SUPPORTING INFORMATION AVAILABLE

Inferring the anthropogenic NO_x emission trend over the United States during 2003 - 2017 from satellite observations: Was there a flattening of the emission tend after the Great Recession?

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Table S1. Summary of major satellite instruments for remote sensing of atmospheric NO_2 VCD in the past decade

Instrument	Satellite	Launch date	End date	Operator	Equator crossing time (local time)	UV/Vis Spectral range (nm)	Spectral resolution (nm)	Swath length (km)	Nadir pixel resolution (km × km)	Global coverage (days)
SCIAMACHY	ENVISAT[1]	03/01/2002[2]	04/08/2012[2]	ESA[3]	10:00[1]	240 – 805[4]	0.24 – 0.48[4]	960[5]	60 × 30[5]	6[5]
GOME-2A	MetOp-A[6]	10/19/2006[6]	in operation	EUMETSAT[7]	9:30[8]	240 – 790[8]	0.26 – 0.51[8]	1920 before Jul. 15th, 2013; 960 after Jul. 15th, 2013[8]	80 × 40 before Jul. 15th, 2013; 40 × 40 after Jul. 15th, 2013[8]	1.5[9]
GOME-2B	MetOp-B[6]	09/17/2012[6]	In operation	EUMETSAT	9:30[8]	240 – 790[8]	0.26 – 0.51[8]	1920[8]	80 × 40[8]	1.5[9]
OMI	EOS-Aura[10]	07/152004[10]	In operation	NASA	13:45[10]	270 – 500[11]	0.45 – 1.0[11]	2600[11]	24 × 13[11]	1[11]

[1] Refer to https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat
[2] Refer to https://en.wikipedia.org/wiki/Envisat
[3] The European Space Agency
[4] Refer to http://www.iup.uni-bremen.de/sciamachy/instrument/performance/index.html
[5] Refer to Boersma et al. (2008), Boersma et al. (2009), and (Lee et al., 2009)
[6] Refer to https://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/index.html
[7] The European Organization for the Exploitation of Meteorological Satellites
[8] Refer to EUMETSAT (2015)
[9] Refer to Lee et al. (2009) and Wang et al. (2017)
[10] Refer to https://aura.gsfc.nasa.gov/
[11] Refer to https://aura.gsfc.nasa.gov/omi.html

Table S2. Summary of satellite NO_2 TVCD products and their retrieval information

NO_2 TVCD products	Version	Available period	DOAS fitting method	Stratosphere–troposphere separation	Fitting window (nm)	Albedo / reflectance	A priori profiles	Radiative transfer model	Cloud	Uncertainty
GOME-2B	TM4NO2A (2.3)	12/20/2012 – current	Intensity fit[1]	Assimilation of satellite total slant columns in the TM4 model[2, 3]	405 – 465[1]	Climatology albedo from 3 years of OMI data[4]	TM4 (2° × 3°)[2]	DAK[2]	FRESCO+ (Oxygen A-band around 760 nm)[5]	1.0×10^{15} molecules/cm^2 + 25%[2]
SCIAMACHY	QA4ECV (v1.1)	08/02/2002 – 04/08/2012	Optical Density[1, 6]	Assimilation of OMI total slant columns in the TM5 - MP model[6, 7]	425 – 465[6]	Climatology albedo based on SCIAMACHY[8]	TM5-MP (1° × 1°)[6]	DAK	FRESCO+	35% - 45% over polluted scenes; > 100% over background regions (Pacific Ocean)[6]
GOME-2A	QA4ECV (v1.1)	02/01/2007 – 12/31/2016			405 – 465[1, 6]	Climatology albedo based on GOME-2A[8]			FRESCO+	
OMI-QA4ECV	QA4ECV (v1.1)	10/012004 – Current			405 – 465[1, 6]	Climatology albedo from 5 years of OMI data[6]			Improved O_2-O_2 (477 nm)[9]	
OMI-NASA	SPv3	01/01/2005 – 07/31/2017	Stepwise intensity fit with monthly averaged solar irradiance spectrum[1, 10]	Based on OMI total slant columns over regions with low estimated TVCD contributions (TVCD contributions less than 0.3×10^{15} molecules/cm^2)[10]	402 – 465[1, 10]	OMI climatology albedo[10]	GMI (1° × 1.25°)[10]	TMORAD[10]	O_2-O_2 (477 nm)[10, 11]	SPv2.1 TVCD has uncertainties of about 30% under clear-sky conditions to about 60% under cloudy conditions[12], and the relative difference between SPv3 and SPv2.1 is less than ~20%[10].
OMI-BEHR[13]	v3.0B	01/01/2005 – 07/31/2017				Based on MCD43D BRDF product (for land) and model parameterization (for ocean)	WRF-Chem (12 km)			~ 45% on average[14]

[1] Refer to Zara et al. (2018)
[2] Refer to Boersma et al. (2011). "TM4" is the Tracer Model, version 4. "DAK" is the Doubling-Adding KNMI (DAK) radiative transfer model.
[3] Refer to Williams et al. (2009)
[4] Refer to Kleipool et al. (2008)
[5] Refer to Wang et al. (2017) and Wang et al. (2008)
[6] Refer to Boersma et al. (2018)
[7] Refer to Williams et al. (2017)
[8] Refer to Tilstra et al. (2017)
[9] Refer to Veefkind et al. (2016)
[10] Refer to Bucsela et al. (2013), Bucsela et al. (2016), Krotkov et al. (2017), and Marchenko et al. (2015). "TMORAD" is the TMOS radiative transfer model.
[11] Refer to Acarreta et al. (2004)
[12] Refer to Lamsal et al. (2014), Oetjen et al. (2013), and Tong et al. (2015)
[13] Refer to Laughner et al. (2018). OMI-BEHR uses the SCD from OMI-NASA SPv3 but updates inputs for the AMF calculation, such as a prior NO_2 vertical profiles and surface reflectance. Besides, OMI-BEHR only provides NO_2 TVCD over the contiguous United States (CONUS). As in this study, we used the OMI-NASA datasets archived in the OMI-BEHR product, so we only obtained OMI-NASA datasets extended to July 31, 2017.
[14] Average uncertainty over the CONUS is calculated based on the file from http://behr.cchem.berkeley.edu/behr/BEHR-us-uncertainty.hdf

Table S3. Selection criteria for satellite NO_2 TVCD pixel data

NO_2 TVCD products	Period	Solar zenith angle	albedo	Cloud radiance fraction	Snow or ice covered	AMFtrop/AMFgeo	Flag for retrieval success	Retrieval quality flag	Rows in swath
GOME-2B	01/01/2013 – 12/31/2017	< 80°	<= 0.3	<= 50%	No	> 0.2	Yes		All
SCIAMACHY	01/01/2003 – 12/31/2011	< 80°	<= 0.3	<= 50%	No	> 0.2	Yes		All
GOME-2A	01/01/2008 – 12/31/2016	< 80°	<= 0.3	<= 50%	No	> 0.2	Yes		All
OMI-QA4ECV[1]	01/01/2005 – 12/31/2017	< 80°	<= 0.3	<= 50%	No	> 0.2	Yes		6 - 21
OMI-NASA[1]	01/01/2005 – 12/31/2016	< 80°	<= 0.3	<= 50%			Yes	Yes	6 – 21
OMI-BEHR[1]	01/01/2005 – 12/31/2016	< 80°	<= 0.3	<= 50%			Yes	Yes	6 - 21

[1] Rows 6-21 are selected to remove the anomalies developed in the OMI sensor (Boersma et al., 2018; Zhang et al., 2018).

Table S4. Summary of annual trends of AQS NO_2 surface concentrations and satellite NO_2 TVCD products in each region during different periods[1]

		Northeast		Midwest		South		West	
		AQS site	CONUS	AQS site	CONUS	AQS site	CONUS	AQS site	CONUS
AQS NO_2 VMR at 13:00 -14:00	2003 – 2011	-6.8 ± 0.7%		-6.1 ± 1.2%		-6.6 ± 0.7%		-7.6 ± 1.2%	
	2011 – 2017	-8.0 ± 1.2%		-6.4 ± 0.8%		-5.8 ± 0.6%		-7.2 ± 1.6%	
AQS NO_2 VMR at 10:00 – 11:00	2003 – 2011	-6.6 ± 0.5%		-5.8 ± 1.5%		-6.5 ± 1.3%		-7.1 ± 1.6%	
	2011 – 2017	-7.6 ± 1.0%		-6.8 ± 0.5%		-5.7 ± 0.1%		-6.1 ± 1.1%	
SCIAMACHY	2003 – 2011	-17.1 ± 2.7%	-11.0 ± 3.3%	-12.9 ± 6.8%	-6.5 ± 0.8%	-9.1 ± 1.0%	-6.2 ± 1.5%	-9.1 ± 1.8%	-7.0 ± 1.4%
	2011 – 2017								
GOME2B	2003 – 2011								
	2013 – 2017	-11.4 ± 3.7%	-10.8 ± 3.9%	-9.9 ± 13.1%	-4.4 ± 27.2%	-8.9 ± 3.0%	-7.5 ± 3.6%	-11.8 ± 3.0%	-10.6 ± 2.3%
OMI-QA4ECV	2005 – 2011	-14.2 ± 6.3%	-10.6 ± 3.8%	-9.2 ± 4.2%	-8.4 ± 2.8%	-9.2 ± 2.7%	-8.2 ± 1.5%	-10.5 ± 1.6%	-8.7 ± 0.9%
	2011 – 2017	-18.0 ± 16.2%	-7.6 ± 4.2%	-7.6 ± 3.3%	-7.0 ± 1.7%	-4.8 ± 1.4%	-4.6 ± 1.0%	-6.4 ± 1.4%	-4.8 ± 1.2%
OMI-NASA	2005 – 2011	-11.8 ± 1.3%	-11.0 ± 1.8%	-10.9 ± 4.8%	-10.0 ± 4.1%	-10.0 ± 3.5%	-9.5 ± 1.9%	-10.2 ± 1.8%	-8.5 ± 0.9%
	2011 – 2016	-10.0 ± 4.9%	-8.5 ± 3.8%	-13.2 ± 3.2%	-9.2 ± 2.7%	0.3 ± 19.2%	-8.0 ± 5.5%	-9.0 ± 5.7%	-6.6 ± 3.9%
OMI-BEHR	2005 – 2011	-11.8 ± 1.8%	-10.9 ± 1.9%	-12.2 ± 7.3%	-9.8 ± 4.4%	-9.5 ± 3.1%	-8.8 ± 2.0%	-9.9 ± 1.1%	-8.2 ± 0.4%
	2011 – 2016	-8.2 ± 3.4%	-6.6 ± 1.7%	-27.4 ± 24.3%	-8.1 ± 3.0%	-7.2 ± 2.3%	-5.0 ± 1.3%	-13.2 ± 14.5%	-7.0 ± 4.8%

[1] Annual trends are the averages of regional seasonal trends (e.g, Figure 7).

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