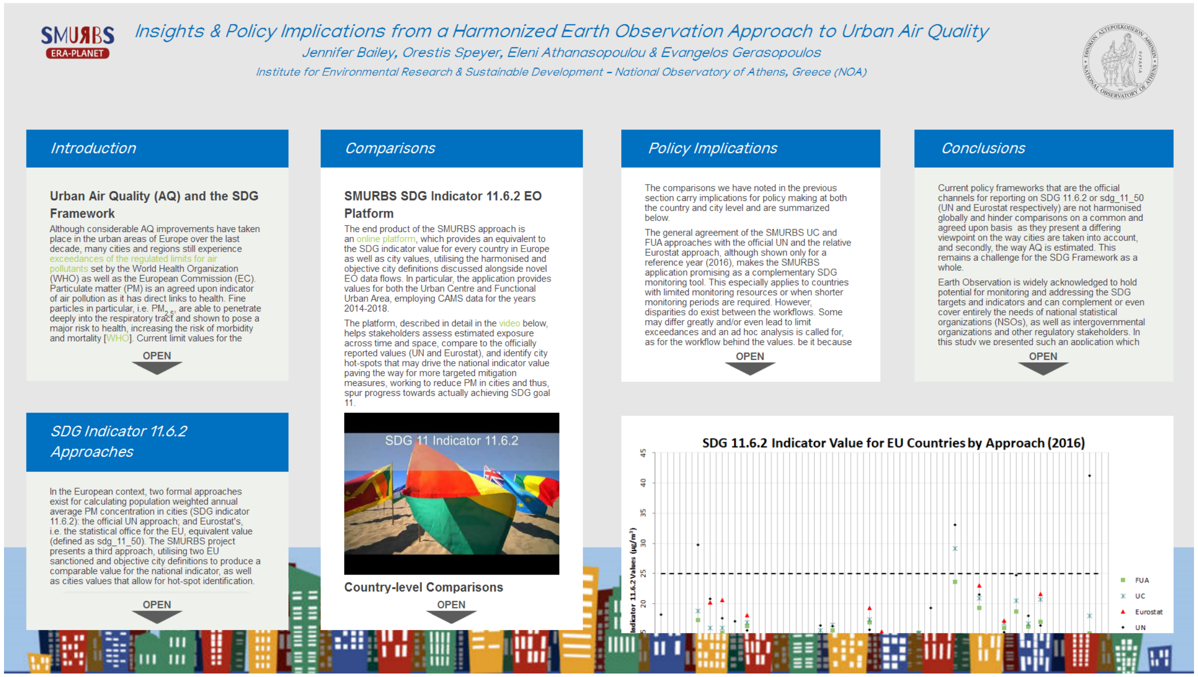

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INTRODUCTION

Urban Air Quality (AQ) and the SDG Framework

Although considerable AQ improvements have taken place in the urban areas of Europe over the last decade, many cities and regions still experience exceedances of the regulated limits for air pollutants (https://www.eea.europa.eu/publications/europes-urban-air-quality) set by the World Health Organization (WHO) as well as the European Commission (EC). Particulate matter (PM) is an agreed upon indicator of air pollution as it has direct links to health. Fine particles in particular, i.e. $PM_{2.5}$, are able to penetrate deeply into the respiratory tract and shown to pose a major risk to health, increasing the risk of morbidity and mortality [WHO (https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)]. Current limit values for the annual average concentration of $PM_{2.5}$ stand at 10μg/m^3 (WHO (https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf;jsessionid=0F93514FA43496914BA9233AB7DC4B78?sequence=1)) and 25 μg/m^3 (EU (https://ec.europa.eu/environment/air/quality/standards.htm)).

Urban AQ has been included as an indicator within the UN Sustainable Development Goals Framework (SDG). Under goal 11, i.e. the "city" goal, indicator 11.6.2 has been designated as “annual mean levels of fine particulate matter (e.g. $PM_{2.5}$ and PM_{10}) in cities (population weighted).” Indicator 11.6.2 is a tier 1 indicator, meaning it has a conceptually clear, established methodology, standards are available and data is regularly produced by countries, with WHO as the custodian agency. In particular, countries with AQ monitoring networks provide the annual mean concentrations and corresponding number of inhabitants to derive the national population-weighted exposure to PM in cities using a generalised formula (https://unstats.un.org/wiki/display/SDGeHandbook/Indicator+11.6.2) [UNSD (https://unstats.un.org/sdgs/metadata/files/Metadata-11-06-02.pdf)]:

$$Annual\ mean\ levels = \frac{\sum C_n * P_n}{\sum P_n}$$

Where C_n is the estimated mean annual $PM_{2.5}$ for a city, n, and P_n is the population of the geographical area (e.g. city) in question. The same formula is used to derive country estimates (both rural and urban), by aggregating the grid cells that include the country (as opposed to the city).

Earth Observation (EO) in support of SDGs

Sixty percent of the EU population is currently living in urban areas and this figure is expected to reach 80% by 2050. Cities serve as a de facto concentration and population exposure hot spot of poor AQ. However, it is there where opportunities for achieving a meaningful impact on AQ exists. Moreover, EO has been acknowledged (http://www.earthobservations.org/documents/publications/201703_geo_eo_for_2030_agenda.pdf) to have great potential in helping to address the SDG Framework, including indicator 11.6.2. This study, in the context of the SMURBS (https://smurbs.eu/) H2020 project, puts the above indicator to the test. It provides an alternative EO methodology for acquiring the indicator value, focusing on the European domain, and explores its sensitivity to various city definitions and the ensuing policy implications.

SDG INDICATOR 11.6.2 APPROACHES

In the European context, two formal approaches exist for calculating population weighted annual average PM concentration in cities (SDG indicator 11.6.2): the official UN approach; and Eurostat's, i.e. the statistical office for the EU, equivalent value (defined as sdg_11_50). The SMURBS project presents a third approach, utilising two EU sanctioned and objective city definitions to produce a comparable value for the national indicator, as well as cities values that allow for hot-spot identification.

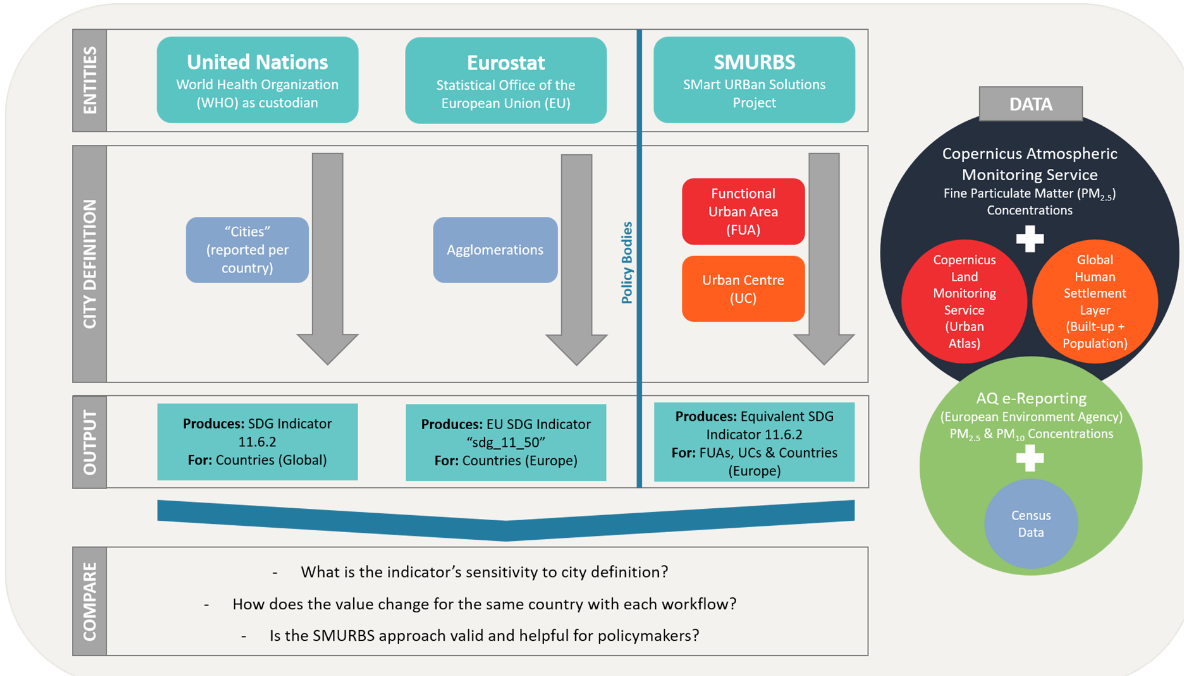

Figure 1: *Conceptual workflows for the approaches of the two different policy entities (UN & Eurostat) as well as the SMURBS project approach for producing comparable values of SDG indicator 11.6.2.*

In Fig. 1, the different approach's workflows are shown with respect to the data and different city definitions adopted. We will briefly describe the approaches and then carry on with their comparison and finally, explore the sensitivity of the indicator.

UN Approach

WHO is the indicator's custodian agency, who gathers once every two years the data/values at the country-level. The output is a national aggregate estimate for the indicator, taking into account the cities' population and the respective PM values from AQ monitoring networks and, where not available, additional data such as satellite retrievals of aerosol optical depth, chemical transport models, topography, etc. [method from Shaddick et al, 2016 (https://arxiv.org/pdf/1609.00141.pdf)]. City definitions differ between countries with respect to the criteria used and the ensuing total extent, population and AQ measurements utilized.

Eurostat Approach

Eurostat, monitoring EU progress towards sustainable development in the EU context, has adopted an EU SDG indicator set, designating indicator sdg_11_50 (https://ec.europa.eu/eurostat/cache/metadata/en/sdg_11_50_esmsip2.htm): "exposure to air pollution by particulate matter," again population weighted. The indicator takes annual mean concentration of PM at urban background stations that can be found in the European Environment Agency's (EEA) AQ e-reporting (https://www.eea.europa.eu/data-and-maps/data/aqereporting-8#tab-figures-produced) database and fall within European agglomerations.

Agglomerations (http://dd.eionet.europa.eu/vocabularyconcept/aq/zonetype/agg/view?facet=HTML+Representation) are defined as a zone that is a conurbation (i.e. extended urban area, towns and suburbs) with a population in excess of 250,000 inhabitants or, where the population is 250,000 inhabitants or less, with a given population density per km^2 to be established by the EU Member States.

The main difference from the UN approach derives from the fact that only agglomerations are used to calculate the nation-wide value.

SMURBS Approach - UCs & FUAs

SMURBS, in response to the aforementioned use of different methodologies that hinder comparisons, utilizes two EU endorsed, objective city definitions and PM data from the Copernicus Atmospheric Monitoring Service (CAMS), as opposed to in situ measurements.

With respect to the first city definition, we followed the JRC's Global Human Settlement Layer initiative, where the Degree of Urbanization (DEGURBA (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Territorial_typologies_manual_-_degree_of_urbanisation)) classifications were re-calculated using both population density criteria and density of built-up area derived from primary databases and not Local Administrative Unit (LAU) data to produce the Urban Centre (UC (https://ghsl.jrc.ec.europa.eu/)) database. In particular, an UC consists of contiguous grid cells with 1) population density of at least 1,500 inhabitants per km^2 OR 2) density of built-up area greater than 50% per km^2 AND 3) at least 50,000 total population. This definition is primarily driven by satellite information and is completely agnostic to national definitions of LAUs and is, therefore, more objective.

The second city definition exploits the UC database, overlays it against the LAUs and categorizes the latter based off of criteria that labels the units as cities or not. Following, the Functional Urban Area (FUA (https://ec.europa.eu/regional_policy/sources/docgener/focus/2012_01_city.pdf)) is defined as a city integrated with its commuting zone which is provided by each Member State. The FUA database was provided by the Copernicus Land Monitoring Service (CLMS (https://land.copernicus.eu/local/urban-atlas/urban-atlas-2012)).

Finally, PM annual average concentrations from CAMS (http://www.regional.atmosphere.copernicus.eu/) are derived from the annual average regional ensemble reanalysis product for the years 2014-2018 (with the first three years validated and the rest interim), which contains modeled information validated with all available in situ or satellite information. The spatial resolution of the product is 11km. CAMS values are masked using the shapefiles of the city definitions and then a pixel-weighted concentration average is produced in a GIS environment. Population is then combined with the concentration to produce the indicator value per city and at country level.

COMPARISONS

SMURBS SDG Indicator 11.6.2 EO Platform

The end product of the SMURBS approach is an online platform (http://apcg.meteo.noa.gr/sdg1162/), which provides an equivalent to the SDG indicator value for every country in Europe as well as city values, utilising the harmonised and objective city definitions discussed alongside novel EO data flows. In particular, the application provides values for both the Urban Centre and Functional Urban Area, employing CAMS data for the years 2014-2018.

The platform, described in detail in the video (https://youtu.be/PIfkIOg5XiI) below, helps stakeholders assess estimated exposure across time and space, compare to the officially reported values (UN and Eurostat), and identify city hot-spots that may drive the national indicator value paving the way for more targeted mitigation measures, working to reduce PM in cities and thus, spur progress towards actually achieving SDG goal 11.

[VIDEO] https://www.youtube.com/embed/PIfkIOg5XiI?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0

Country-level Comparisons

Considering the official reporting and policy context of indicator 11.6.2, the UN value serves as the reference when comparing the three approaches (UN, Eurostat, SMURBS). UN reported indicator values have only been published for 2016 (following a 2-year report frequency), and while both the Eurostat and the SMURBS approach maintain longer time series, we will look only at 2016 to provide a descriptive analysis considering the different outcomes. It is noteworthy that 9 country values have not been reported by Eurostat for 2016, two of which are EU-28 countries.

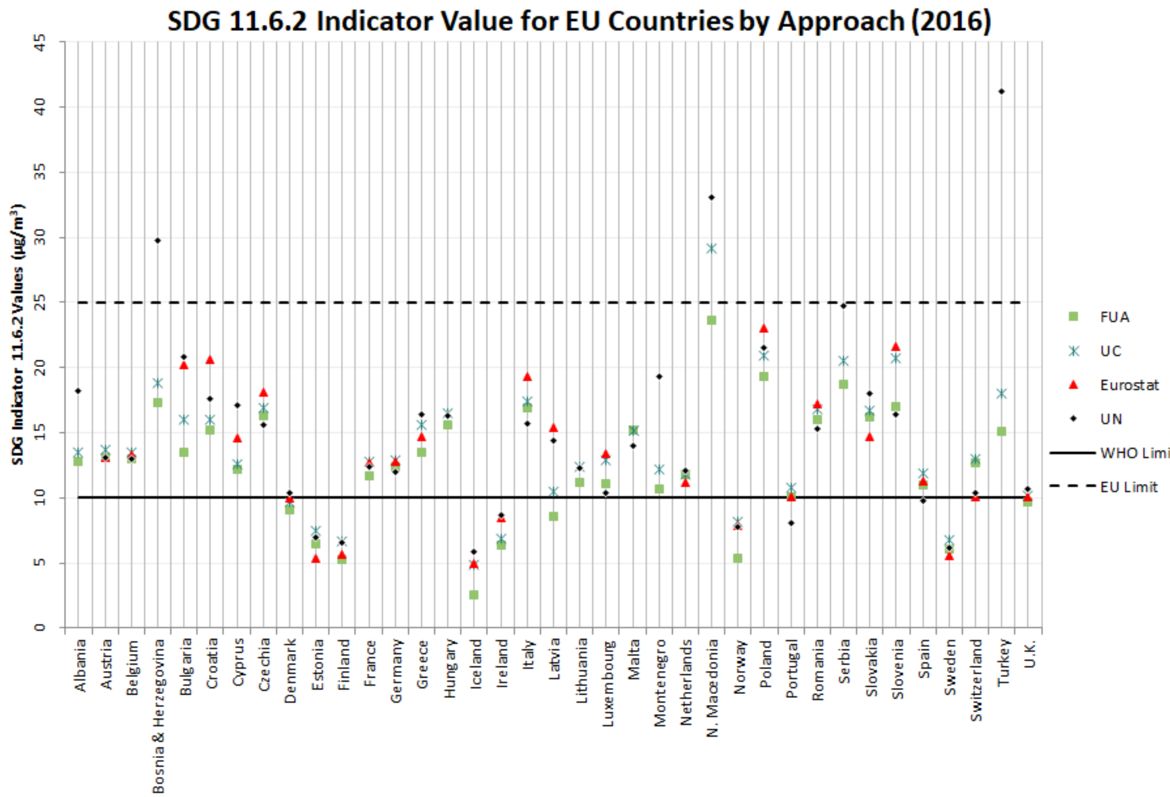

Figure 2: *Plot showing SDG Indicator 11.6.2 values from the different approaches (UN, Eurostat, SMURBS - FUA & UC) for 2016 per country. WHO and EU limit values for annual average $PM_{2.5}$ concentrations are also shown.*

Fig. 2 shows all country, all approach plot against the WHO (10 µg/m^3) and EU (25 µg/m^3) PM limit values to gauge country performance based on the indicator values resulting from the different approaches as well as bring out the differences between them. Countries are categorised in three different groupings (Table 1), each carrying distinct policy implications: general agreement between yields of all approaches available for the country; approach-driven limit exceedances (either WHO or EU) for countries; and countries that maintain a wide divergence between values or have major outlier values.

Table 1: *Policy relevant groupings of countries based off of 2016 country values from all indicator approaches.*

Policy Relevant Groupings	*Country*	*Description*
General Agreement All values are similar	Austria	UC slightly larger
	Belgium	UC slightly larger
	Denmark	UN slightly larger
	France	UC slightly larger
	Germany	UC slightly larger
	Netherlands	UN slightly larger
	United Kingdom	UN slightly larger
Approach Driven Limit Exceedances – WHO or EU Values are above and below a certain limit depending on the approach	Bosnia & Herzegovina*	UN well above EU limit
	Denmark	UN exceeds & Eurostat equivalent with WHO limit
	Latvia	UN & Eurostat well above & UC slightly exceeds WHO limit
	North Macedonia*	UN & UC well above EU limit
	Portugal	UC, FUA & Eurostat slightly above WHO limit
	Spain	UC, Eurostat & FUA slightly above WHO limit
	Turkey*	UN well above EU limit
	United Kingdom	UN, UC & Eurostat slightly above WHO limit
Wide Divergence / Outlier Divergence in values greater than 20% of EU limit value, i.e. 5 $\mu g/m^3$	Albania*	UN 5+ $\mu g/m^3$ greater than FUA
	Bosnia & Herzegovina*	UN 10+ & 12+ $\mu g/m^3$ greater than FUA & UC, respectively. UN is a major outlier
	Bulgaria	UN & Eurostat 7+ $\mu g/m^3$ & 6+ $\mu g/m^3$ greater than FUA, respectively
	Latvia	Eurostat & UN 6+ $\mu g/m^3$ & 5+ $\mu g/m^3$ greater than FUA, respectively
	Montenegro*	UN 8+ $\mu g/m^3$ & 7+ $\mu g/m^3$ greater than FUA & UC, respectively
	North Macedonia*	UN & UC 9+ $\mu g/m^3$ & 5+ $\mu g/m^3$ greater than FUA, respectively
	Serbia*	UN 5+ $\mu g/m^3$ greater than FUA
	Slovenia	Eurostat is 5+ $\mu g/m^3$ greater than UN
	Turkey*	UN 26+ $\mu g/m^3$ and 23+ $\mu g/m^3$ greater than FUA and UC, respectively

** Non-EU28 country and, therefore, do not have a reported Eurostat value.*

The countries of the first grouping with values in general alignment also operate an expansive and well distributed AQ monitoring network (more details can be found in the official European Environmental Agency portal (https://www.eea.europa.eu/data-and-maps/explore-interactive-maps/up-to-date-air-quality-data)). This network feeds both the reanalysis product of CAMS and the official reporting of the Indicator. Thus, agreement is expected in the concentration fields. Moreover, the dense AQ monitoring in urban areas in particular, both in UCs and FUAs, assures a better representation of these populated areas, to which the Indicator is more sensitive, further explaining the agreement.

As concentration limit exceedances are always examined in a policy context, this grouping is of particular importance as it presents both EU (more important in Europe) and WHO exceedances. While an ad hoc analysis for the countries within this group goes beyond the scope of this study, three countries (Bosnia & Herzegovina, North Macedonia, & Turkey) present a notable pattern as official (UN) values are well above the EU limit, while the other approaches mostly fall under it. This is probably due to the fact that very polluted AQ stations are utilised in the official reporting, which are not in some way representative of the whole country (or even the city at hand). For this reason, North Macedonia's UN and UC values agree better than with FUA, where the capital city of Skopje in probably the one driving the national value. Considering the global policy framework presented by the WHO limit, safe levels of exposure in cities are only obtained by a handful of countries. The FUA value being lowest in these countries could be due to the "diluting" of some cities' signal because of the more expansive area the FUAs hold, thus lowering the national value.

Finally, the 9 countries of the last grouping present more than 20% of the EU limit value difference (5 $\mu g/m^3$) between any of the approaches. Here, the choice of city definition has a definitive policy relevant impact on the national indicator. Turkey again stands out according to the UN official value, which is well beyond the EU limit (41 $\mu g/m^3$) and the level of PM pollution there would be absolutely detrimental to health (and extremely critical since the country holds a population of more than 80 million). However, following the UC or FUA SMURBS approach, the indicator values becomes more than 50% lower, both within the EU limit. Outlier values of the UN or Eurostat approaches could again mean sparse or non-representative monitoring stations used in the official reporting.

Following this descriptive comparison, we examined the differences of UC, FUA and Eurostat against the UN official value for 2016 for all countries (37 values) and how these differences correlate to each other. In particular, after calculating the per country difference, we produced the Pearson correlation coefficient for each approach. UC and FUA are very well correlated as they give a value of $\rho= 0.9781$. Eurostat, on the contrary, is very poorly correlated with the SMURBS approaches as it receives a value of $\rho=0.4138$ and 0.5583 for FUA and UC, respectively. This translates to the modeled approaches, i.e. UC and FUA, being correlated to each other, meaning they differ in the same pattern from UN, as was somewhat expected by the common concentration fields used, but not to the Eurostat in situ approach. The latter is of course, platform-wise, closer to the UN approach.

Lastly, in order to compare the SMURBS approaches per se, the percentage difference between the UC and FUA indicator values for all 37 countries for all years of validated data (2014-2016) was calculated. As can be seen in the frequency distribution (Fig. 3), UC is primarily larger than the FUA in the 0-20% difference range. This was as expected since the UC engulfs the (usually) most polluted and densely lived in urban area, while the FUA with the commuting zone inclusion expands over a wider area and the average concentration tends to drop.

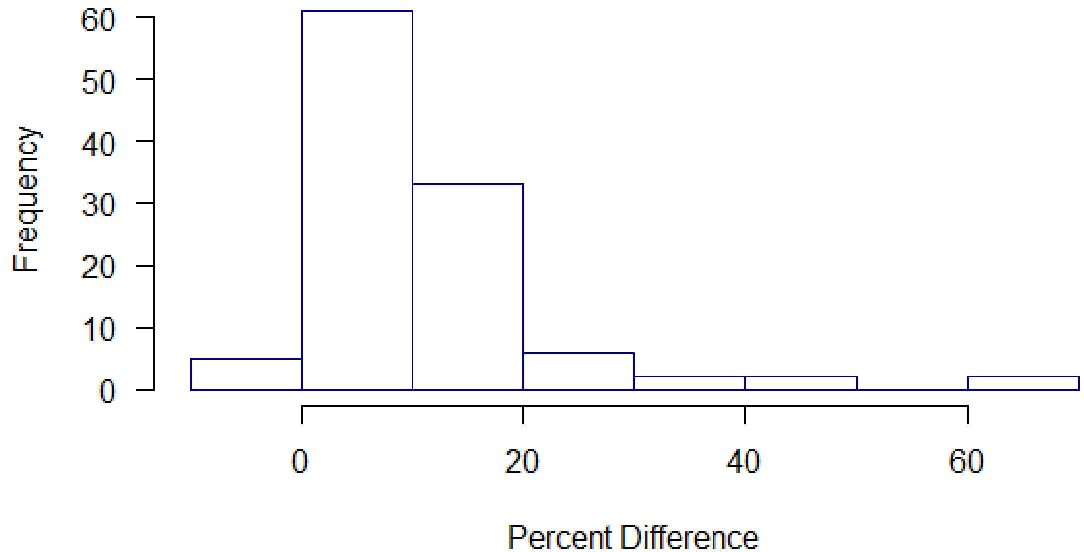

Figure 3*: Frequency distribution of the percentage difference between UC and FUA derived national indicator values for 2014-2016.*

As can be seen in the frequency distribution (Fig. 3), the UC value is primarily larger than the FUA deduced value (primarily between 0-10% and 10-20% larger). This was as expected since the UC is a dense, more concentrated urban area by definition and the FUA is more diluted due to the commuting zone inclusion.

City-level Comparisons - UCs & FUAs

Moving down to the city level, the only approaches that offer such information and opportunity for comparisons are UC and FUA. We calculated the frequency distribution of percentage difference between the UC and FUA values for each city in Europe (Fig. 4). From the two datasets, a single one of 620 cities, that had both a FUA and at least one UC, was constructed for the period 2014-2016. As expected, UC is generally higher than FUA, mostly in the 0-10% range, for the same city. Utilizing a mixed effects model, we then compared the methodologies as a whole, i.e. took into account the entirety of the 1820 (620*3) point dataset. We discerned that the two approaches differ at the whole European domain with a value of 0.55 (95%DE: 0.52-0.66) $\mu g/m^3$.

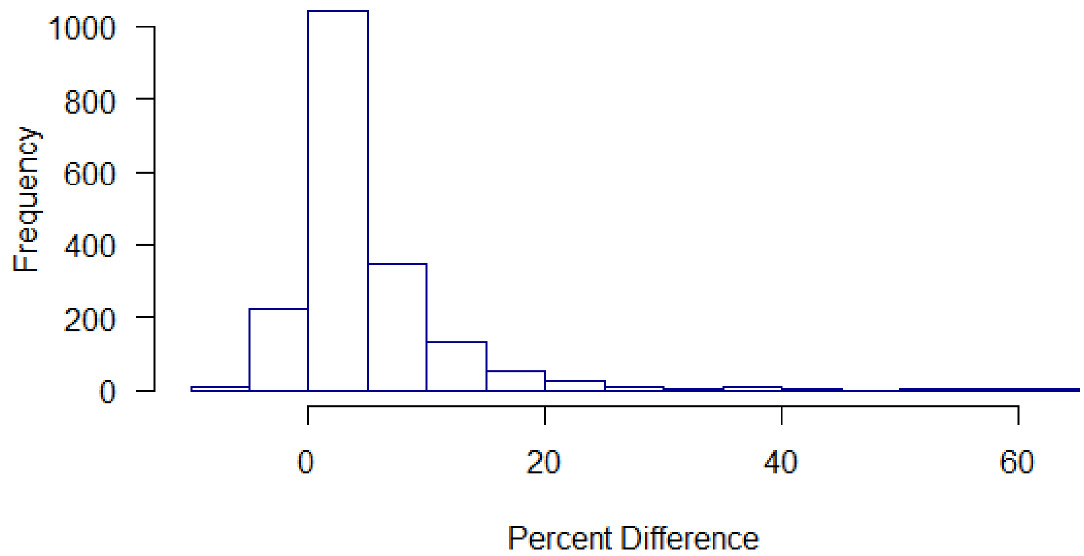

Figure 4: *Frequency distribution of the percentage difference between UC & FUA city-level indicator values for 2014-2016.*

While the above overall difference between the two SMURBS city definitions may seem negligible, there are still local consequences that may greatly affect a particular city. For example, urban extent and pattern may greatly differ between FUA and UC. As can be seen in Fig. 5a, London, being a huge economic centre that translates into an extended commuting zone, has an expansive FUA. When the UC approach is followed, London breaks down in one central UC and several UC satellites as can be seen in Fig. 5b. In the case of London, this does not affect greatly the concentration as the average difference between UC and FUA is 0.42 $\mu g/m^3$ for the period 2014-2016. One example that exemplifies the sensitivity of $PM_{2.5}$ concentration (and the Indicator itself) is the city of Nice in southern France. As can be seen in Fig. 5c, the FUA extends from the seacoast far to the north. The UC of Nice is however restricted along the coastline (Fig. 5d). The corresponding average difference for the same period is 3.70 $\mu g/m^3$, a notable $PM_{2.5}$ quantity.

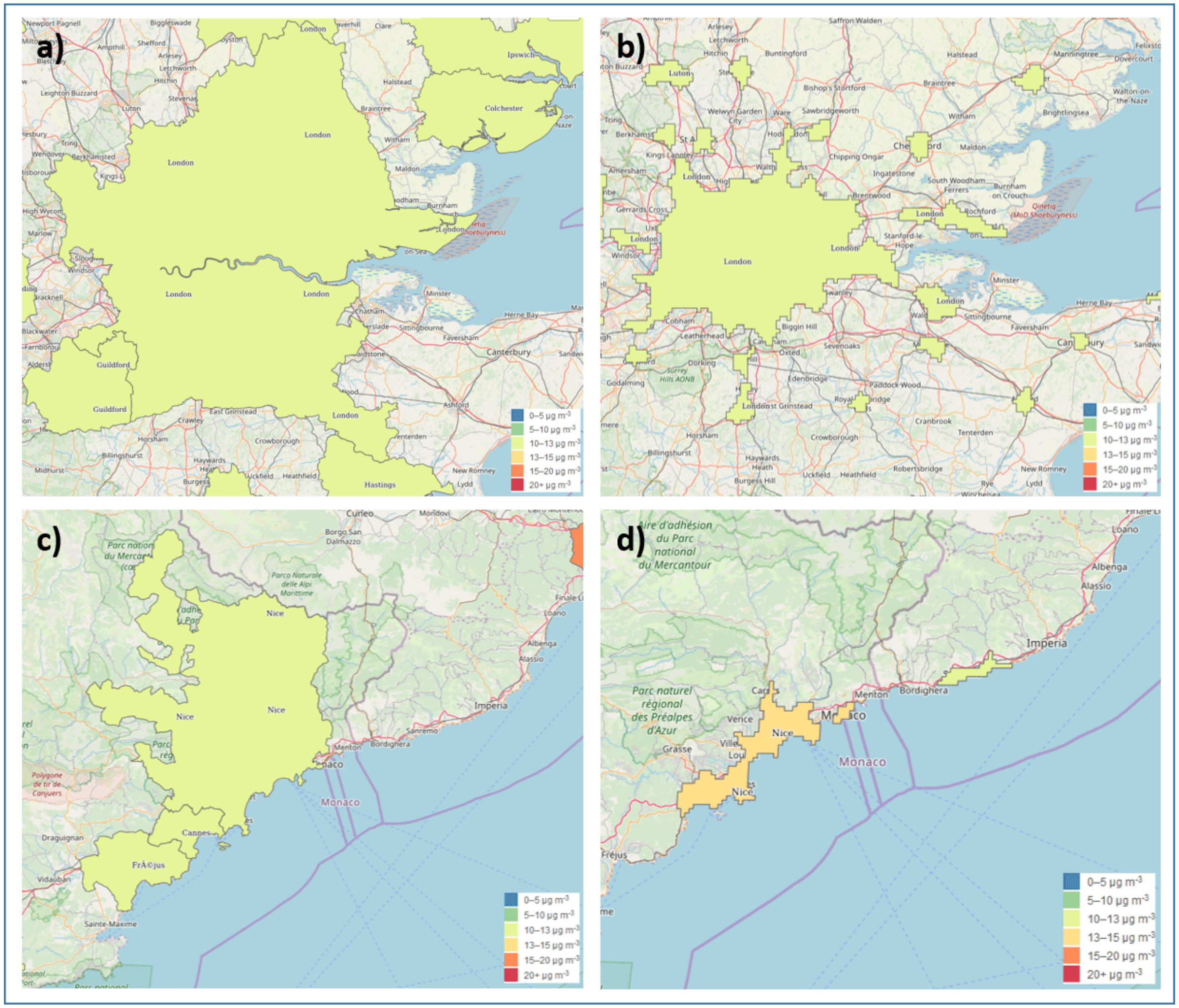

Figure 5: *Annual average $PM_{2.5}$ concentrations (a and b) for London FUA/UC(s) and (c and d) for Nice FUA/UC for the year 2016.*

Cities also have the power to influence and in some cases drive the national indicator value. For example, northern Italy (i.e. Milano, Brescia, Bergamo) can provide insight into where targeted mitigation measures could take place that would improve the overall national value. Fig. 6 shows both FUA and UC values for Italy, and the cities with higher indicator values are primarily located in the north.

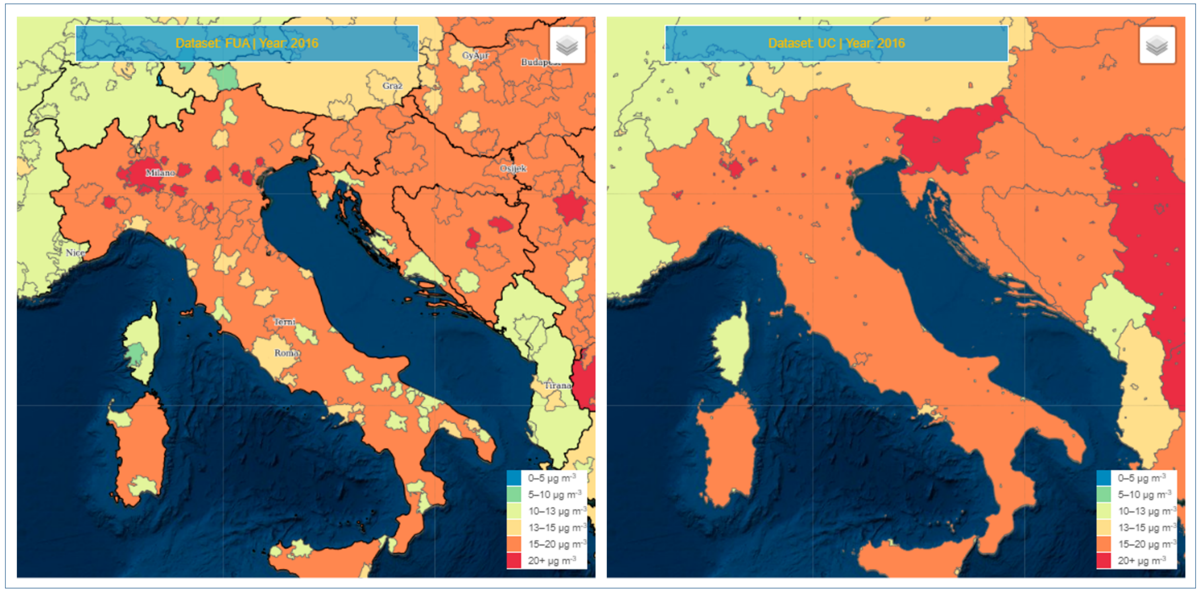

Figure 6: *Both FUA (left) and UC (right) for 2016 showing Italy, notably the city hotspots in northern Italy.*

POLICY IMPLICATIONS

The comparisons we have noted in the previous section carry implications for policy making at both the country and city level and are summarized below.

The general agreement of the SMURBS UC and FUA approaches with the official UN and the relative Eurostat approach, although shown only for a reference year (2016), makes the SMURBS application promising as a complementary SDG monitoring tool. This especially applies to countries with limited monitoring resources or when shorter monitoring periods are required. However, disparities do exist between the workflows. Some may differ greatly and/or even lead to limit exceedances and an ad hoc analysis is called for, as for the workflow behind the values, be it because of model/monitoring inconsistencies, the definition of the country's cities or both. Moreover, the SMURBS approaches differ in a similar pattern from the UN indicator values while the Eurostat shows a different correlation. This may be attributed to the platform used, i.e. model versus in situ, and raises the question on the absolute validity of either in SDG indicator reporting. Finally, when explicitly comparing the UC and FUA derived national values, the UC is generally between 0-20% larger than FUA, and this will need to be considered if countries or reporting systems begin utilizing the Urban Centre definition of a city.

With respect to city-level policy implications, we found that the UC ranges mainly from 0 to 5% larger than FUA on the city-level for the 620 cities that formed the overlapping dataset between the two definitions, which in terms of average difference translates to 0.55 $\mu g/m^3$. Although this difference may imply that the methodologies do not diverge greatly, large local discrepancies do exist, which due to the critical health repercussions of $PM_{2.5}$, may carry health implications for citizens. Furthermore, the two approaches occasionally depict completely different geographical patterns of the city at hand, thus local choice of the most representative and realistic definition is perhaps warranted. It has been shown that some cities drive the national indicator value, acting as AQ hotspots and representing areas of high exposure. The SMURBS application enhances the ability to identify such areas and enables more targeted mitigation policy that can eventually have an impact on the country performance on SDGs.

CONCLUSIONS

Current policy frameworks that are the official channels for reporting on SDG 11.6.2 or sdg_11_50 (UN and Eurostat respectively) are not harmonised globally and hinder comparisons on a common and agreed upon basis as they present a differing viewpoint on the way cities are taken into account, and secondly, the way AQ is estimated. This remains a challenge for the SDG Framework as a whole.

Earth Observation is widely acknowledged to hold potential for monitoring and addressing the SDG targets and indicators and can complement or even cover entirely the needs of national statistical organizations (NSOs), as well as intergovernmental organizations and other regulatory stakeholders. In this study we presented such an application which utilises objective and non-arbitrary city definitions, as well as AQ information derived by EO platforms (in situ, model, satellite) to deliver national and disaggregated city-level information on the indicator, the latter being crucial for hot-spot identification. From its inception, the design was developed with the imperative found in the Resolution adopted by the General Assembly on Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development (A/RES/71/313 (http://ggim.un.org/documents/A_RES_71_313.pdf)) that calls for spatially disaggregated indicators. Although agreement occurred for several countries, comparisons between the indicator approaches yielded differences with respect to EU and WHO limit exceedances, wide divergences with ensuing exposure impacts, countries that necessitate an explicit investigation to delineate the divergence and finally, city-specific differences. All these disparities carry policy implications both at the country, but also on a per city level, thus suggesting that a critical review of the current SDG 11.6.2 workflow is perhaps called for, so as it remains impactful globally and accomplishes the ultimate ambition.

The outlook, limited only by the availability of available modelled and satellite derived PM data, is to move from the European level to global, complementing and helping in the World Health Organization’s efforts as the custodian agency for the SDG indicator, as well as communicating with Eurostat on the European level sustainable development agenda. The SMURBS platform offers a sustainable and scalable methodology, and presents an opportunity for countries that lack the capacity for dense and representative AQ monitoring networks.

ABSTRACT

Earth observation (EO) offers a promising and necessary approach to addressing environmental issues and sustainable development from the city to the global scale. The full potential is currently untapped as global harmonization is necessary for comparability and scalability, as well as streamlining EO integration into informed and efficient decision making. Focusing specifically on city needs, local and national authorities regulate urban air pollution, while the UN SDG 11 indicator 11.6.2 explicitly targets air pollution accounting for population in "cities" and aggregating to the national level. EO brings forth novel monitoring methods to achieve this alongside more traditional ones. However, how a city is spatially defined is an ongoing area of research and policy activity where the definitions differ, which can greatly impact the estimation of exposure to air pollution. To address the varying definitions and move toward a harmonized global approach, the H2020 SMURBS/ERA-PLANET project has created a workflow and tool that adopts two well established definitions of cities to assess population-weighted particulate matter (PM) pollution for approximately 800 European cities. The workflow utilizes the Copernicus Atmospheric Monitoring Service (CAMS – regional ensemble reanalysis) data for $PM_{2.5}$, an open and free European-wide source of air pollution data, overlaid with two European Commission acknowledged city boundary definitions: the Functional Urban Area and the JRC's Degree of Urbanisation Urban Centre. These two approaches yield different results allowing stakeholders to comprehend the city boundary sensitivity of the indicator. Statistical analysis on the results will highlight cases throughout Europe to showcase how important and potentially policy relevant the differences can be based on a city's definition, especially if there is a divergence when aggregated to the national level. The workflow and corresponding online platform can be replicated and scaled up to the global level, which can provide a much needed resource for developing countries and give decision makers an EO-based and consistent tool to help meet societal challenges that are intertwined with urban growth.