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High resolution satellite observations give new view of UK air quality

Richard J. Pope[1,2], Ailish M. Graham[1], Martyn P. Chipperfield[1,2] and J. Pepijn Veefkind[3,4]
[1]*School of Earth and Environment, University of Leeds, Leeds, UK*
[2]*National Centre for Earth Observation, University of Leeds, Leeds, UK*
[3]*Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands*
[4]*Department of Geosciences and Remote Sensing, Delft University of Technology, Delft, The Netherlands*

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Abstract:
New state-of-the-art satellite measurements of tropospheric column NO_2 from the TROPOMI instrument, on-board Sentinel 5 – Precursor (S5P) launched in October 2017, allow for an unprecedented high resolution (sub-10 km) assessment of UK air quality (AQ) from space. We present first results from TROPOMI and compare them with its predecessor, the Ozone Monitoring Instrument (OMI), to quantify previously unresolved UK pollution hotspots (e.g. Bristol, Southampton and Liverpool). The TROPOMI tropospheric column NO_2 data represents a powerful new tool to quantify UK AQ, evaluate atmospheric composition models and potentially derive new emission inventories from space.

1. Introduction:

Poor air quality (AQ) in the UK is an important health concern estimated to result in approximately 40,000 premature deaths per year (Holgate, 2014) and to cost society £8-20 billion annually (House of Commons, 2010). Key pollutants of concern include ozone (O_3), nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$ – atmospheric particles with a diameter less than 2.5 µm), which have been linked to increased risk of cardiovascular and respiratory conditions. It is therefore vitally important to monitor AQ in order to understand the processes controlling pollution levels (e.g. emissions and meteorology). Government policy helped to set up the Automated Urban and Rural Network (AURN - DEFRA, 2015), which provides near-real-time surface measurements of hazardous pollutants using over 100 monitoring sites across the UK. However, the limited spatial coverage of the network struggles to be representative of widespread pollution given the strong gradients in surface emissions and complex meteorology. To help address this issue, over the past few decades satellite measurements have been increasingly used to observe global and regional air pollution. While providing measurements of integrated columns or vertical profiles through the atmosphere, rather than surface concentrations, the spatial coverage of satellite products allows us to monitor AQ nationally (e.g. resolve different cities) and to detect changes over time (e.g. Pope et al., 2018).

One of the most commonly used satellite observations relevant to AQ is tropospheric column NO_2 ($TCNO_2$), derived by Differential Optical Absorption Spectroscopy (DOAS - Eskes and Boersma, 2003) using Ultraviolet (UV) sensors. Compared to other important pollutants, NO_2 is relatively easy to observe from space. Some of the first such measurements were made from the Global Ozone Monitoring Experiment (GOME), launched in 1995 on the ERS-2 satellite (Burrows et al., 1999). GOME successfully detected $TCNO_2$ pollution from anthropogenic regions (e.g. Europe and the USA) and wildfires/biomass burning in the tropical regions, but its coarse horizontal resolution of 40 km ×

320 km (Burrows et al., 1999) precluded the study of AQ on the national scale. Since GOME there have been several satellite instruments measuring $TCNO_2$ at higher spatial resolutions. The Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), on-board Envisat (2002-2012), retrieved $TCNO_2$ at a resolution of 60 km × 30 km (University of Bremen, 2018), while GOME-2 on-board the MetOP A and B satellites (launched in 2006 and 2012, respectively) measures $TCNO_2$ at 40 km x 80 km (Miles et al., 2015). Most recent satellite-based studies of regional AQ (e.g. Pope et al., 2014; Zhou et al., 2012; Laughner et al., 2016) use $TCNO_2$ measurements from the Ozone Monitoring Instrument (OMI) on-board AURA (2004-present), which has a spatial resolution of 13 km x 24 km (Boersma et al., 2008). For example, Pope et al., (2018) used OMI $TCNO_2$ to identify large UK pollution hotspots (e.g. Greater London, the Yorkshire power stations) and to quantify changes over the timespan covered by the data.

In October 2017, the European Space Agency (ESA) launched the TROPOMI instrument on-board Sentinel 5 – Precursor (S5P) as part of the Sentinel programme using multiple satellites and instruments to observe the Earth system (ESA, 2018a). TROPOMI measures $TCNO_2$ at the unprecedented resolution of 3.5 km × 7 km (Veefkind et al., 2012; ESA, 2018b) which has the potential to transform how we can observe near-surface pollution from space. The increased resolution of TROPOMI will provide a much clearer picture of localised pollution sources than has hitherto been possible. To illustrate this, here we present the first high resolution survey of UK $TCNO_2$ from space using TROPOMI data and compare with its predecessor, OMI.

2. Data

We obtained OMI (DOMINO vn2.0) and TROPOMI (TM5-MP-DOMINO vn1.0) $TCNO_2$ data from the Royal Netherlands Meteorological Institute (KNMI). Both instruments are nadir viewing, provide global coverage and measure in the Ultraviolet-Visible (UV-Vis) spectral range (TROPOMI can also view in the Near Infrared - NIR) with local overpass times of ~13.30 (Boersma et al., 2011; Veefkind et al., 2012). We filtered the data sets using quality control flags and only retained data in pixels with geometric cloud fractions less than 0.2. However, degradation of OMI in the latter years of the instrument record, mainly caused by the OMI row anomaly (reduced quality of the radiance data at all wavelengths for a particular viewing angle; KNMI, 2012), limited the robustness of direct comparisons between both instruments for 2018. Therefore, we mapped OMI data for June-July-August (JJA) 2005-2015 over the UK on a 0.05° × 0.05° (5-6 km × 5-6 km) grid using the approach of Pope et al ., (2018), while new TROPOMI data for JJA 2018 was mapped onto a 0.025° × 0.025° (2-3 km × 2-3 km) grid.

3. Observed UK tropospheric column NO_2

The JJA $TCNO_2$ UK distributions (**Figure 1**) are similar for both OMI and TROPOMI with peak NO_2 concentrations over the urban hotspots (e.g. Greater London, Birmingham and Greater Manchester). Over Greater London, $TCNO_2$ from OMI is >10 $\times 10^{15}$ molecules cm^{-2} (**Figure 1a**) while that from TROPOMI is >6 $\times 10^{15}$ molecules cm^{-2} (**Figure 1b**). This OMI-TROPOMI difference is wide spread across the UK. OMI $TNCO_2$ decreased significantly over UK hotspots between 2005 and 2015 (Pope et al., 2018 – e.g. ~20% over London). Thus the OMI long-term average concentrations are expected to be larger than those for TROPOMI in 2018. This is most evident over north-eastern England where a large signal from the Yorkshire power stations (Pope et al., 2016) is detected in the long-term OMI average (**Figure 1a**), but a strong decline in the emitted pollutants yields a less prominent $TCNO_2$

pattern in the recent TROPOMI data (**Figure 1b**). Other contributing factors to the OMI-TROPOMI offset are likely to be that satellite instruments measuring in the UV are prone to systematic differences/calibration issues (Boersma et al., 2008; Irie et al., 2012) and that the two products use different algorithms to retrieve $TCNO_2$. Recently, KNMI used a new retrieval scheme (QA4ECV), which is more closely related to that of TROPOMI, to reprocesses the entire OMI $TCNO_2$ record. Comparisons between OMI-QA4ECV and TROPOMI over China have shown smaller systemic biases (9%) than those presented here (TROPOMI, 2018).

The key advances of TROPOMI over OMI $TCNO_2$ are the larger data volumes per orbit and the higher spatial resolution. With only three months of TROPOMI data it is already possible to generate high resolution UK pollution maps, while for OMI a longer, multi-year JJA time-series is required. The higher resolution of TROPOMI can also reveal isolated hotspots where OMI identifies either a coarse resolution larger scale signal (e.g. over Greater Manchester-Merseyside) or is not sensitive enough to detect clear gradients between sources (e.g. Hampshire).

Figure 2 focusses on the Hampshire, West Country/South Wales, Central Scotland and Greater Manchester/Merseyside regions of the UK where the superior TROPOMI resolution reveals sources previously undetectable by satellite. Over Hampshire (**Figure 2a**), there is a clear gradient between the Southampton-Portsmouth conurbations (4.5-4.7 $\times 10^{15}$ molecules/cm^2) and surrounding area. Peak $TCNO_2$ is located over Southampton and the coastline along the Solent estuary where shipping emissions of nitrogen oxides (NO_x) are high. Comparisons with the most recently available National Atmospheric Emissions Inventory (NAEI, 2014) NO_x emission data (e.g. release of NO_x from sources such as traffic and industry), provided at a 1 km × 1 km spatial resolution, for JJA 2015 support this. Peak rates of over 1 µg/m^2/s are co-located over Southampton, along the Solent and Portsmouth (**Figure 3a**). Slight spatial differences observed between the emission and satellite maps can be explained by the transport and chemical processes influencing the observed $TCNO_2$ concentrations. For a chemical species with a long lifetime (e.g. methane, CH_4, lifetime of ~9.4 years; McNorton et al., 2016), it will be transported over large distances and its distribution will not have a strong link with source regions. However, as NO_2 as a relatively short lifetime (i.e. 6-12 hours: Pope et al., 2015), $TCNO_2$ concentrations are more strongly co-located with the emission sources, though the impact of transport is detected in the $TCNO_2$ data. To further demonstrate the benefits of satellite data, surface AURN NO_2 concentrations (JJA 2010-2016) are over-plotted on the emissions maps (**Figure 3**). Over Hampshire, there are only two sites (coloured pink or yellow if below or above 15 µg/m^3) in the domain representing the limited spatial coverage the network provides to monitor AQ.

Over the West County and South Wales (**Figure 2b**), three clear hotspots exist over Bristol, Cardiff and Port Talbot. OMI only detects a broad signal over the region at approximately 5.5-6.0 $\times 10^{15}$ molecules/cm^2. However, TROPOMI reveals a clear signal in NO_2 attributable to pollution from emissions in Bristol (>3.5 $\times 10^{15}$ molecules/cm^2). It also detects the major motorway network (M5 and M4) and shipping activity at Avonmouth. All of these sources can also be seen in the NAEI NO_x emissions (**Figure 3b**) with peaks of over 1 µg/m^2/s at Avonmouth. On the opposite side of the River Severn, the Cardiff and Newport signal can also be detected at approximately 3.0-3.2 $\times 10^{15}$ molecules/cm^2. The signal at Port Talbot is clearer than that of Swansea (next city westwards along the coastline) and is dominated by large shipping emissions. In **Figure 3b**, total NO_x emissions at Port Talbot peak at 0.8-0.9 µg/m^2/s, extending out into the sea (~0.4 µg/m^2/s). Again, there are only a few

AURN sites in the region with limited spatial information on the regional AQ, highlighting the advantages and novelty of satellite observations.

In Central Scotland (**Figure 2c**), the $TCNO_2$ signal is weaker and noisier, but clear hotspots still exist over Glasgow (>3.0 $\times 10^{15}$ molecules/cm^2) and the Forth Estuary (2.0-2.5 $\times 10^{15}$ molecules/cm^2). Edinburgh, Falkirk, Livingston and Dunfermline $TCNO_2$ hotspots all collocate with NAEI NO_x emissions sources (0.3-0.5 µg/m^2/s, **Figure 3c**), but peak emissions (0.8-0.9 µg/m^2/s) exist over the Forth Estuary (i.e. shipping and transport across the Forth). OMI $TCNO_2$ data over the same region struggles to detect these signals and only indicates a broad signal around the Forth Estuary and over Glasgow. In the background regions, given the low $TCNO_2$ concentrations, there is a significant level of noise in the TROPOMI data, unlike the other three UK regions discussed here.

OMI detects elevated $TCNO_2$ over Manchester (**Figure 1a**) but no clear hotspot over Liverpool; only an NO_2 gradient between the Irish Sea and Manchester. However, in **Figure 1b**, TROPOMI identifies two separate hotspots over Manchester (5.5-6.5 $\times 10^{15}$ molecules/cm^2) and Liverpool (5.0-5.5 $\times 10^{15}$ molecules/cm^2). Between the two hotspots (**Figure 2d**), $TCNO_2$ concentrations are still elevated (4.0-5.0 $\times 10^{15}$ molecules/cm^2) where other smaller cities/towns (e.g. Wigan and Warrington) and motorways (e.g. M62 and M6) are located. In **Figure 3d**, Manchester and Liverpool have peak emissions of >1 µg/m^2/s and 0.7-0.9 µg/m^2/s, respectively, generally co-located with the satellite hotspots. Between the two cities, NO_x emissions from the M6, M62 and M56 range from 0.5 to 1.0 µg/m^2/s, contributing to the enhanced $TCNO_2$ concentrations between the cities. Out of the four sub-regions, the largest number of AURN sites are in this domain (all above 15 µg/m^3 for JJA), but significant gaps still exist in the surface network (**Figure 3d**).

Overall, TROPOMI provides a new high resolution $TCNO_2$ product which can be utilised to observe and quantify UK pollution hotspots not previously detectable from space. This is most evident over Central Scotland and the West Country / South Wales, where the concentrations are lower and the background $TCNO_2$ concentrations are noisier.

4. Summary and Outlook

Over recent decades, satellite instruments have had increasing capability to measure air pollutants from space at ever increasing spatial resolutions. The launch of S5P in 2017 is yielding, through TROPOMI, the first data set of tropospheric column NO_2 retrieved at a sub-10 km × sub-10 km resolution. This research demonstrates the ability of TROPOMI to detect UK pollution hotspots, not previously possible with satellite data. This new data from TROPOMI provides an exciting opportunity to better monitor and quantify air pollutant sources at unparalleled spatial resolutions, help inform public policy, evaluate and develop air quality modelling frameworks (which provide important pollutant forecasts) and potentially derive new emissions data sets from space to evaluate the NAEI equivalent. Our article has focussed on observations over the UK, but the impact of the new TROPOMI data will be similar the world over.

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Figures:

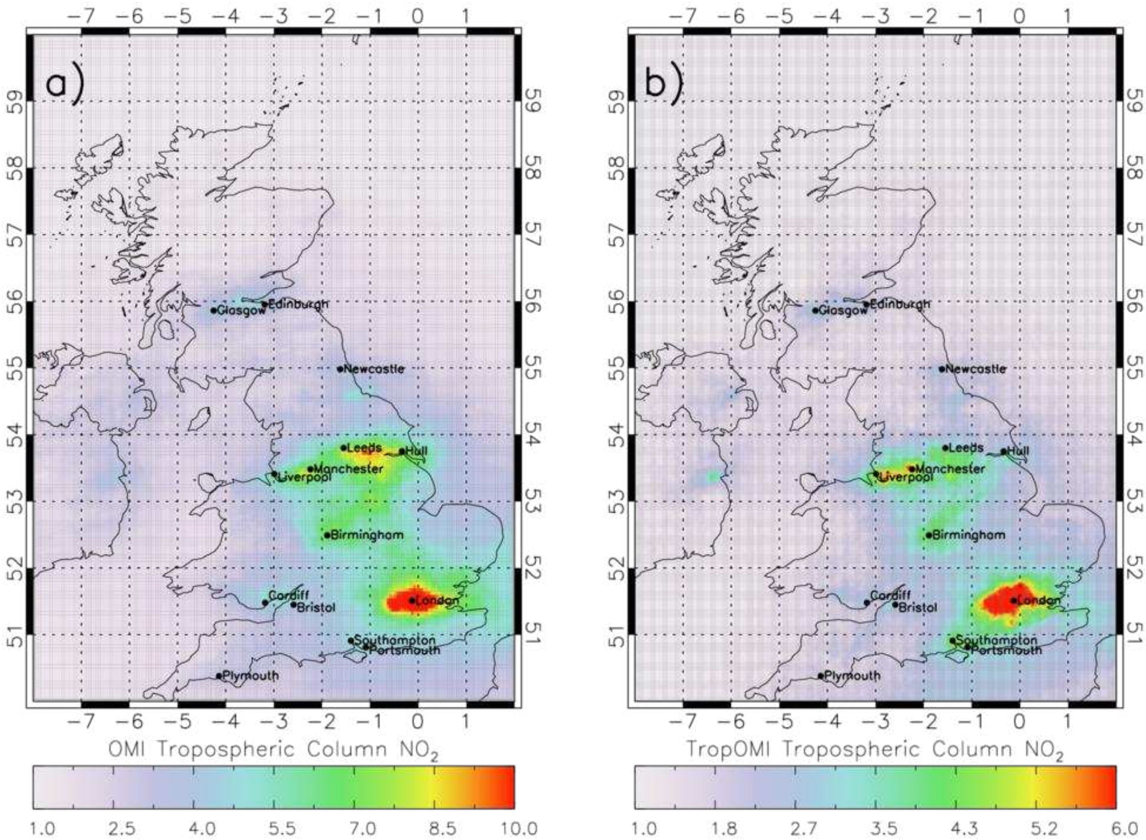

Figure 1: Mean satellite tropospheric column NO_2 ($TCNO_2$, 10^{15} molecules/cm^2) for June-July-August (JJA) from a) the Ozone Monitoring Instrument (OMI) (2005-2015 mean) and b) TROPOMI (2018).

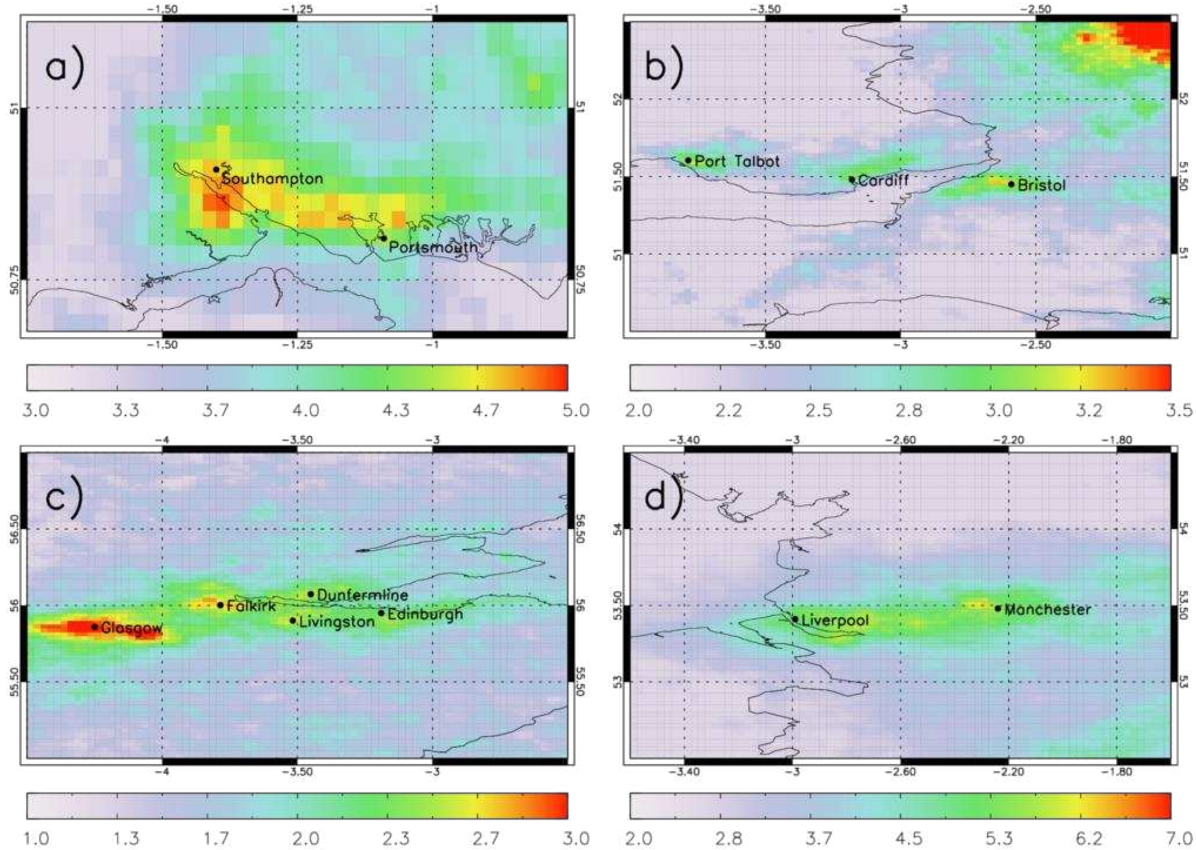

Figure 2: TROPOMI $TCNO_2$ (10^{15} molecules/cm^2) for JJA in 2018 for the UK regions: a) Hampshire, b) West Country - South Wales, c) Central Scotland and d) Greater Manchester-Merseyside. Note the difference in spatial scale between panel a) and panels b)-d).

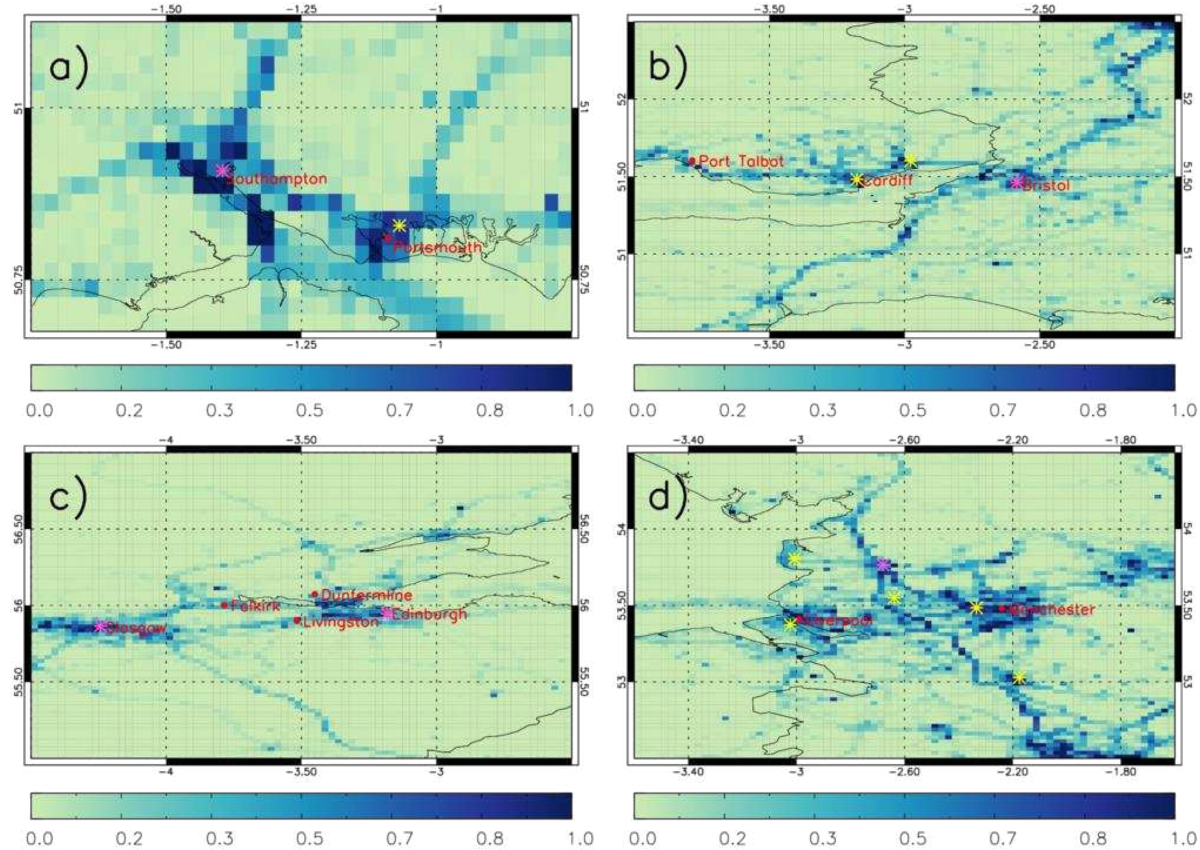

Figure 3: National Atmospheric Emissions Inventory (NAEI) nitrogen oxide (NO_x) emissions (µg/m^2/s) for JJA 2015 for the same UK regions as shown in Figure 2: a) Hampshire, b) West Country and South Wales, c) Central Scotland and d) Greater Manchester-Merseyside. Stars represent the location of urban background and rural Automated Urban and Rural Network (AURN) surface NO_2 measurements and the colour indicates the mean observed value (pink ≤ 15 µg/m^3 and yellow > 15 µg/m^3).