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A global catalogue of SO_2 sources and emissions derived from the Ozone Monitoring Instrument

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ATMOS 2015 Conference, University of Crete, Heraklion, Greece, 8-12 June 2015

OMI Principal Component Analysis (PCA) Algorithm SO_2 Data

Sources:

OMI - NASA Goddard (http://so2.gsfc.nasa.gov)

We used Level 2 data product with constant AirMass Factor (0.36) that corresponds to boundary layer

Data filtering:

- by cloud fraction (<0.2)
- by solar zenith angle (<70)
- only no snow conditions
- “row anomaly” – affected data excluded
- OMI cross track positions 10-50 (near nadir small pixels)
- days with SO_2 from volcanic eruptions were excludes

Reference:

Li, C., Joiner, J., Krotkov, N. A. and Bhartia, P. K.: A fast and sensitive new satellite SO_2 retrieval algorithm based on principal component analysis: Application to the ozone monitoring instrument, Geophys. Res. Lett., 40(23), 6314–6318, doi:10.1002/2013GL058134, 2013.

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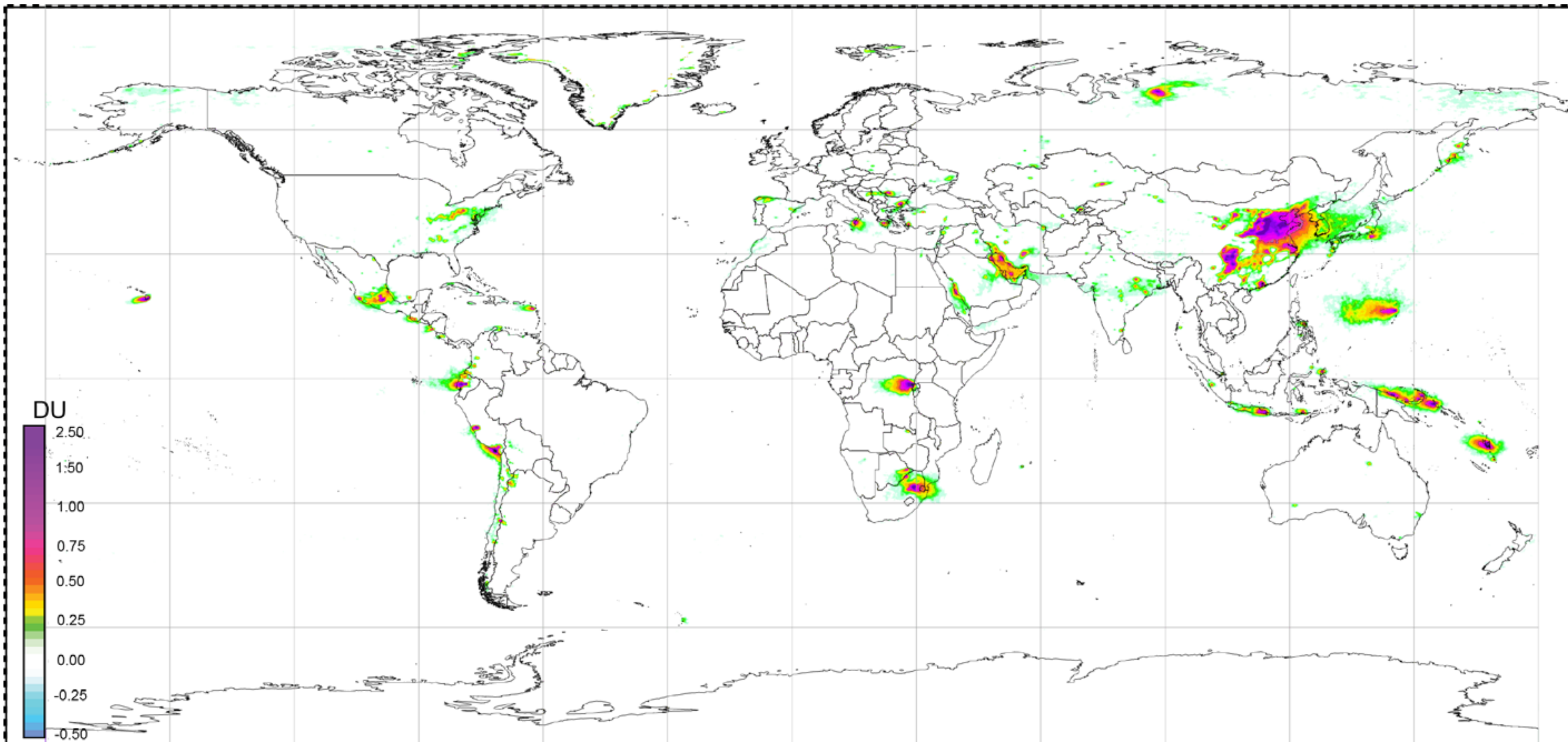
Mean OMI PCA SO_2 values for 2005-2007

- Unlike most of the previous satellite SO_2 data products, OMI PCA data sets does not have “background” biases
- SO_2 sources appears mostly as “hotspots”
- ***Our analysis is focused on point sources***



The area affected by the North Atlantic Anomaly is hidden

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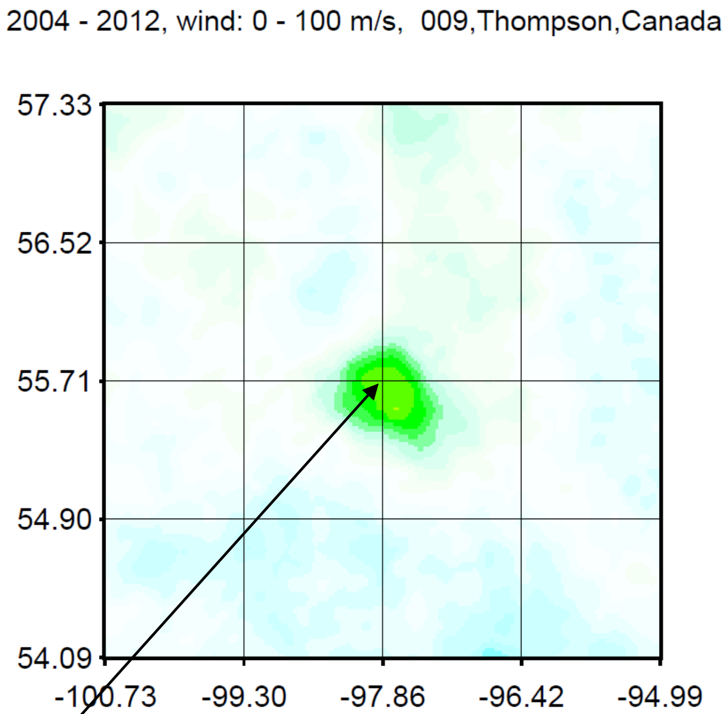
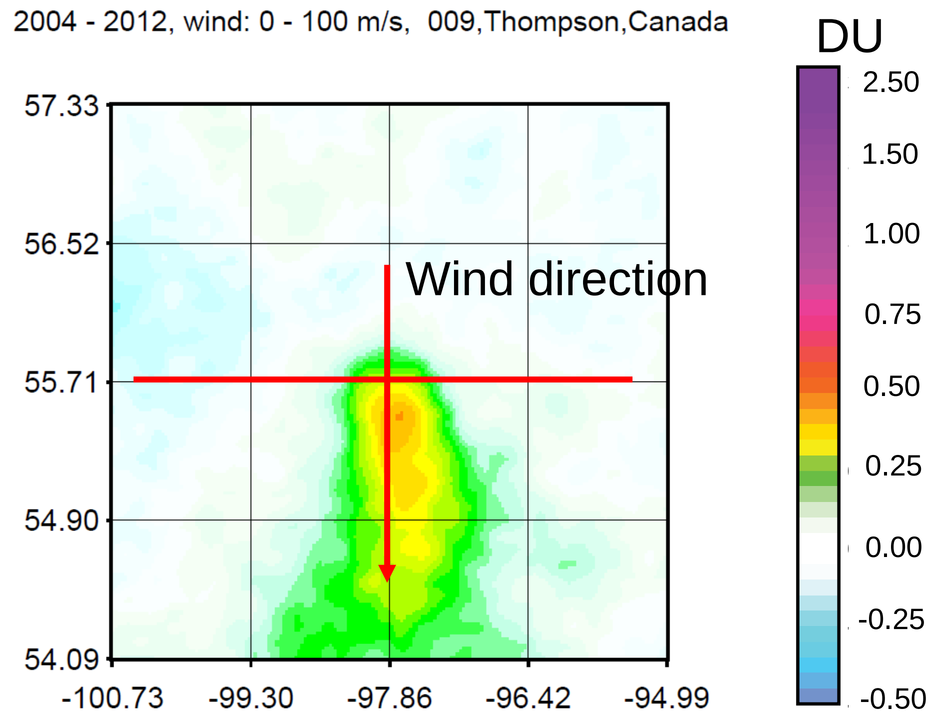
Merging satellite data and meteorology

Mean SO_2 from OMI near Thompson, Manitoba (55N, 98 W).

The same data after rotation of all pixels around the source in a upwind-downwind direction.



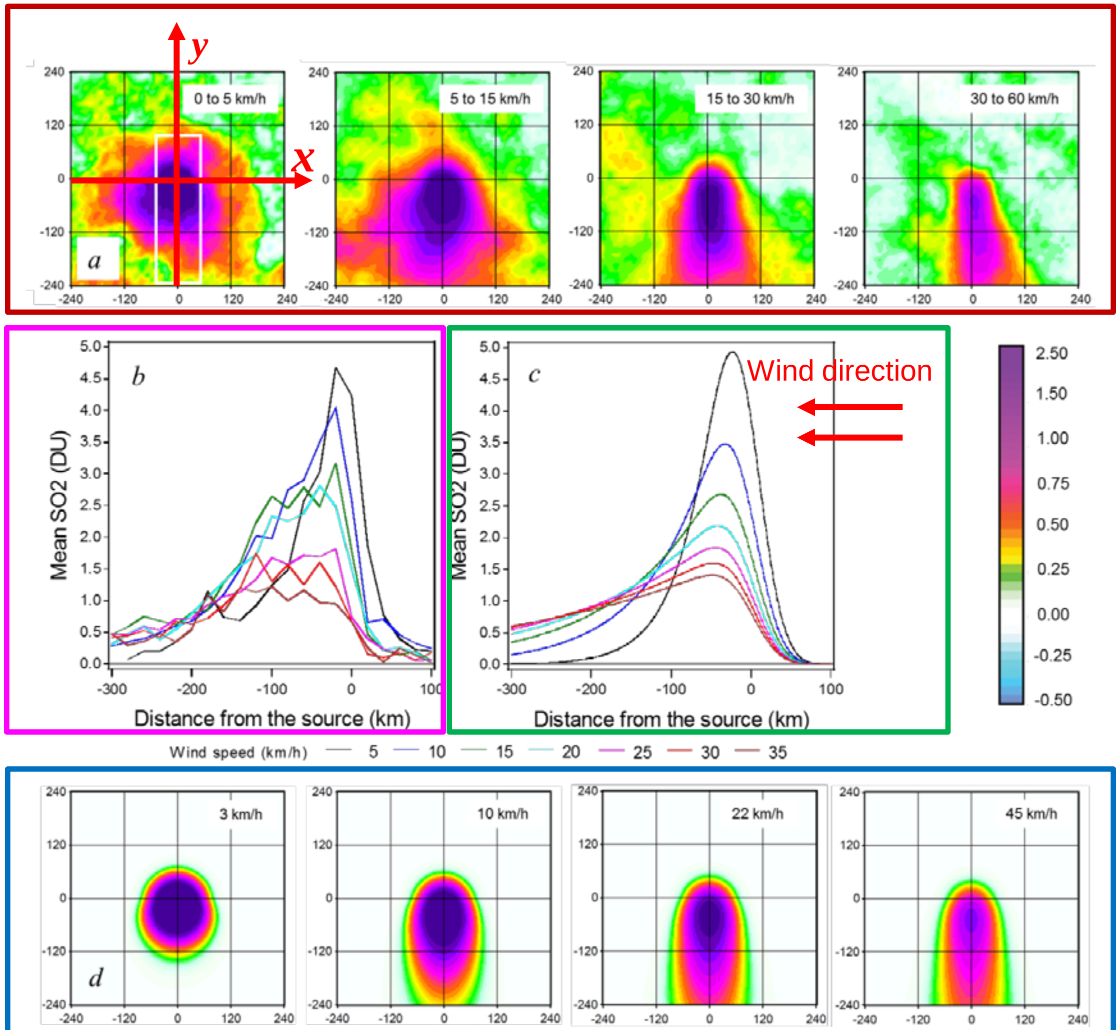


Downwind decay of pollutants can be studied using a rotation scheme in which the locations of all observation are adjusted so that the have a common wind-direction

Emission Estimates: The fitting algorithm: $OMI_{SO2} = a\,f(x,y)\,g(y,w)$

$f(x, y)$ - Gaussian function, $g(y, w)$ - Exponentially modified Gaussian function;

x, y are the coordinates, w is the wind speed



OMI PCA data:

a. Mean total column SO_2 (in DU) near **Norilsk (69°N, 88°E)** after rotation of all pixels in a upwind-downwind direction for 2005-2013 stratified by the wind speed. The axis show the distance from the source in km.

b. Mean total column SO_2 near Norilsk for different wind speed groups for the area within ±50 km across the wind direction (the white rectangle in (a)) as a function of the distance from the source (negative for the downwind), after rotation of all pixels in a upwind-downwind direction.

Fitting results:

c. Exponentially modified Gaussian function $g(y, w)$, where y is the distance from the source and w is the wind speed that represents the best fit to Norilsk data on the left.

d. The fitting results for different wind speeds as indicated on the plot.

Fioletov et al., GRL, 2015

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It is assumed that SO_2 concentrations (emitted from a point source) decline with time (t) as $exp(-\lambda t)$, i.e., with a constant decay rate ($\tau = 1/\lambda$)

σ represents the spread due to diffusion

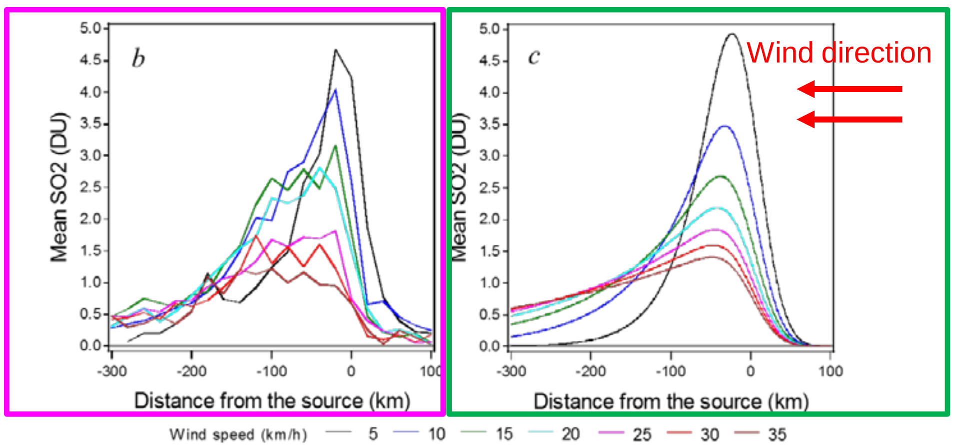
$$f(x,y) = \frac{1}{\sigma_1 \sqrt{2\pi}} exp\left(-\frac{x^2}{2\sigma_1^2}\right);$$

$$g(y,w) = \frac{\lambda_1}{2} exp\left(\frac{\lambda_1(\lambda_1\sigma^2 + 2y)}{2}\right) \cdot erfc\left(\frac{\lambda_1\sigma^2 + y}{\sqrt{2}\sigma}\right);$$

$$\sigma_1 = \begin{cases} \sqrt{\sigma^2 - 1.5y},\ y < 0 \\ \sigma,\ y \geq 0 \end{cases};$$

$$\lambda_1 = \lambda / w;$$

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt$$



Parameters σ, λ, and a, were estimated from the fit

Since $\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y) \cdot g(y,w) dx dy = \int_{-\infty}^{\infty}\left(\int_{-\infty}^{\infty} f(x,y) dx\right) \cdot g(y,w) dy = \int_{-\infty}^{\infty} g(y,w) dy = 1$, a is the SO_2 mass

Emissions: $E = a/\tau$, where (1) τ is prescribed or (2) estimated as $1/\lambda$

If both τ and σ are prescribed, then a is the only parameter that can be estimated by simple linear regression

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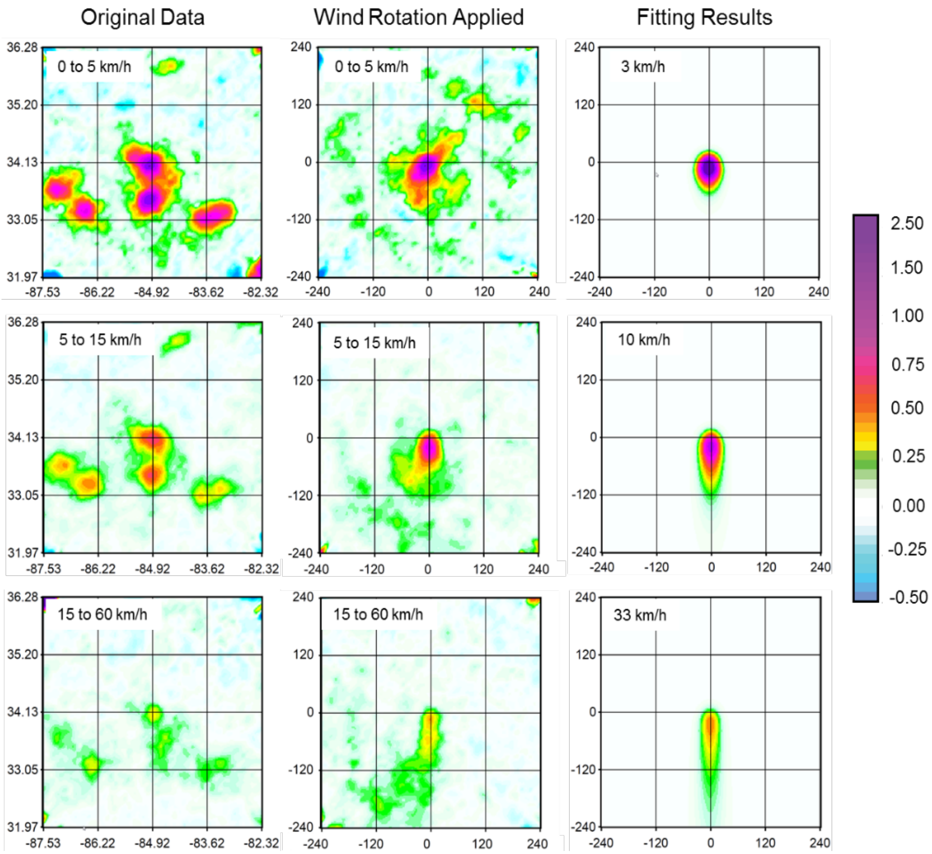
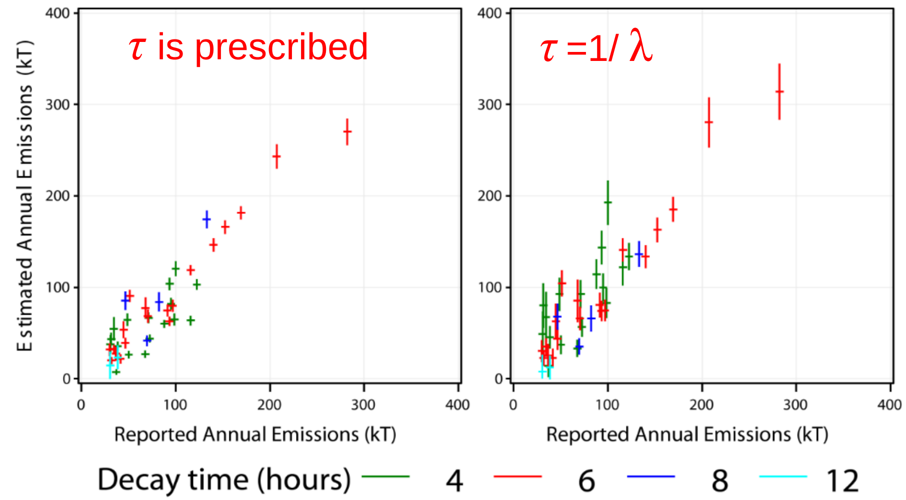
Estimation of emissions from US major sources using OMI PCA data



The mean column SO_2 values (in DU) for 2005-2007 near the largest US SO_2 source (**Bowen power plant in Georgia**, 170 kt y^{-1} in 2005) located in the center of each plot. The data are stratified by the wind speed. The right column demonstrates the fitting results for different wind speeds as indicated on the plot.



(left) Scatter plots of annual SO_2 emission from the largest US sources in 2005 vs. emissions calculated from OMI data for 2005-2007 assuming a constant the decay time (τ=6 hours) estimated from the best fit of the reported emissions

(right) The same plot but with emissions calculated from OMI data with both parameters estimated from the fit. Emissions are given in kt y^{-1} calculated assuming a constant emission rate.

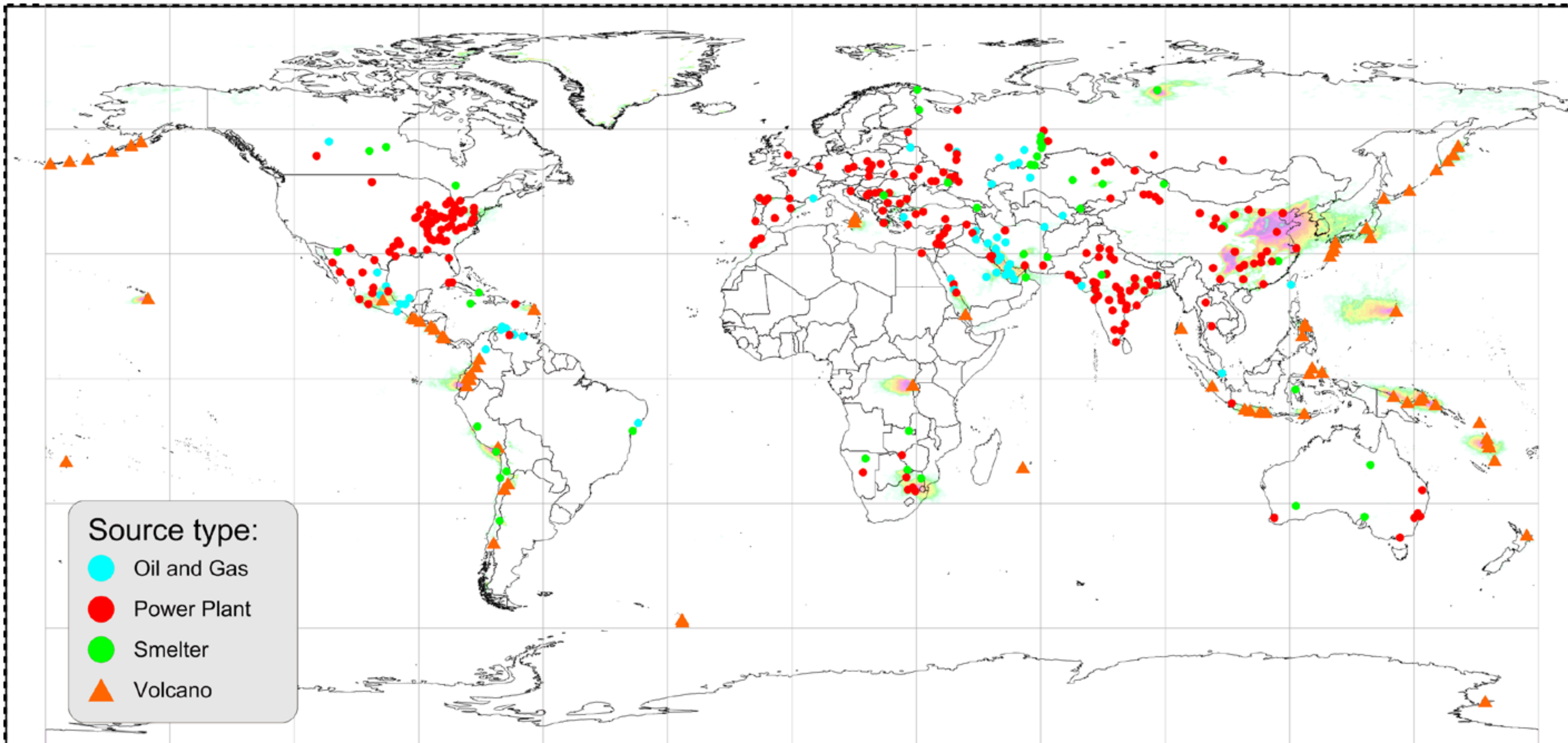
The error bars represent the one sigma confidence intervals. Different colors indicate estimated decay times ($\tau = 1/\lambda$).

Fitting window: 30km x 30 km x 30 km x 150 km

Fioletov et al., GRL, 2015

OMI SO_2 "catalogue"

- Determine "hotspots" as areas where mean values are above 0.1 DU and over ~5 sigma level
- Check "hotspots" against databases of power plants, smelters, oil and gas refineries, other industrial sources, and volcanoes
- At present, 386 sites based on 2005-2007 data (222 Power Plants, 44 Smelters, 48 Oil and Gas industry-relates sources, 72 Volcanoes) with annual emissions from 30 to 5000 kt.
- ***The catalogue includes site locations, source types and annual emission estimates for 2005-2014***



Note: China source inventory is not complete because there are too many sources

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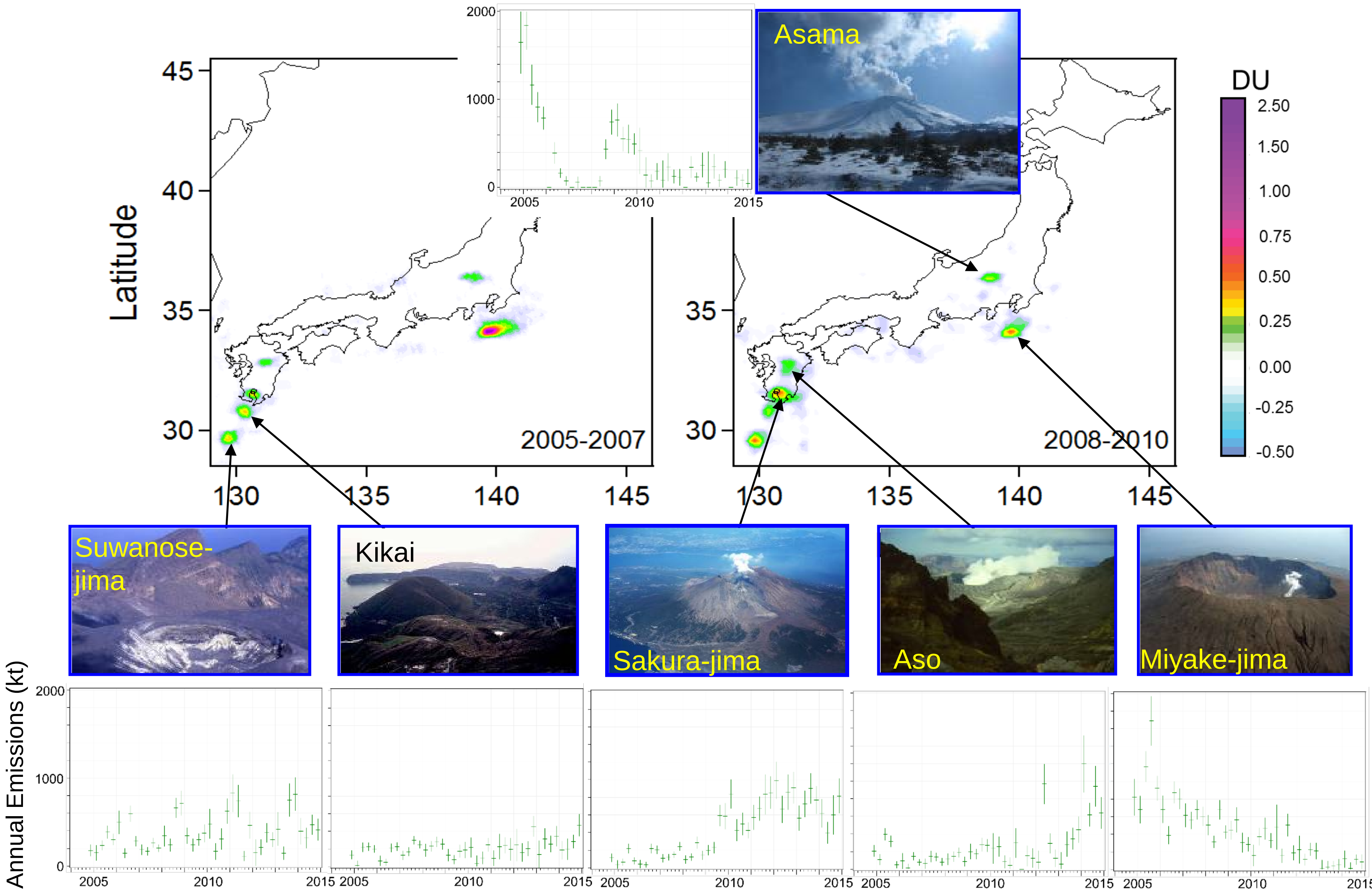
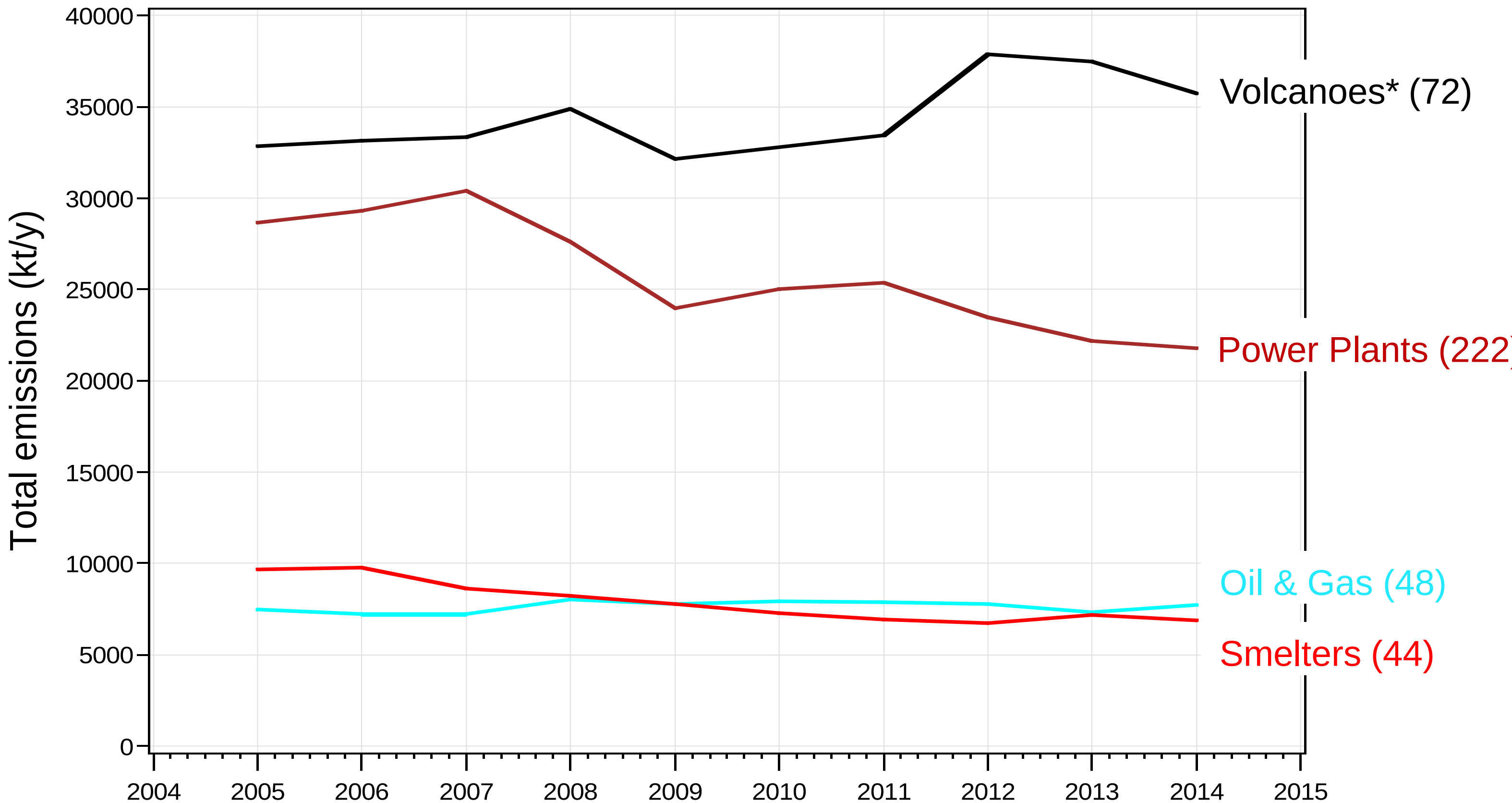
Catalogue example: Degassing SO_2 from Volcanoes in Japan



Total Annual Emissions by the Source Type

Estimated from sources seen by OMI



*Excluding explosive eruptions

- There is a substantial decide in emissions from power plants in USA, China, Europe, and other countries due to scrubber installation
- Large smelters in Peru, Kazakhstan, Canada, etc., were either closed or reduced their emissions in recent years

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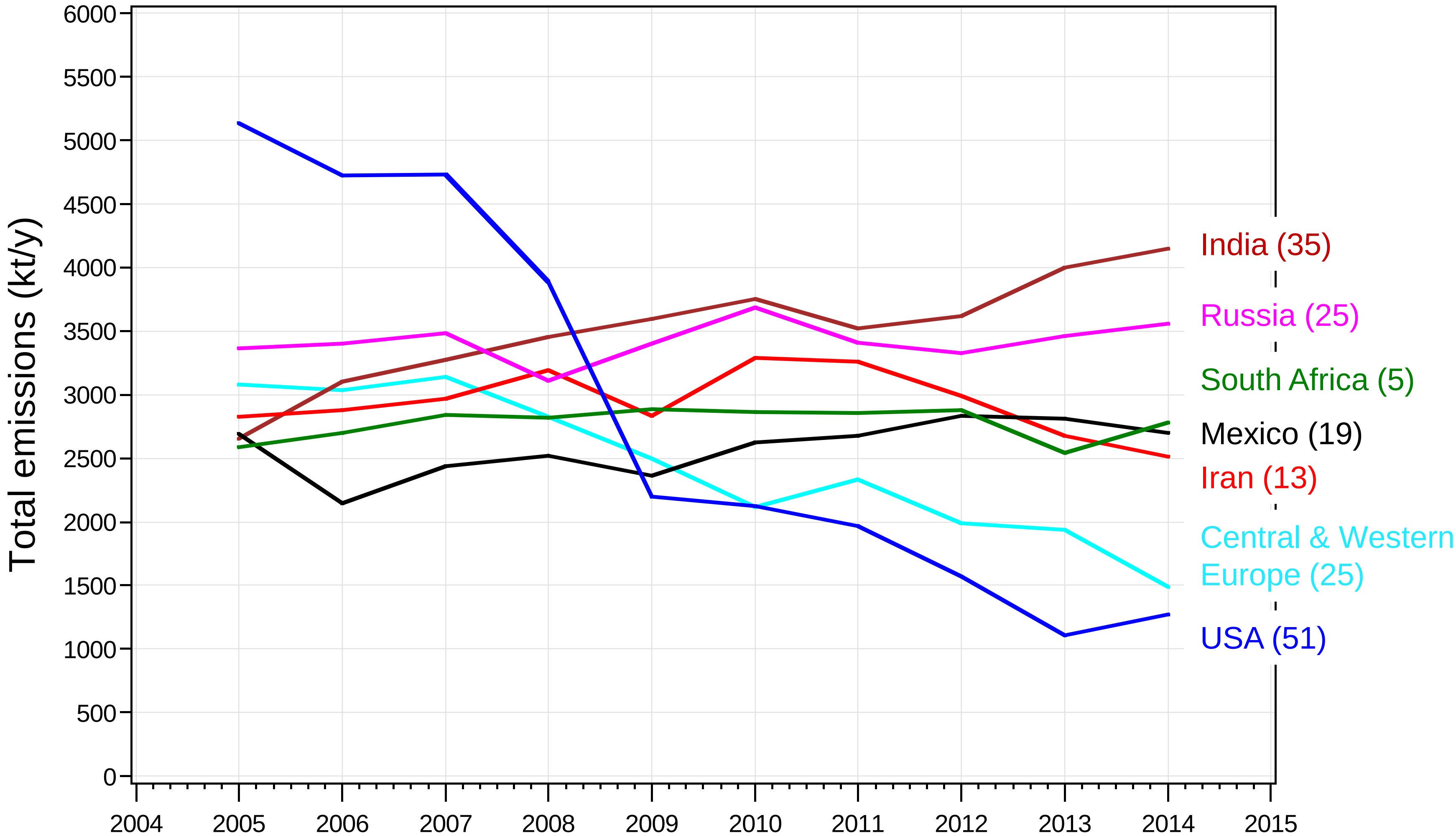
Total Annual Emissions by Country/Region

Estimated from sources seen by OMI



The number of sites from the catalogue is shown in brackets

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OMI bottom-up emission estimates vs. emissions inventories

Average total SO_2 emissions for 2005-2011 by region (kt y^{-1}) estimated from OMI data and from emission inventories (Klimont et al., *Environm. Res. Lett*., 2013) and the ratio of the OMI-based estimates to the inventory values. The number of sites for each country/area in the catalogue is also shown.

Country/Area	Number of sites	OMI-based estimates	Emission inventories	Ratio
China*	29	6268	31352	0.20
Canada	7	546	2071	0.26
EU-15	13	1117	3214	0.33
USA	51	3624	10010	0.35
India	35	3335	8410	0.40
Central Europe	17	2056	3609	0.57
Turkey	5	867	1515	0.57
Central America	11	1398	2298	0.61
Russia	25	3467	5344	0.66
Australia	9	976	1391	0.70
Central Asia	12	1494	2095	0.72
Ukraine**	11	1195	1323	0.91
South Africa	5	3041	2689	1.13
Middle East	37	7210	5509	1.31
Mexico	19	2512	1158	2.40

*Source catalogue for China is incomplete
**Also includes Belarus

As OMI sees only relatively large sources, it is expected that OMI underestimates country emissions leading to a ratio less than 1. Ratios greater than 1 may indicate missing or underestimated sources in inventories.

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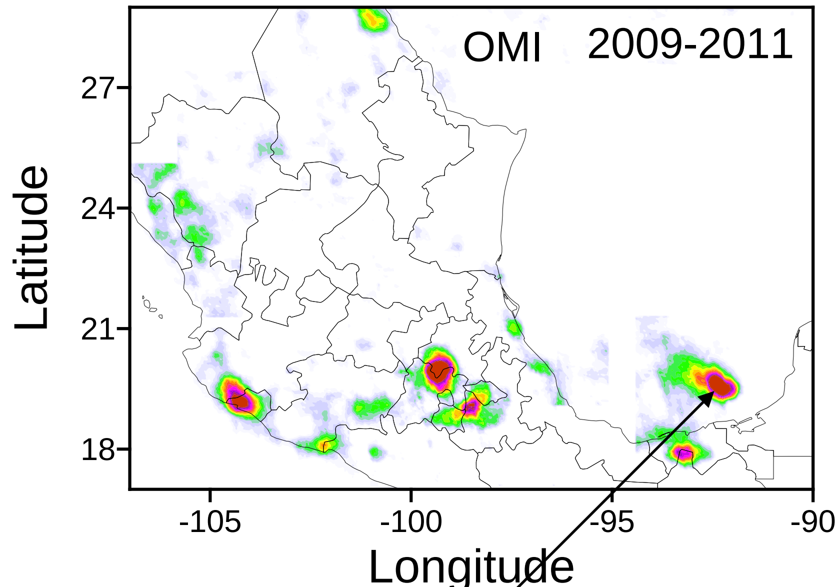
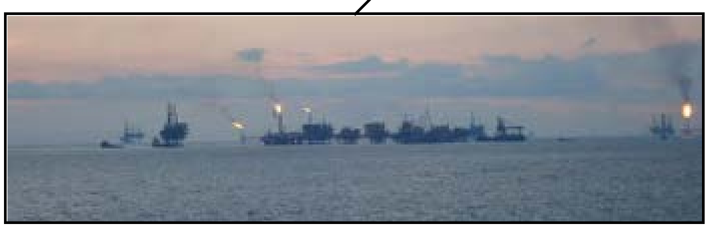
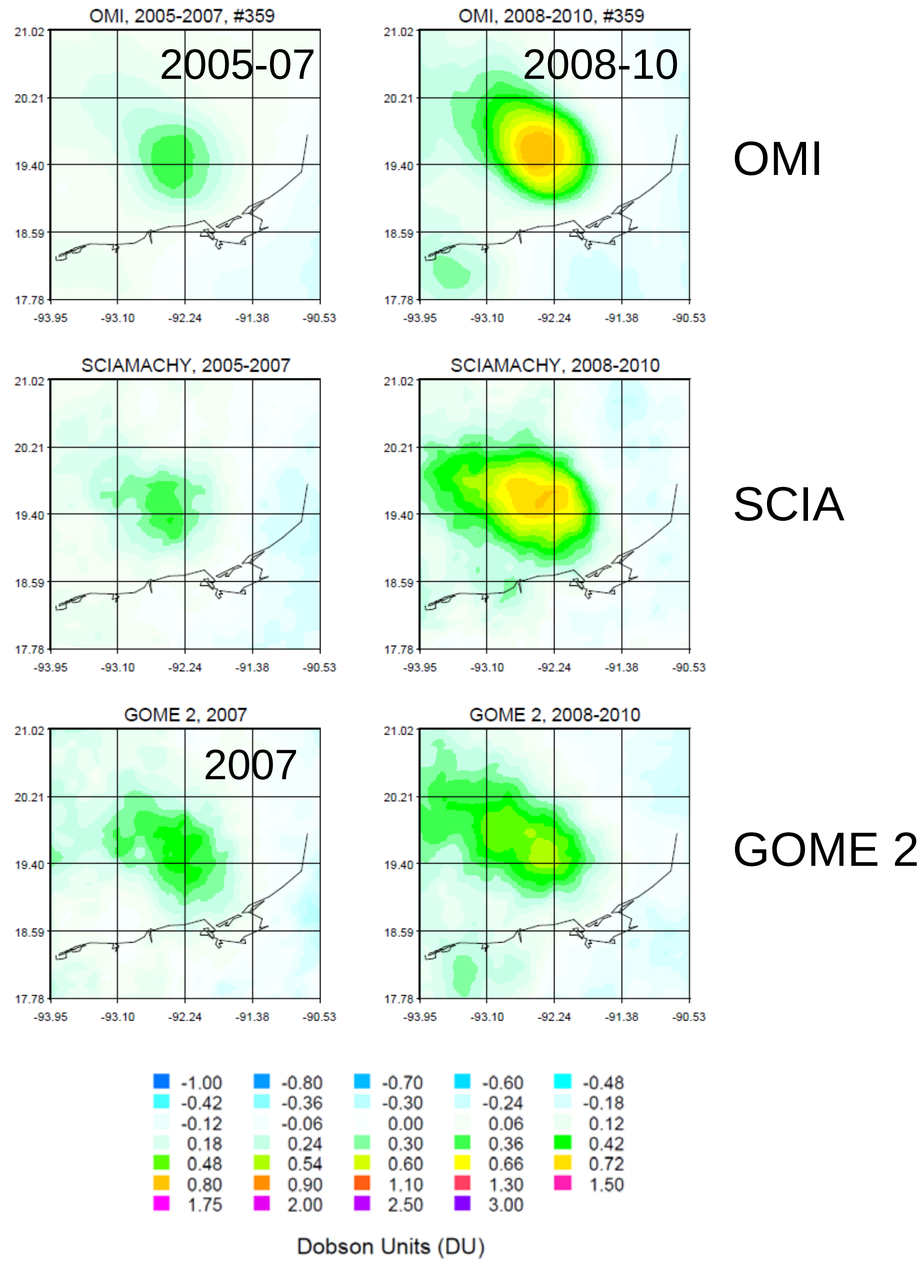
Cantarell and Ku-Maloob-Zaap Oil Fields, Mexico







Oil production:

800,000+500,000 bpd

OMI-estimated SO_2 emissions:

about 200 kT/y in 2005-2007

about 330 kT/y in 2008-2011

Summary

- A catalogue of ~400 volcanic and anthropogenic sources SO_2 with annual emissions estimates will be available from the NASA SO_2 group
- Sources emitting as little as 30 kt y^{-1} can be detected
- Satellite-based emission estimates can be used for validation, intercomparisons of different stellate data products, etc. They also can be used to verify available emission inventories
- SO_2 emissions from the largest US and European sources declined by about 80% and 50% respectively during 2005-2014, emissions from India increased by ~70%
- Emission inventories for Mexico and Middle East may be incomplete. Missing sources?
- More work is requited (more realistic AMFs, seasonal variations, etc.)

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Thanks for your attention!

Fioletov, V. E., C. A. McLinden, N. Krotkov, K. Yang, D. G. Loyola, P. Valks, N. Theys, M. Van Roozendael, C. R. Nowlan, K. Chance, X. Liu, C. Lee, and R. V. Martin, Application of OMI, SCIAMACHY, and GOME-2 satellite SO_2 retrievals for detection of large emission sources, *J. Geophys. Res.*, 118, doi:10.1002/jgrd.50826, 2013.

Fioletov V.E, C. A. McLinden, N. Krotkov, and C. Li**,** Lifetimes and emissions of SO_2 from point sources estimated from OMI, *Geophys. Res. Lett*, 42, 10.1002/2015GL063148, 2015