A global SCIAMACHY-based trend analysis of tropospheric NO_2 over megacities

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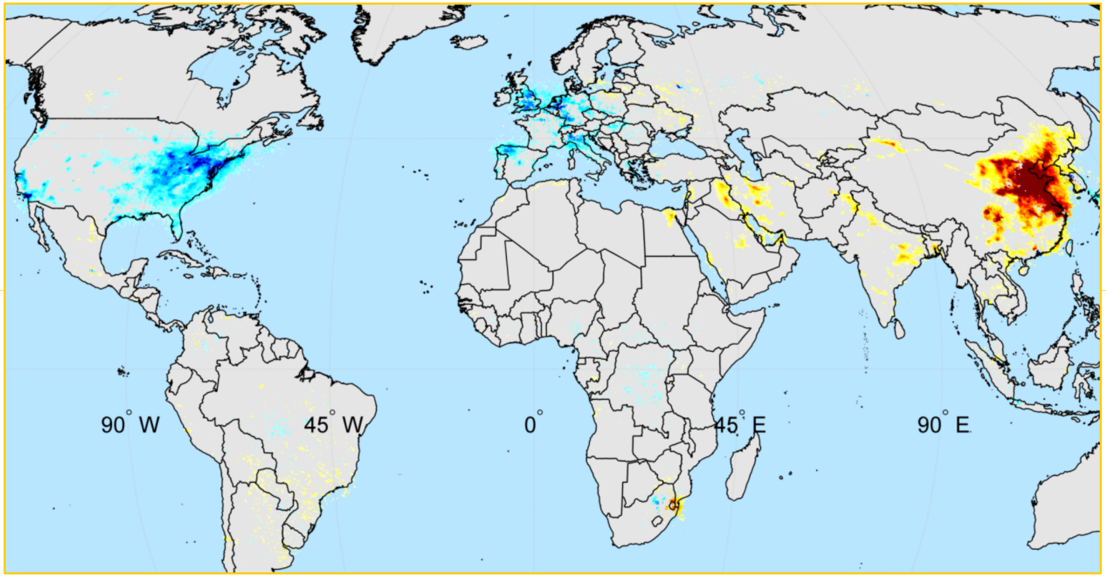
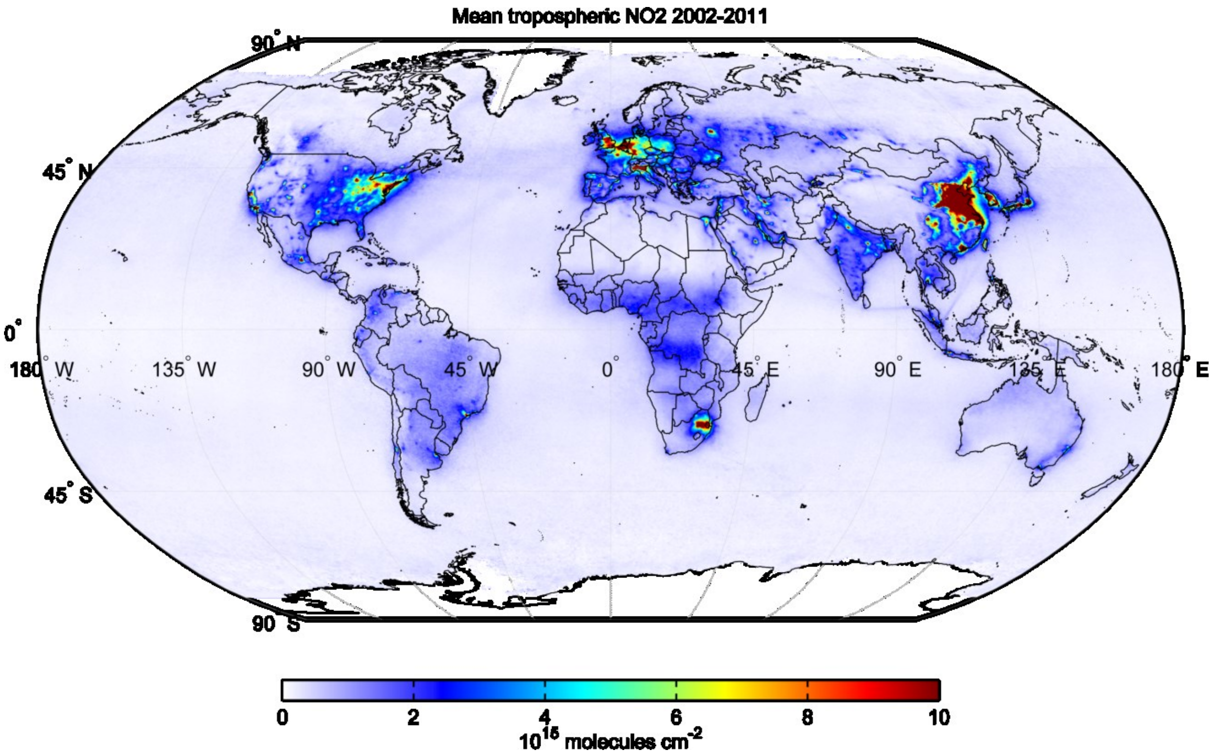


Outline

- Part 1: Overview of 2011/2012 global study on NO2 trends
  - Methodology
  - Results
- Part 2: Updated Results
  - Expanded dataset
  - Focus on megacities

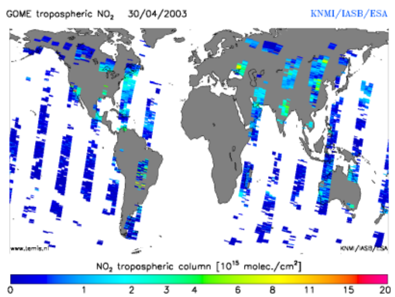
Introduction

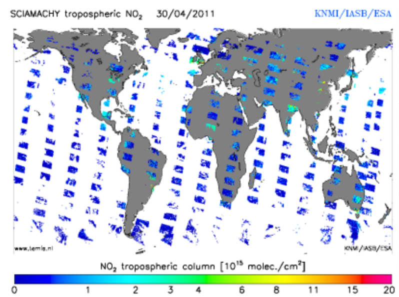
- Nitrogen Dioxide (NO_2) is one of the major air pollutants and is highly variable in space and time
- Satellite observations allow for quantification of dynamics in NO_2 concentrations
- Main project goal: Investigate NO_2 trends in Europe and compare with stations and model output
- Secondary goal: NO_2 trends over megacities worldwide

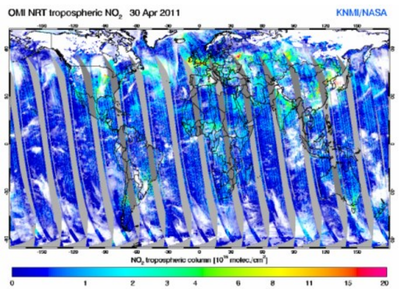


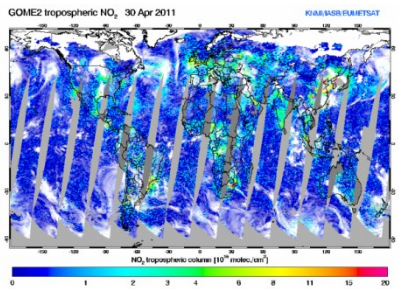
Average tropospheric NO_2 column between 2002 and 2011 as observed by SCIAMACHY

Primary instruments for NO_2









Sensor	GOME	SCIAMACHY	OMI	GOME-2
Data availability	1996 to 2003	2002 to 2012	2004 to present	2006 to present
Spatial resolution at nadir	40 km × 320 km	60 km × 30 km	13 km × 24 km	80 km × 40 km
Daily coverage	Partial	Partial (due to alternating nadir/limb observation)	Near-Global (significantly reduced due to instrument failure since 2007)	Near-Global

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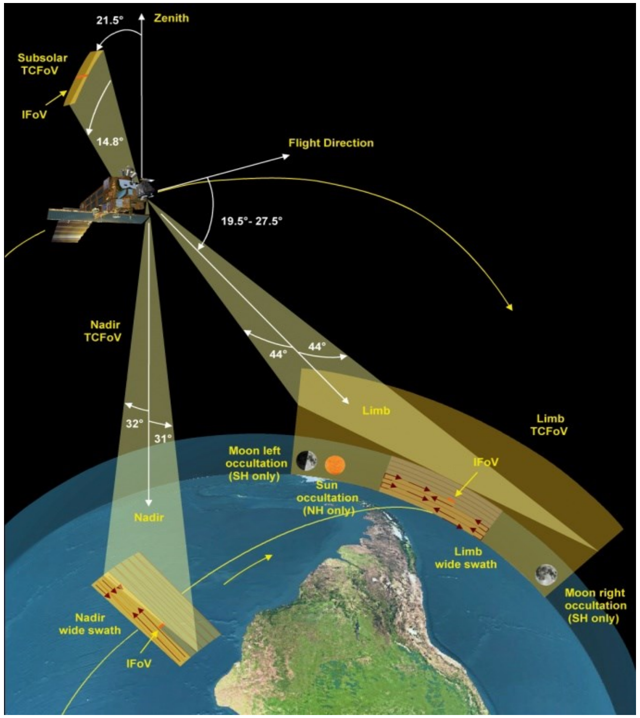
Methodology: Data

- Monthly average tropospheric NO_2 concentration between August 2002 and August 2011 used
- NO_2 product based on combined retrieval, modelling and assimilation approach developed at KNMI (Boersma et al., 2004)
- Version 2.0 of the retrieval algorithm was used (Boersma et al., 2011)
- Gridded to 0.25 degree spatial resolution (= 28 km at equator, 20 km at 45° N)
- Overall retrieval error dependent on pollution level: From ~25% in polluted regions up to 100% in very clean regions



SCIAMACHY (Scanning Imaging Absorption spectroMeter for Atmospheric CartograpHY)

Onboard of Envisat (launched 2002)

240 to 2380 nm in 8192 channels

Spatial resolution typically 60 x 30 km

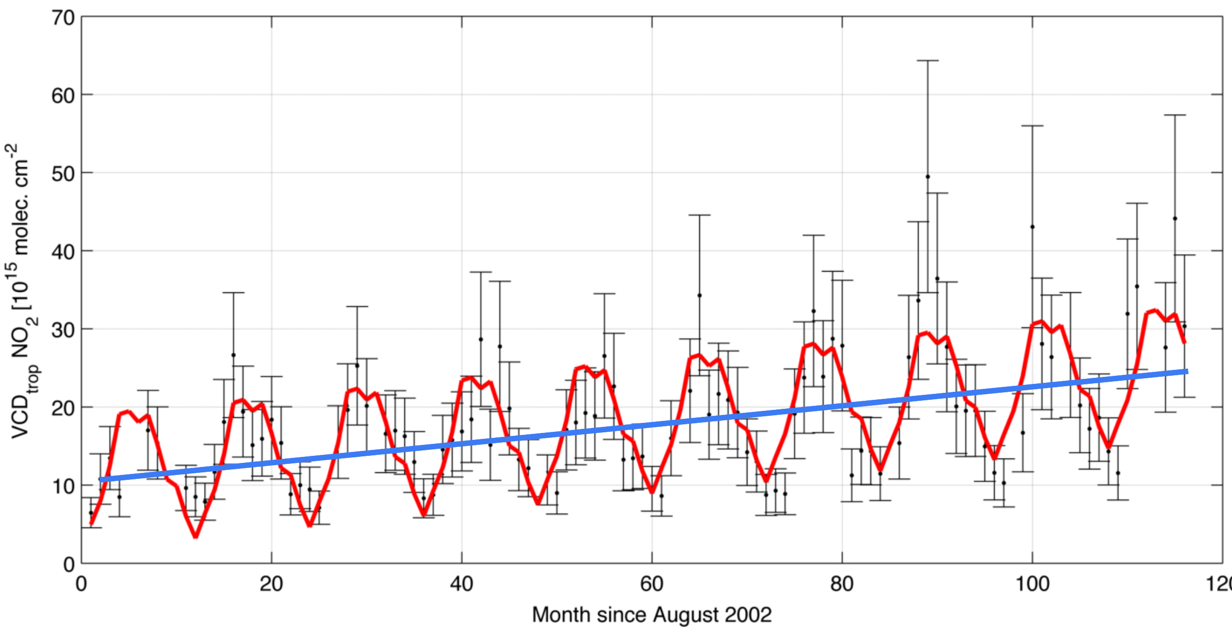
Statistical Model Fitting

- At each grid cell, time series were extracted and a statistical model fitted
- Model fits several components to the time series at each grid cell
  - Constant/Offset
  - Seasonal cycle
  - Linear trend component
  - Random error
- Fitting process uses *Multidimensional unconstrained nonlinear minimization (Nelder-Mead method)*
- Uncertainty estimates computed for all trends
- Significance level of α = 0.05 used

$$C_t = \mu + S_t + \frac{1}{12}\omega t + R_t$$

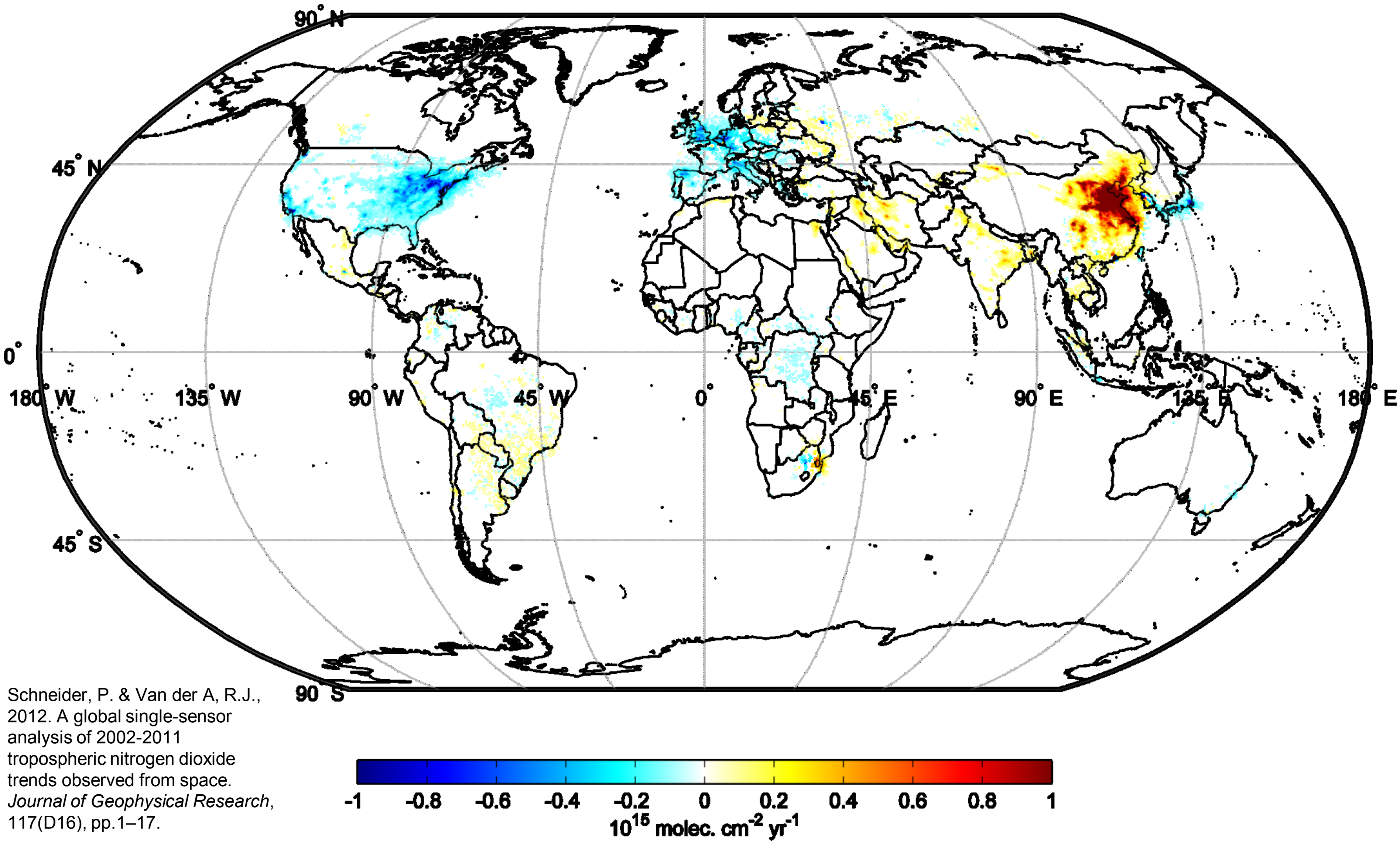
$$S_t = \sum_{j=1}^{4}\left[\beta_{1,j}\sin\left(\frac{2\pi j t}{12}\right) + \beta_{2,j}\cos\left(\frac{2\pi j t}{12}\right)\right]$$

$$R_t = \phi R_{t-1} + \epsilon_t$$



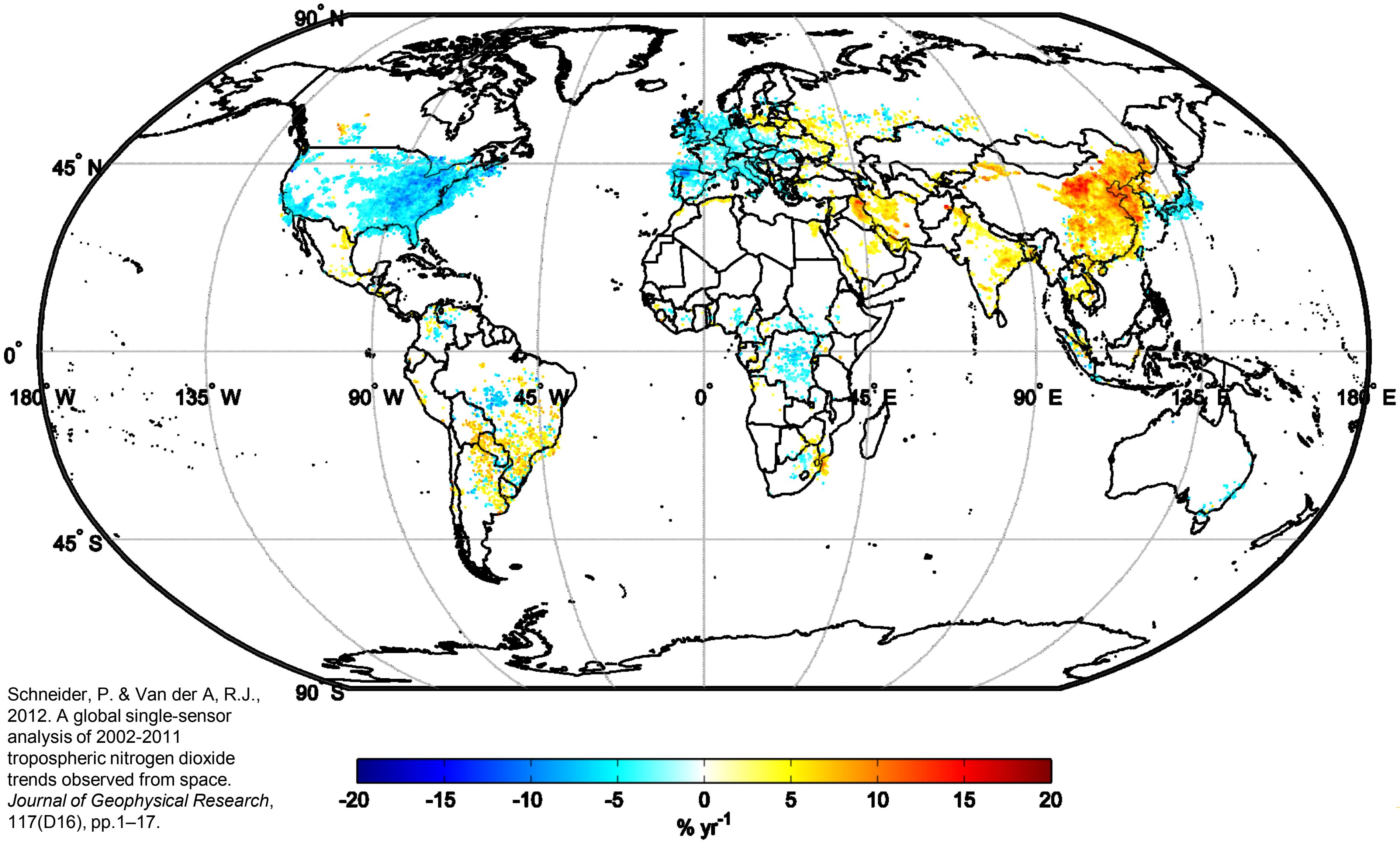
Example of a time series over Eastern China and the fitted statistical model

Global trends: Absolute



Schneider, P. & Van der A, R.J., 2012. A global single-sensor analysis of 2002-2011 tropospheric nitrogen dioxide trends observed from space. *Journal of Geophysical Research*, 117(D16), pp.1–17.

Global trends: Relative



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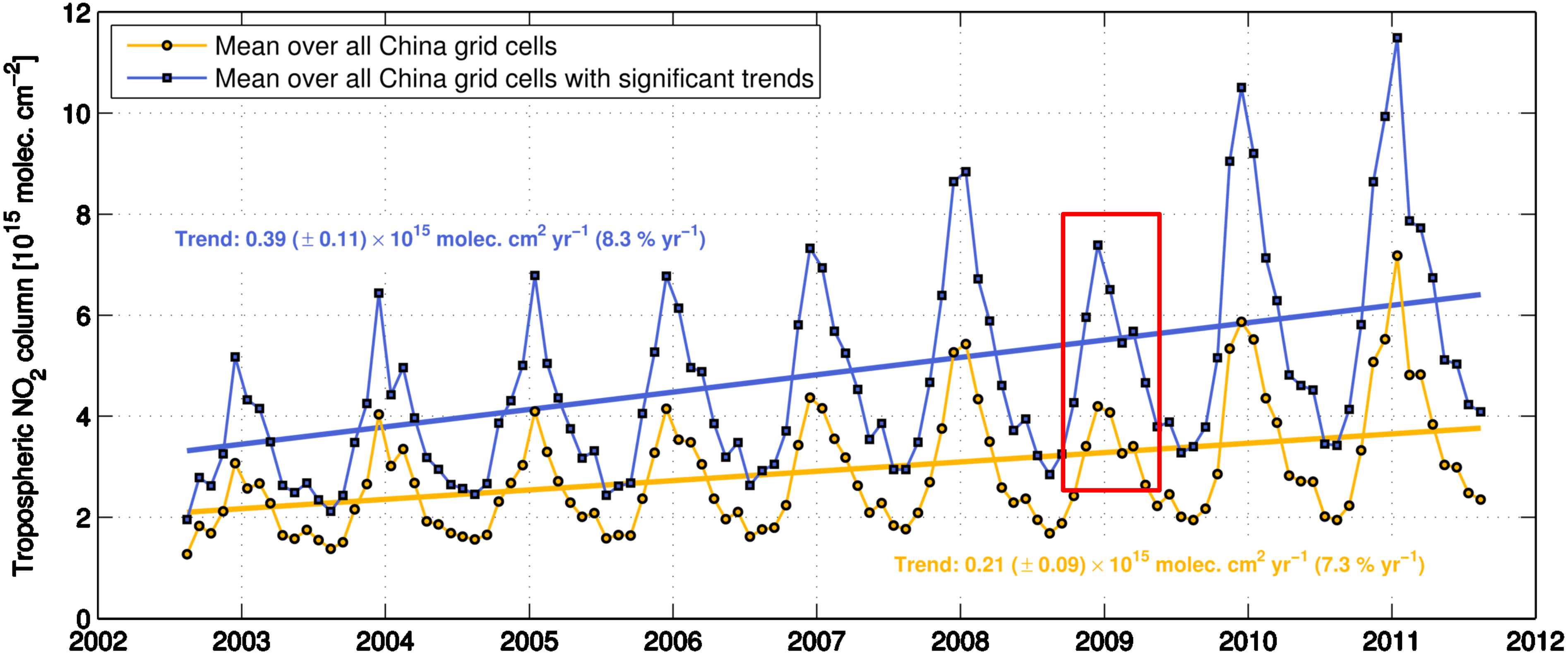
Time Series: China



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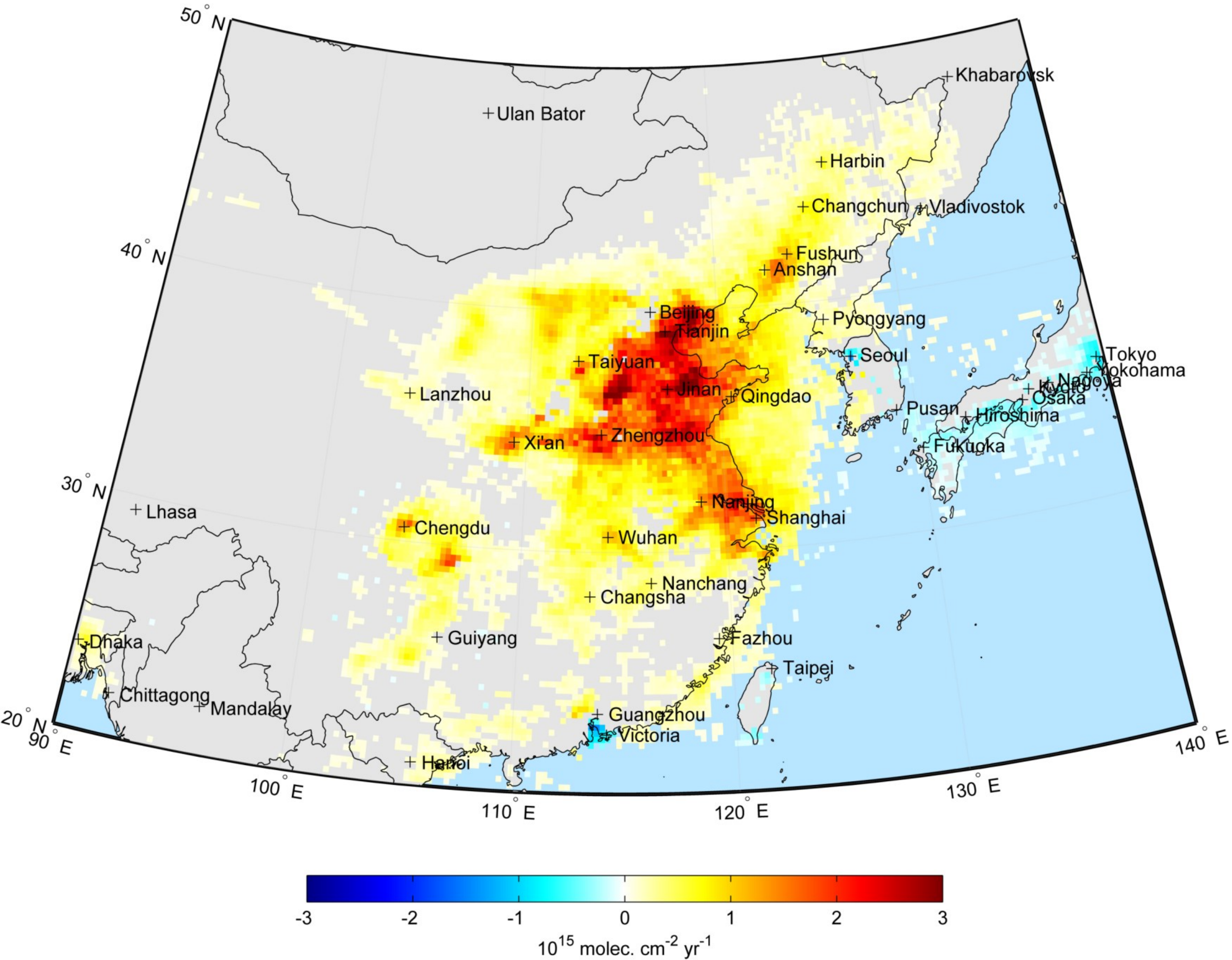
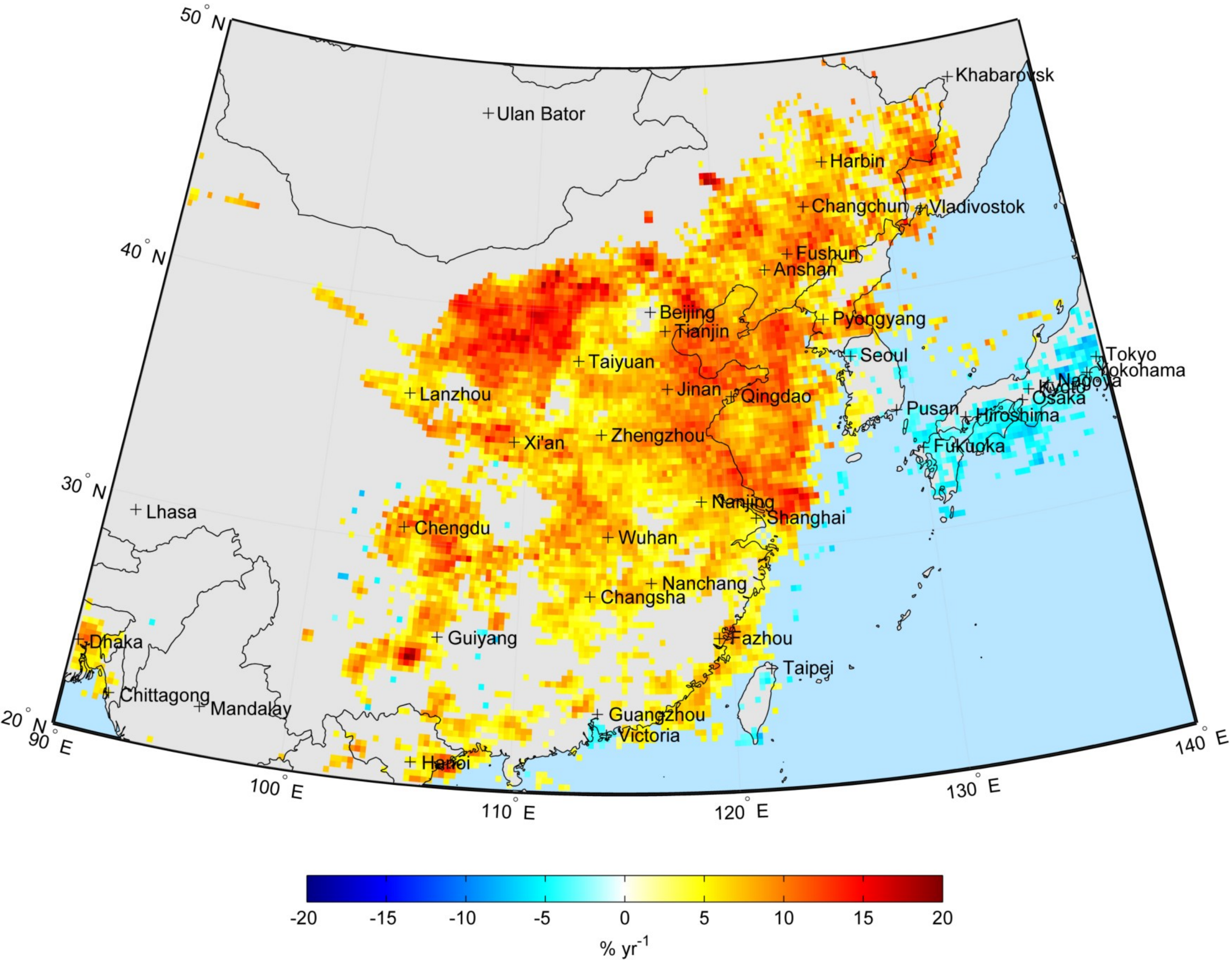
China: Absolute Trends



2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at $p<0.05$ are shown.

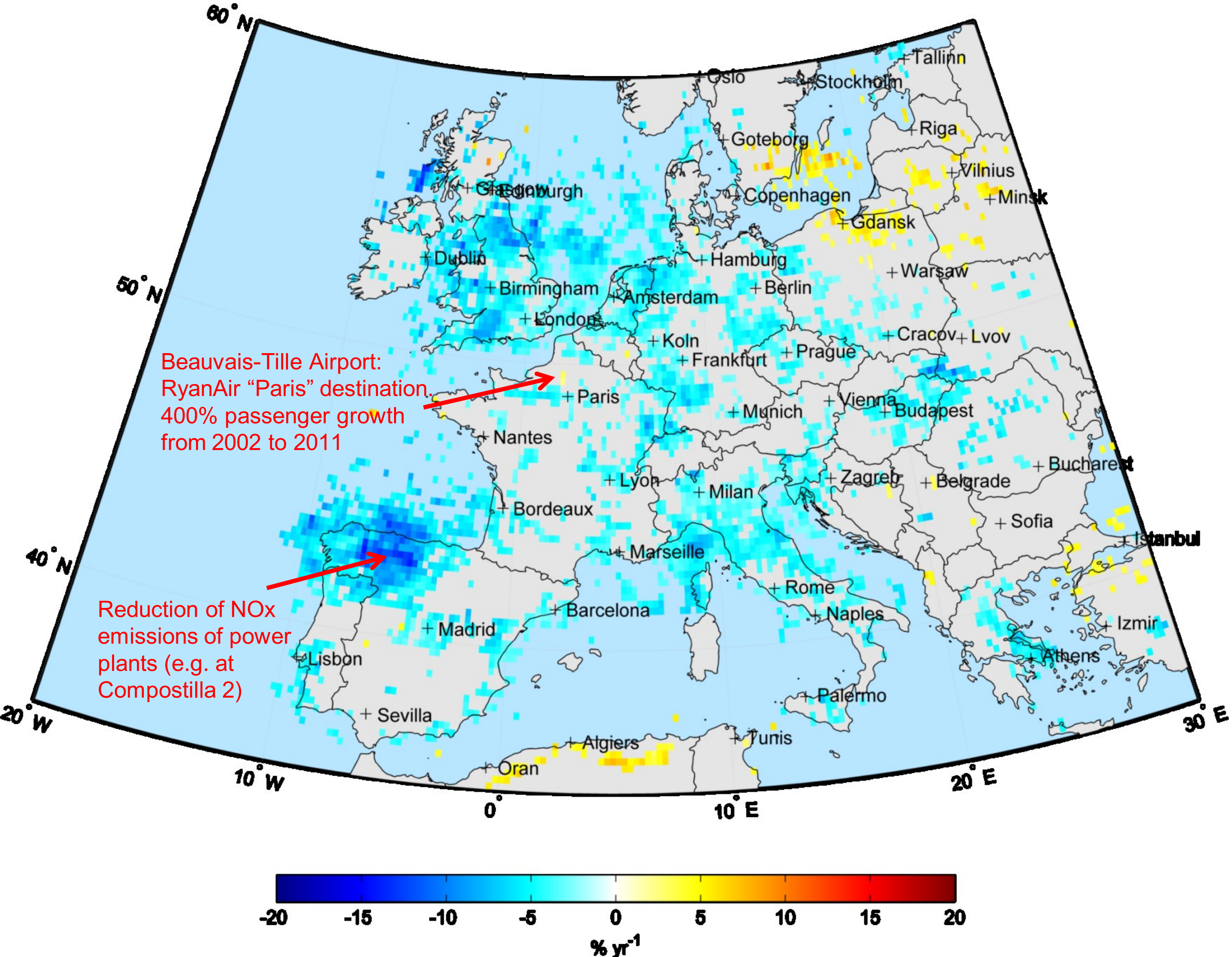
China: Relative Trends



Relative trends based on 2002-2011 long-term mean concentration

2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at $p<0.05$ are shown.

Europe: Relative Trends

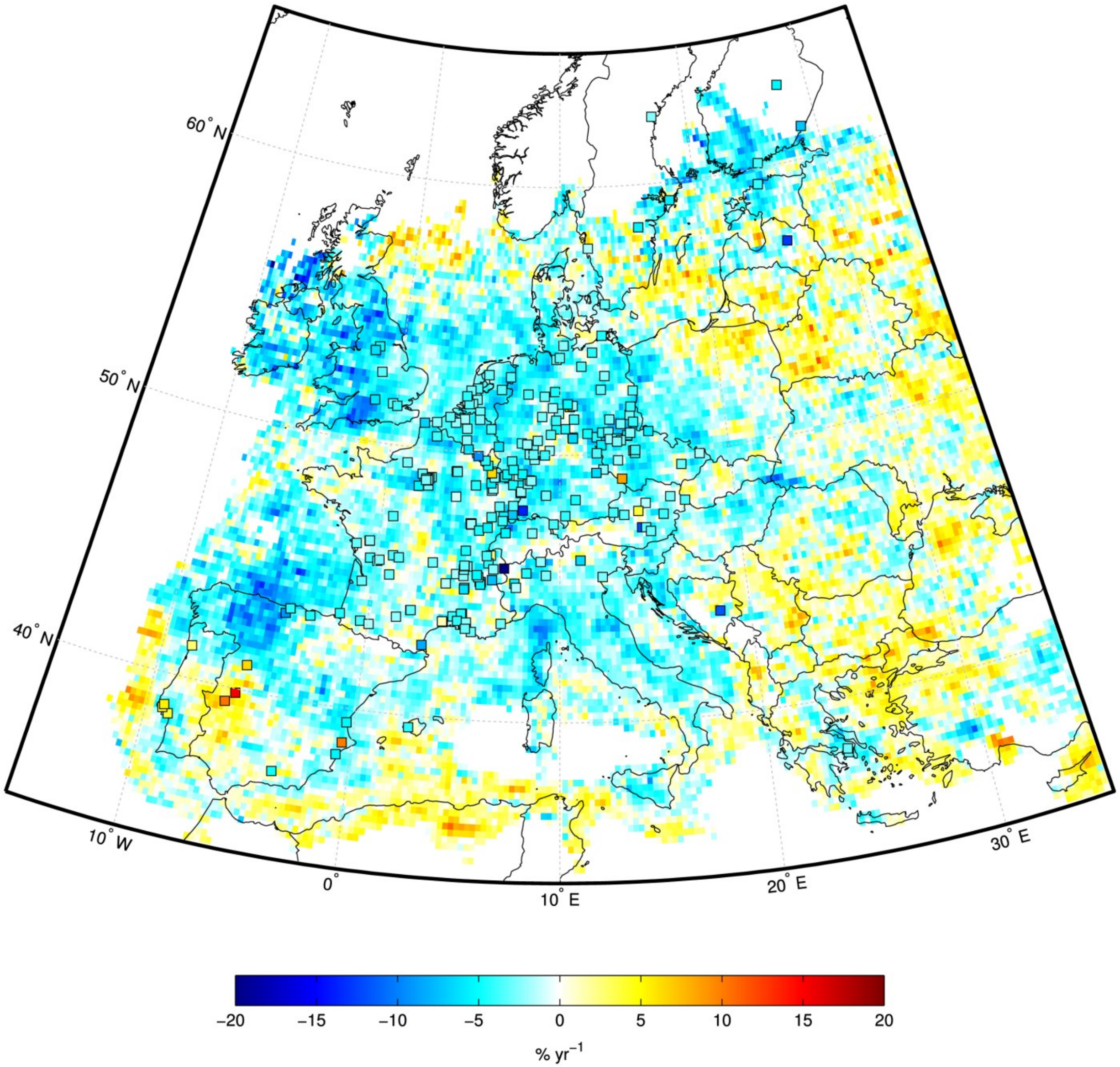


Relative trends based on 2002-2011 long-term mean concentration

2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at $\alpha=0.05$ are shown.

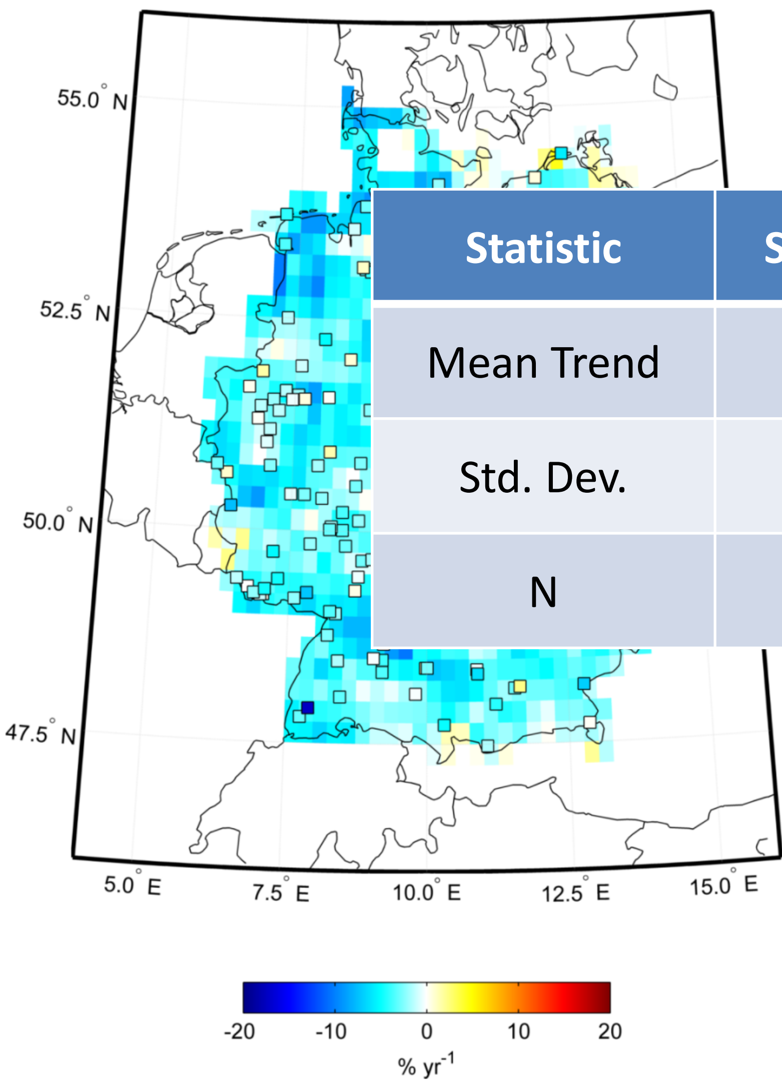
Comparison with station data

- Satellite-derived trends were compared with trends obtained from air quality stations throughout Europe
- Station data was obtained from AirBase
- Study period was limited to 2002-2009
- Spatial patterns in trends similar, but comparison at station level challenging

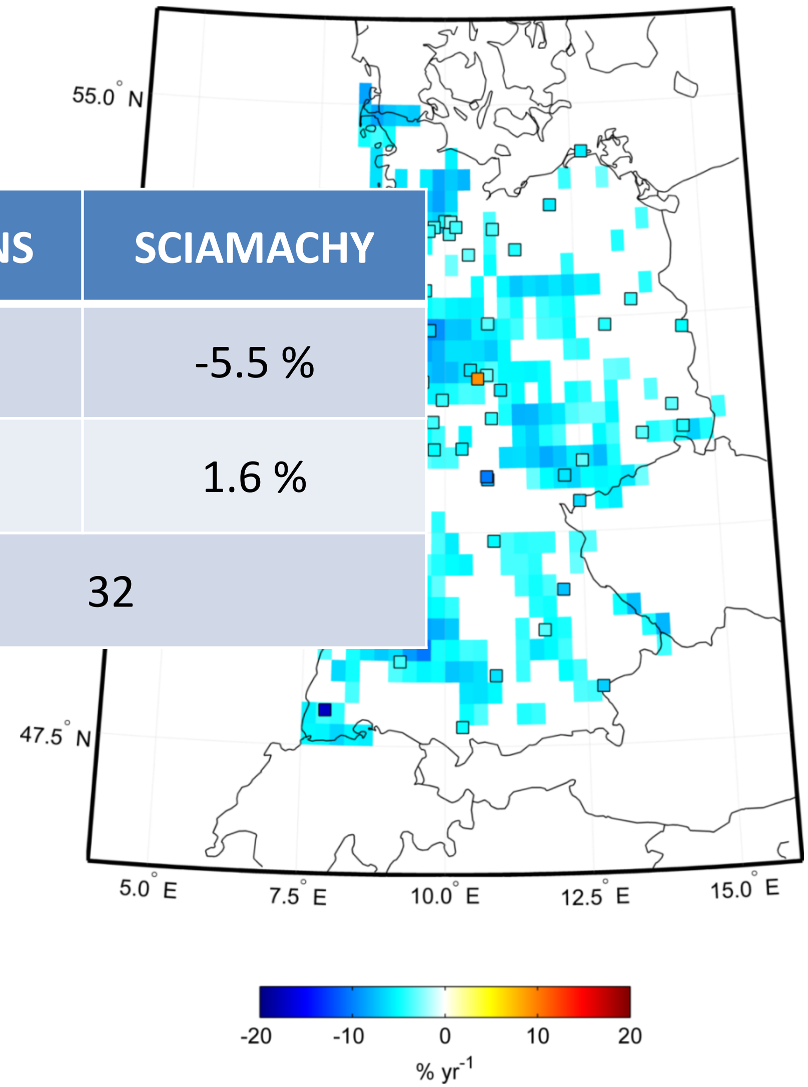


Trend Comparison: Germany

All trends



Only trends significant at 95% level

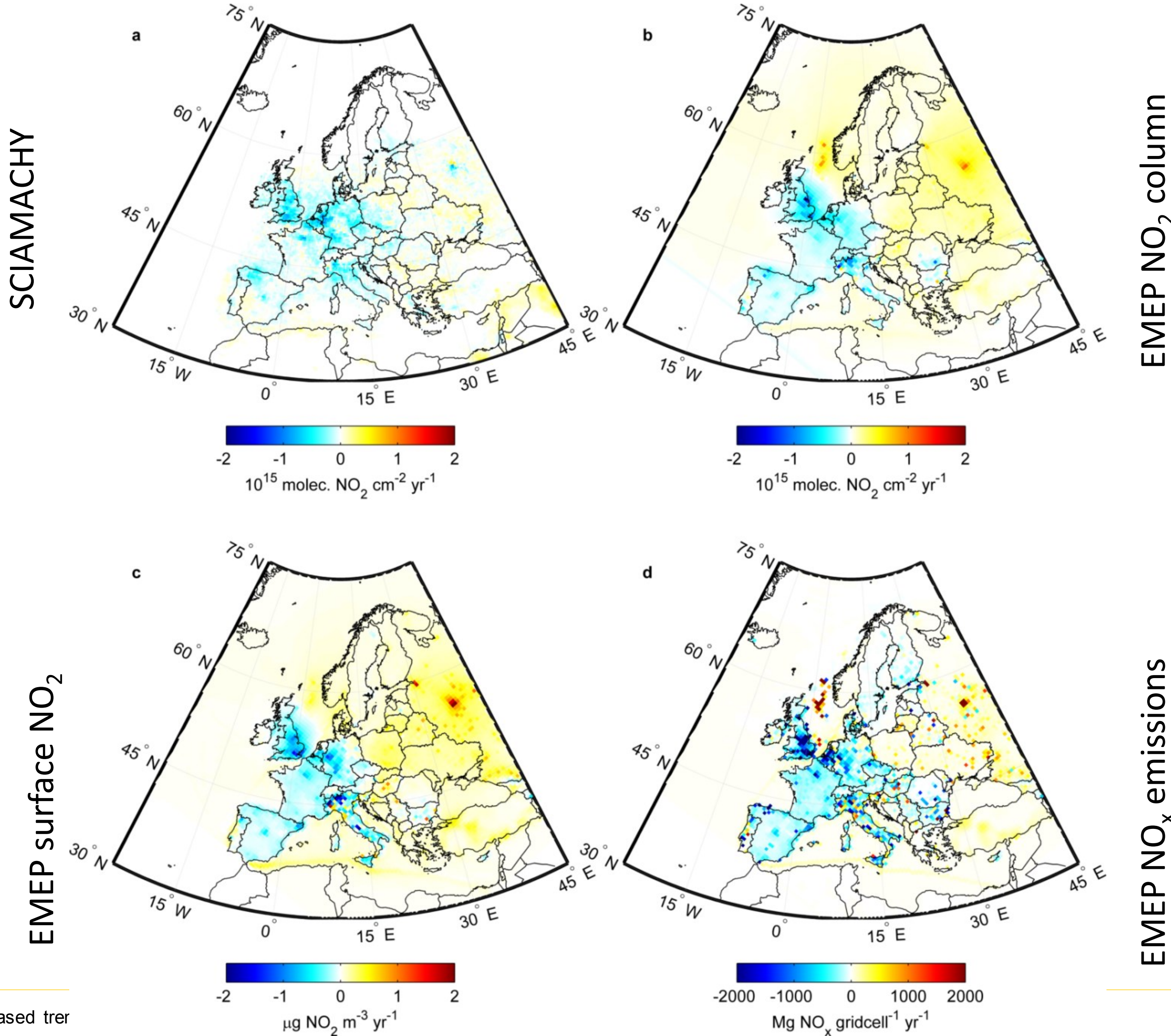


Statistic	STATIONS	SCIAMACHY
Mean Trend	-4.5 %	-5.5 %
Std. Dev.	2.8 %	1.6 %
N	32	

Model comparison

Output from the Unified EMEP model (Simpson et al. 2003) was used in this step

These trends were computed for the period 2002 to 2009, since EMEP data for 2010 and 2011 was not available



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Megacity Trends

Cities with a population of more than 10 million.

Trend period 2002 to 2011

Trends obtained for a 3 x 3 grid cell window

Numbers set in bold indicate trends significant at the 95% level

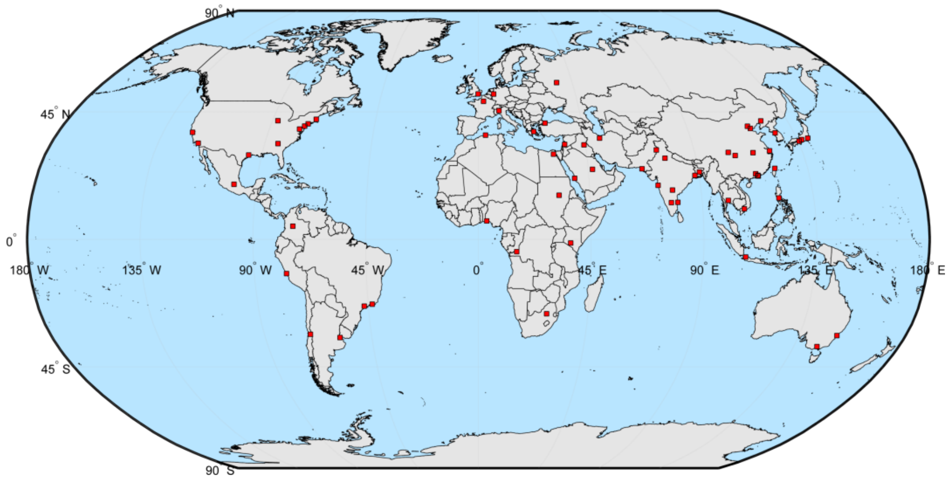
City	N [months]	Absolute Trend [10^{15} molec. cm^{-2} yr^{-1}]	Relative Trend [% yr^{-1}]
Baghdad	107	**0.483 ± 0.081**	**9.373 ± 1.565**
Beijing	100	**0.857 ± 0.394**	**2.481 ± 1.141**
Buenos Aires	99	**0.197 ± 0.102**	**3.110 ± 1.614**
Cairo	109	**0.334 ± 0.108**	**4.590 ± 1.491**
Delhi	101	**0.198 ± 0.106**	**2.718 ± 1.449**
Dhaka	81	**0.447 ± 0.078**	**9.501 ± 1.657**
Guangzhou	77	-0.404 ± 0.314	-1.570 ± 1.222
Istanbul	97	0.008 ± 0.121	0.095 ± 1.440
Jakarta	83	**-0.205 ± 0.111**	**-2.629 ± 1.419**
Karachi	105	**0.086 ± 0.050**	**2.793 ± 1.626**
Kolkata	88	0.083 ± 0.067	2.098 ± 1.691
Lagos	55	**0.091 ± 0.052**	**3.682 ± 2.098**
London	91	**-0.441 ± 0.172**	**-3.302 ± 1.290**
Los Angeles	103	**-0.958 ± 0.258**	**-5.066 ± 1.364**
Manila	83	**-0.139 ± 0.078**	**-3.232 ± 1.821**
Mexico City	80	-0.293 ± 0.187	-1.672 ± 1.069
Mumbai	84	**0.144 ± 0.078**	**2.720 ± 1.476**
Moscow	74	-0.250 ± 0.240	-1.697 ± 1.630
New York	105	**-0.979 ± 0.238**	**-5.307 ± 1.291**
Osaka	81	**-0.350 ± 0.142**	**-2.592 ± 1.056**
Paris	95	**-0.367 ± 0.141**	**-3.295 ± 1.270**
Rio de Janeiro	62	0.050 ± 0.076	1.003 ± 1.530
Sao Paulo	85	-0.040 ± 0.133	-0.346 ± 1.159
Seoul	92	**-0.672 ± 0.300**	**-2.768 ± 1.233**
Shanghai	86	**0.898 ± 0.296**	**3.255 ± 1.074**
Tehran	103	**0.232 ± 0.127**	**2.193 ± 1.195**
Tokyo	99	**-1.232 ± 0.267**	**-5.736 ± 1.245**

More recent work for megacities

- Updated dataset and study with stronger focus on megacities
- Expanded time series by 7 months to include entire archive of SCIAMACHY data (August 2002 to March 2012)
- Significantly expanded list of (mega)cities/agglomerations (from 27 to 66)
- Megacity trends for both 1 x 1 and 3 x 3 grid cell arrays
- More in-depth analysis of megacity trends and relationship with population growth

Computing (Mega)city trends

- Quite liberal selection of study sites
  - All cities with >10 million inhabitants
  - Most cities with >5 million inhabitants
  - Some “special interest” cities with <5 million inhabitants
- Latitude/Longitude of location manually selected over each city
- Two time series extracted over each site
  - Approach A: 1 pixel centered over coordinates
  - Approach B: Average of 3 x 3 pixel array centered over coordinates (for robustness against erroneous data/outliers)
- Statistical model fitted to time series derived from both approaches



Spatial distribution of the study sites

Trend Results (1 x 1)

City	N	Trend	Trend Uncertainty	Rel. Trend	Rel. Trend Unc.
Algiers	115	0.096	0.066	2.4	1.7
Athens	114	**-0.213**	0.081	**-3.6**	1.4
Atlanta	108	**-0.449**	0.111	**-5.4**	1.3
Baghdad	115	**0.600**	0.085	**8.5**	1.2
Bangalore	87	**0.188**	0.058	**6.1**	1.9
Bangkok	116	0.203	0.163	1.9	1.6
Beijing	112	**1.399**	0.574	**3.2**	1.3
Bogota	38	**-0.250**	0.091	**-3.4**	1.2
Boston	108	**-0.828**	0.281	**-9.0**	3.0
Buenos Aires	113	**0.249**	0.107	**3.1**	1.3
Cairo	116	**0.414**	0.067	**5.0**	0.8
Chengdu	73	**1.248**	0.221	**8.0**	1.4
Chicago	113	**-0.684**	0.191	**-5.1**	1.4
Chongqing	67	**1.529**	0.290	**10.2**	1.9
Damascus	115	**0.185**	0.089	**3.1**	1.5
Delhi	112	0.125	0.110	1.4	1.2
Dhaka	107	**0.525**	0.063	**10.3**	1.2
Guangzhou	91	-0.252	0.417	-0.8	1.4
Ho Chi Minh City	108	0.049	0.044	1.4	1.3
Hong Kong	105	-0.424	0.282	-2.5	1.7
Houston	107	**-0.540**	0.157	**-5.4**	1.6
Hyderabad	109	**0.142**	0.056	**4.7**	1.9
Istanbul	108	-0.047	0.230	-0.4	1.9
Jakarta	108	-0.241	0.150	-2.1	1.3
Jeddah	115	0.102	0.086	1.6	1.3
Johannesburg	111	**-0.488**	0.193	**-3.1**	1.2
Kabul	116	**0.299**	0.046	**14.3**	2.18
Karachi	113	**0.194**	0.064	**4.0**	1.3
Khartoum	116	0.018	0.035	1.5	2.9
Kinshasa	80	0.036	0.035	1.5	1.4
Kolkata	109	**0.114**	0.063	**2.6**	1.4
Lagos	83	**0.265**	0.050	**7.8**	1.5
Lahore	113	**0.334**	0.087	**6.0**	1.6

City	N	Trend	Trend Uncertainty	Rel. Trend	Rel. Trend Unc.
Lima	75	**0.363**	0.108	**6.9**	2.0
London	107	-0.255	0.205	-1.7	1.4
Los Angeles	113	**-1.656**	0.308	**-5.8**	1.1
Madras	106	**0.151**	0.058	**3.9**	1.5
Manila	102	**-0.363**	0.074	**-6.0**	1.2
Melbourne	111	-0.103	0.082	-1.6	1.3
Mexico City	104	-0.354	0.276	-1.3	1.0
Moscow	95	-0.185	0.273	-1.2	1.8
Mumbai	103	0.037	0.077	0.6	1.2
Nagoya	101	-0.400	0.244	-2.3	1.4
Nairobi	88	**0.172**	0.040	**13.1**	3.0
New York	113	**-0.950**	0.310	**-4.3**	1.4
Osaka	110	**-0.445**	0.231	**-2.7**	1.4
Paris	108	**-0.471**	0.171	**-3.3**	1.2
Philadelphia	109	**-0.917**	0.205	**-5.9**	1.3
Po Valley	112	**-0.621**	0.214	**-3.4**	1.2
Rhein-Ruhr	104	**-0.452**	0.219	**-2.8**	1.4
Rio de Janeiro	102	-0.073	0.090	-0.9	1.1
Riyadh	115	**0.270**	0.133	**2.1**	1.1
San Francisco	113	**-0.442**	0.124	**-5.0**	1.4
Santiago	115	**0.270**	0.106	**2.8**	1.1
Sao Paulo	104	-0.006	0.161	0.0	1.0
Seoul	106	-0.648	0.594	-2.1	1.9
Shanghai	106	**1.306**	0.347	**4.2**	1.1
Shenyang	106	**1.705**	0.278	**9.4**	1.5
Shenzhen	101	**-0.842**	0.351	**-3.8**	1.6
Sydney	111	**-0.239**	0.116	**-2.9**	1.4
Taipei	96	0.040	0.209	0.4	2.1
Tehran	115	**0.634**	0.216	**3.2**	1.1
Tianjin	111	**3.035**	0.464	**8.2**	1.2
Tokyo	108	**-1.282**	0.306	**-4.9**	1.2
Washington	112	**-0.740**	0.184	**-6.3**	1.6
Wuhan	107	**1.063**	0.188	**6.4**	1.1

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Trend Results (3 x 3)

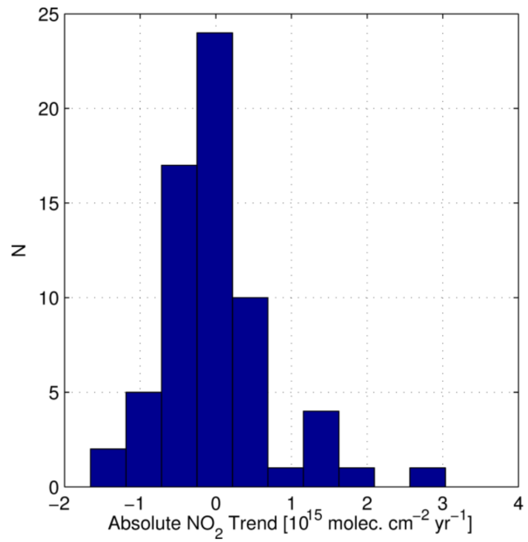
City	N	Trend	Trend Uncertainty	Rel. Trend	Rel. Trend Unc.
Algiers	114	0.095	0.060	2.6	1.7
Athens	112	**-0.245**	0.070	**-5.0**	1.4
Atlanta	104	**-0.400**	0.112	**-5.7**	1.6
Baghdad	113	**0.499**	0.075	**9.4**	1.4
Bangalore	76	**0.125**	0.046	**4.9**	1.8
Bangkok	89	0.120	0.116	1.4	1.3
Beijing	105	**1.637**	0.417	**4.6**	1.2
Bogota	17	**-0.137**	0.077	**-2.6**	1.4
Boston	99	**-0.648**	0.260	**-8.0**	3.2
Buenos Aires	112	**0.192**	0.090	**3.1**	1.4
Cairo	116	**0.297**	0.060	**4.2**	0.9
Chengdu	38	**0.743**	0.178	**6.4**	1.5
Chicago	101	**-0.859**	0.117	**-8.1**	1.1
Chongqing	43	**1.371**	0.131	**11.0**	1.1
Damascus	110	**0.133**	0.074	**3.0**	1.7
Delhi	107	**0.170**	0.098	**2.3**	1.3
Dhaka	88	**0.462**	0.060	**9.6**	1.3
Guangzhou	77	0.182	0.272	0.7	1.0
Ho Chi Minh City	88	0.067	0.048	2.6	1.9
Hong Kong	85	**-0.605**	0.218	**-3.8**	1.4
Houston	96	**-0.446**	0.101	**-5.6**	1.3
Hyderabad	104	**0.101**	0.052	**4.1**	2.1
Istanbul	103	-0.042	0.108	-0.5	1.3
Jakarta	88	-0.163	0.100	-2.1	1.3
Jeddah	115	0.062	0.082	1.1	1.5
Johannesburg	107	**-0.342**	0.158	**-2.5**	1.2
Kabul	101	**0.187**	0.046	**13.3**	3.3
Karachi	113	**0.086**	0.044	**2.8**	1.4
Khartoum	115	0.001	0.037	0.1	3.8
Kinshasa	45	**0.058**	0.032	**2.6**	1.5
Kolkata	94	0.079	0.062	2.0	1.6
Lagos	38	**0.111**	0.061	**3.6**	2.0
Lahore	112	**0.304**	0.086	**6.3**	1.8

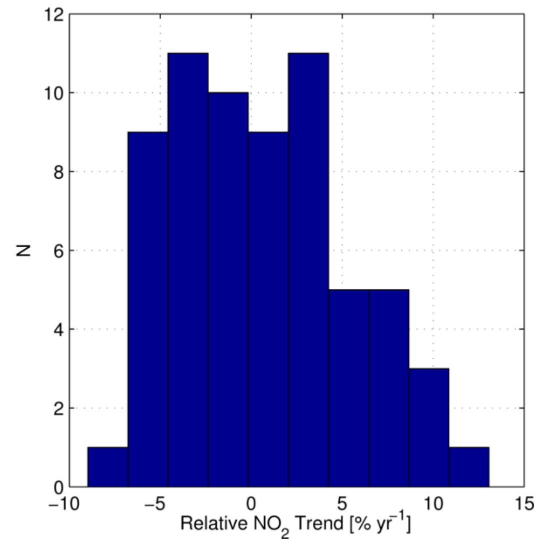
City	N	Trend	Trend Uncertainty	Rel. Trend	Rel. Trend Unc.
Lima	51	**0.228**	0.068	**6.2**	1.9
London	98	**-0.414**	0.140	**-3.1**	1.0
Los Angeles	108	**-1.300**	0.246	**-5.9**	1.1
Madras	97	**0.124**	0.047	**4.2**	1.6
Manila	64	**-0.234**	0.065	**-5.5**	1.5
Melbourne	104	-0.092	0.058	-2.0	1.3
Mexico City	86	-0.187	0.183	-1.1	1.0
Moscow	72	-0.316	0.200	-2.1	1.4
Mumbai	89	**0.134**	0.073	**2.5**	1.4
Nagoya	91	**-0.417**	0.168	**-3.0**	1.2
Nairobi	64	**0.104**	0.031	**11.5**	3.4
New York	105	**-0.936**	0.204	**-5.2**	1.1
Osaka	87	**-0.334**	0.130	**-2.5**	1.0
Paris	101	**-0.319**	0.126	**-2.9**	1.1
Philadelphia	105	**-0.859**	0.136	**-6.7**	1.1
Po Valley	110	**-0.422**	0.170	**-2.5**	1.0
Rhein-Ruhr	93	**-0.402**	0.164	**-2.8**	1.1
Rio de Janeiro	90	0.037	0.072	0.7	1.3
Riyadh	115	**0.232**	0.105	**2.6**	1.2
San Francisco	111	**-0.322**	0.087	**-4.4**	1.2
Santiago	112	**0.150**	0.065	**2.4**	1.0
Sao Paulo	91	-0.013	0.122	-0.1	1.1
Seoul	99	-0.314	0.280	-1.3	1.1
Shanghai	91	**1.192**	0.274	**4.2**	1.0
Shenyang	95	**1.290**	0.198	**8.5**	1.3
Shenzhen	84	**-1.130**	0.220	**-5.8**	1.1
Sydney	105	**-0.138**	0.073	**-2.6**	1.4
Taipei	63	-0.127	0.092	-1.8	1.3
Tehran	112	**0.371**	0.152	**2.8**	1.1
Tianjin	109	**2.882**	0.351	**8.7**	1.1
Tokyo	104	**-1.154**	0.239	**-5.4**	1.1
Washington	105	**-0.761**	0.156	**-7.2**	1.5
Wuhan	105	**0.866**	0.168	**6.2**	1.2

Some statistics (for 1 x 1)

Statistic	Absolute Trends [10^{15} molec. cm^{-2} yr^{-1}]		Relative Trends [% yr^{-1}]	
	All	Significant only	All	Significant only
Mean	0.018	0.079	0.7	1.2
Median	0.018	0.147	0.4	2.7
Std. Dev	0.736	0.879	4.9	5.8

44 out of 65 megacities have a trend significant at the 95% level

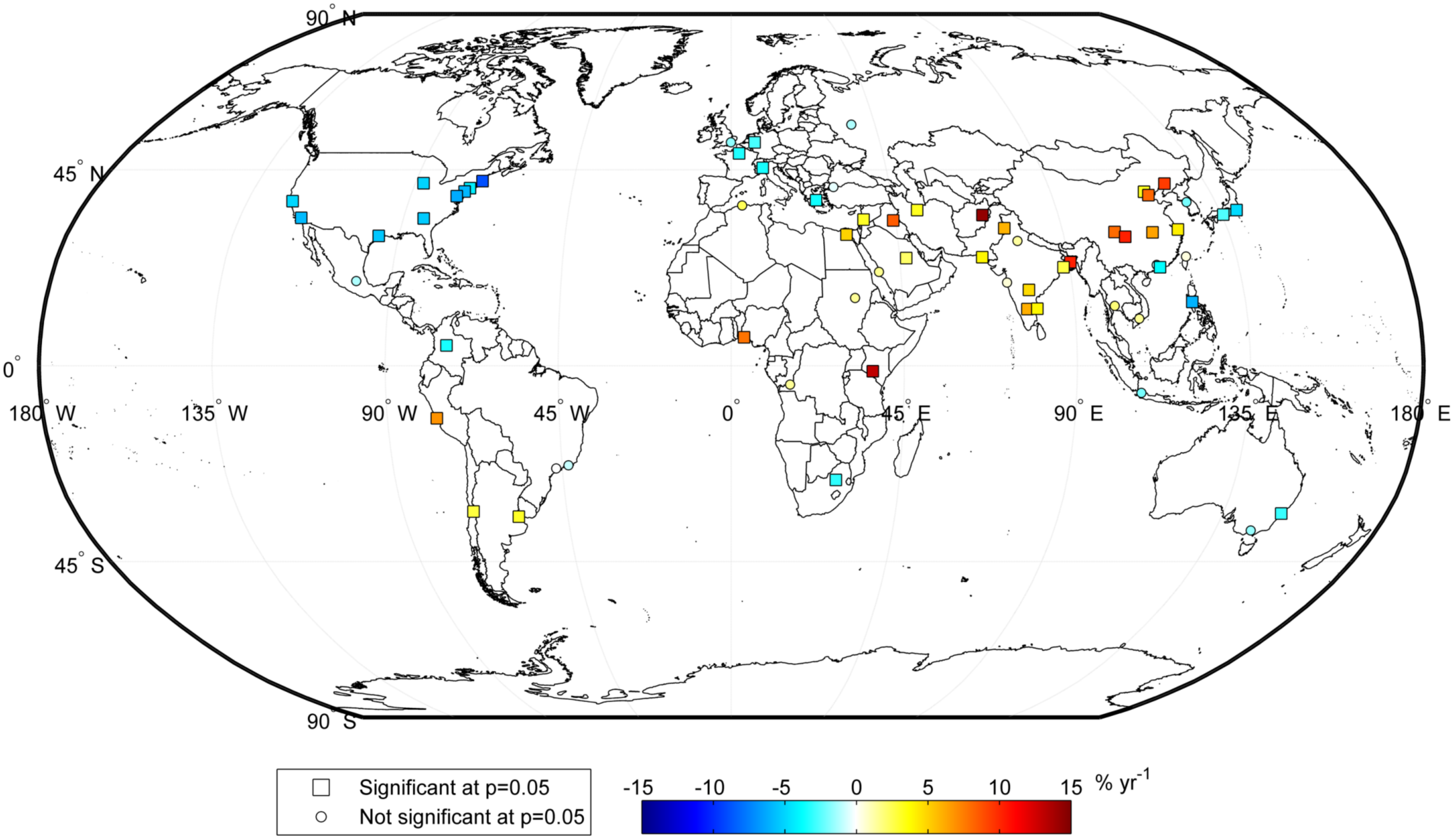




Histograms of absolute (left) and relative (right) NO_2 trends over all studied megacities

Schneider P. and R. van der A: A global SCIAMACHY-based trend analysis of tropospheric NO2 over megacities. PRESCRIBE workshop, Bremen, May 15 2013.

Megacity NO_2 trends



Schneider P. and R. van der A: A global SCIAMACHY-based trend analysis of tropospheric NO2 over megacities. PRESCRIBE workshop, Bremen, May 15 2013.

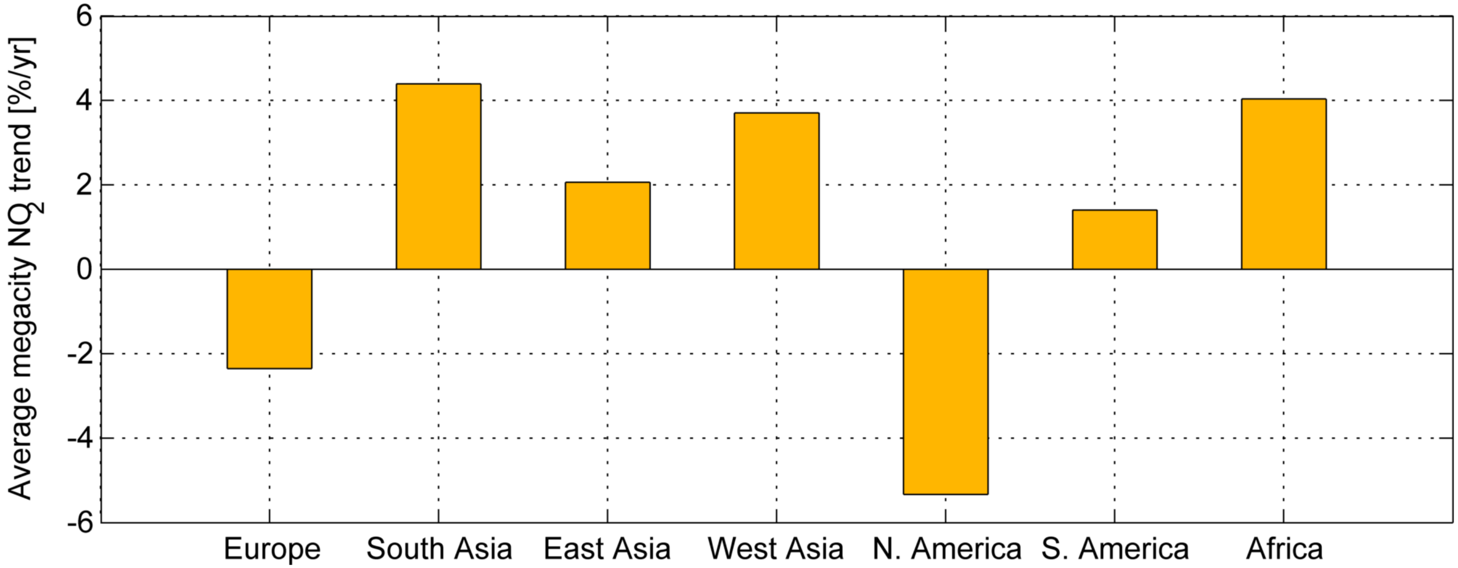
Extreme values

	Absolute Trends	Relative Trends
Maximum	Tianjin, China 3.04 (± 0.47) × 10^{15} molec. cm^{-2} yr^{-1}	Kabul, Afghanistan 14.3 (± 2.2) %/yr
Minimum	Los Angeles, USA -1.66 (± 0.31) × 10^{15} molec. cm^{-2} yr^{-1}	Boston, USA -9.0 (± 3.0) %/yr

Among the "true" megacities (>10M pop), Dhaka (Bangladesh) still has the most rapidly increasing NO2 concentrations with 10.3 (± 1.2) %/yr

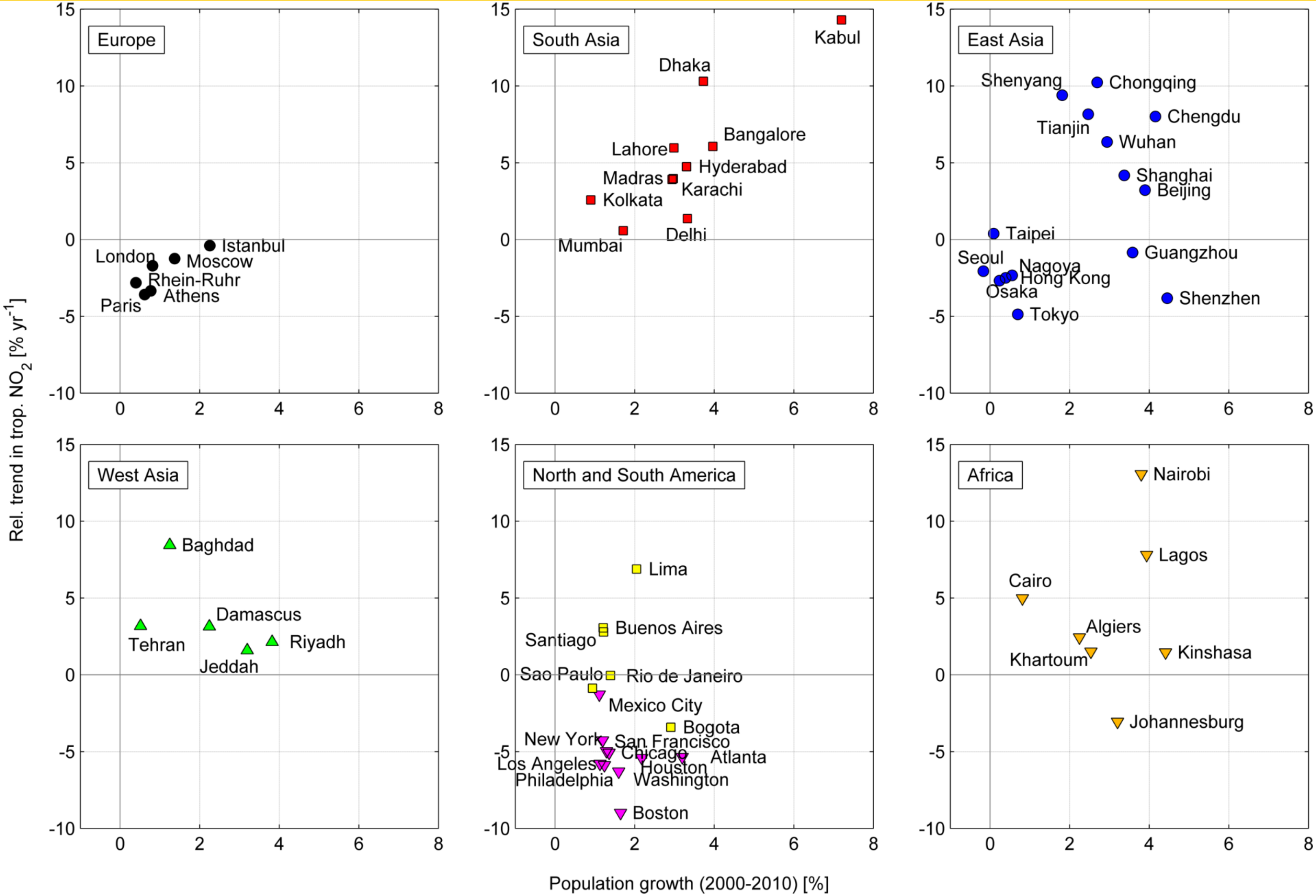
Megacity trends by region

	N	Absolute Trends [10^{15} molec. cm^{-2} yr^{-1}]	Relative Trends [% yr^{-1}]
Europe	7	-0.321	-2.4
South Asia	9	0.201	4.4
East Asia	15	0.469	2.1
West Asia	5	0.358	3.7
North America	10	-0.756	-5.3
South America	6	0.092	1.4
Africa	7	0.073	4.0



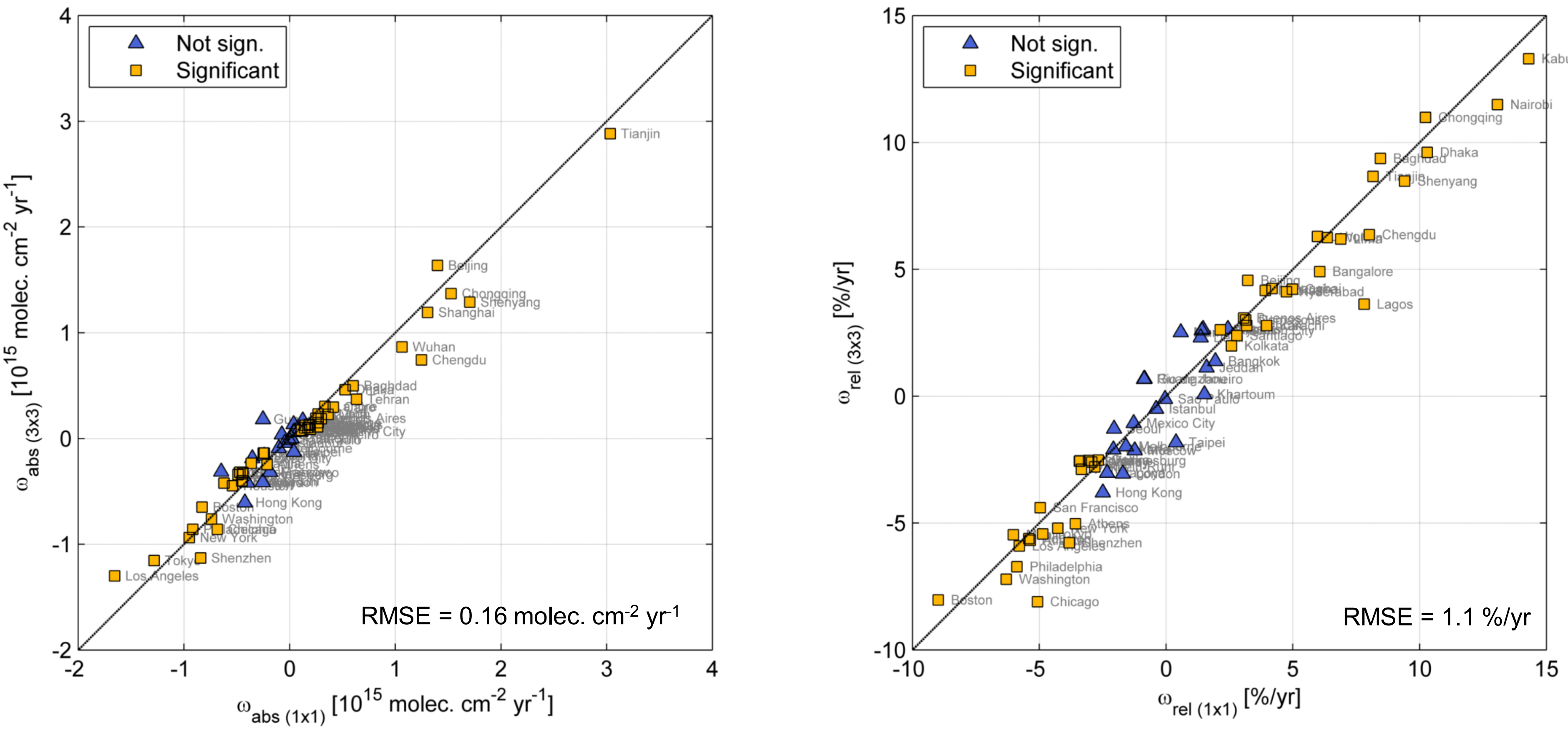
Schneider P. and R. van der A: A global SCIAMACHY-based trend analysis of tropospheric NO2 over megacities. PRESCRIBE workshop, Bremen, May 15 2013.

NO_2 trend vs. Population Growth



Schneider P. and R. van der A: A global SCIAMACHY-based trend analysis of tropospheric NO2 over megacities. PRESCRIBE workshop, Bremen, May 15 2013.

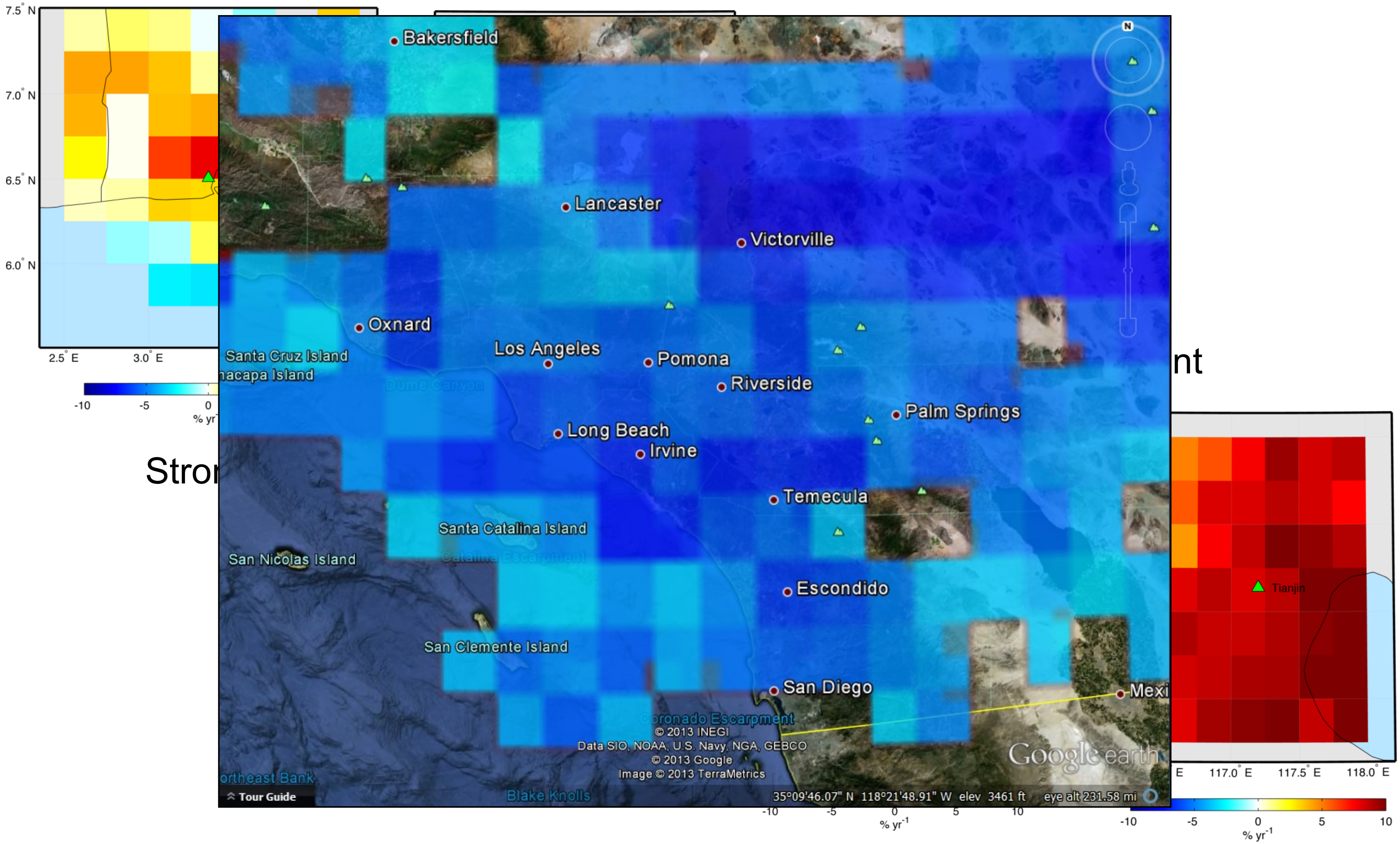
Single grid cell versus 3 x 3



Relationship between trends computed for a single pixel (1 x 1) and an array of 3 x 3 grid cells over each megacity/agglomeration. The Figure shows absolute trends (left) and relative trends (right).

Schneider P. and R. van der A: A global SCIAMACHY-based trend analysis of tropospheric NO2 over megacities. PRESCRIBE workshop, Bremen, May 15 2013.

Spatial heterogeneity at city level



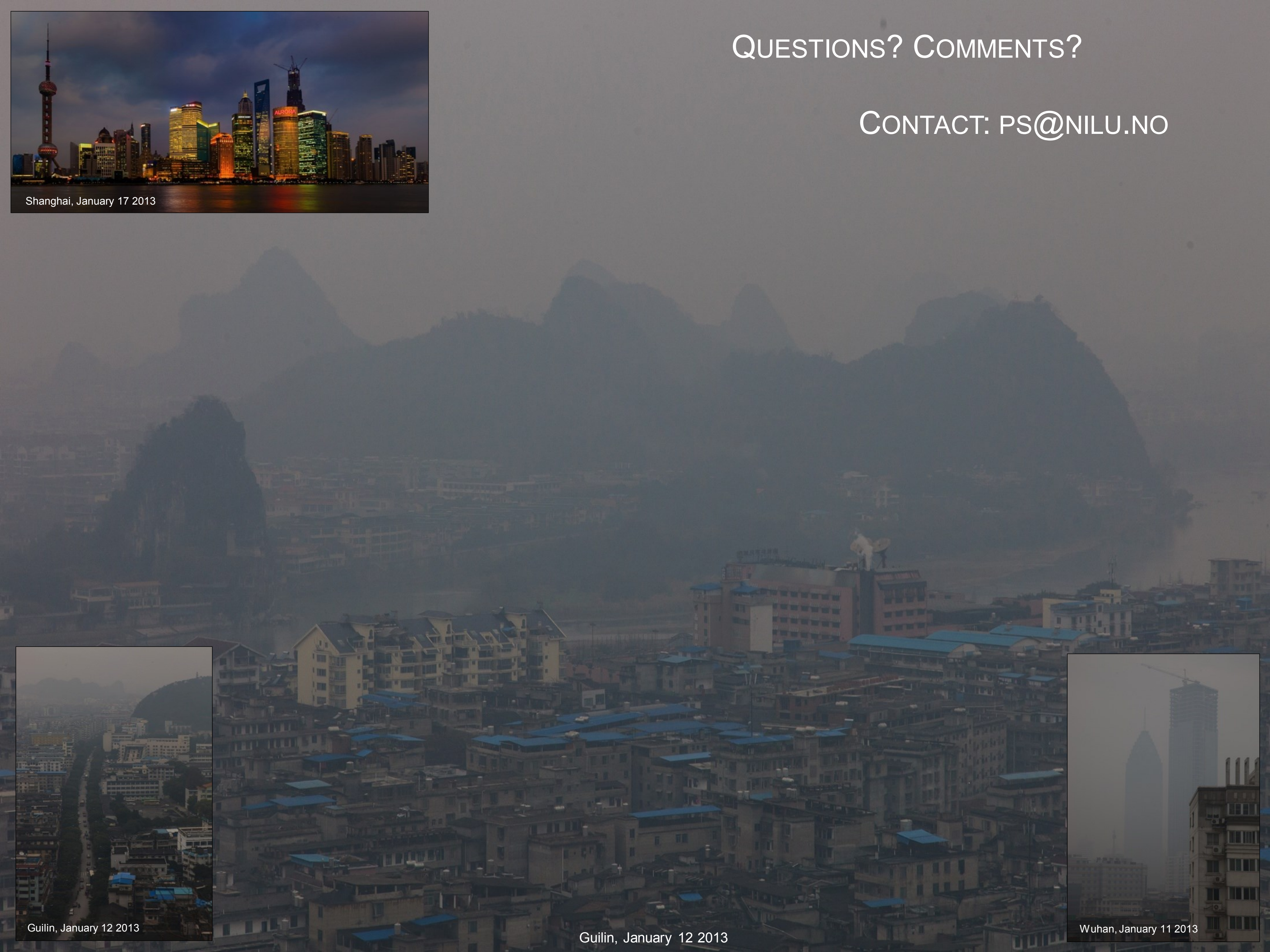
Schneider P. and R. van der A: A global SCIAMACHY-based trend analysis of tropospheric NO2 over megacities. PRESCRIBE workshop, Bremen, May 15 2013.

Summary

- A global 10-year trend analysis of tropospheric NO_2 was carried out w. SCIAMACHY data
- Only a single instrument was used to generate the most homogeneous time series possible → avoids problems with inter-sensor biases and other instrument issues
- Global study results:
  - Fitting a statistical model with seasonal component is a robust way to extract linear trends from monthly data
  - Widespread decreases over US and Europe, rapidly increasing trends over China, Asian megacities
  - Direct comparison with trends of European AQ stations shows similarities in spatial patterns but substantial differences at the individual station level
  - Comparison with trends from EMEP model show similar spatial patterns
- Main results for major agglomerations/megacities (updated)
  - Most rapidly increasing trends in Tianjin, China (abs.) and Kabul, Afghanistan (rel.)
  - Most rapid decreasing trends in Los Angeles (abs.) and Boston (rel.)
  - Grouped by region, varying relationship between NO2 trend and population growth
  - Spatial heterogeneity at city-level influences derived trends
- Obvious step forward: Lengthen the time series by combining data from multiple instruments
  - Requires careful correction of inter-sensor biases, and instrument differences such as spatial resolution, overpass time etc.
  - See presentation by Andreas Hillboll

Questions? Comments?

Contact: ps@nilu.no



Shanghai, January 17 2013

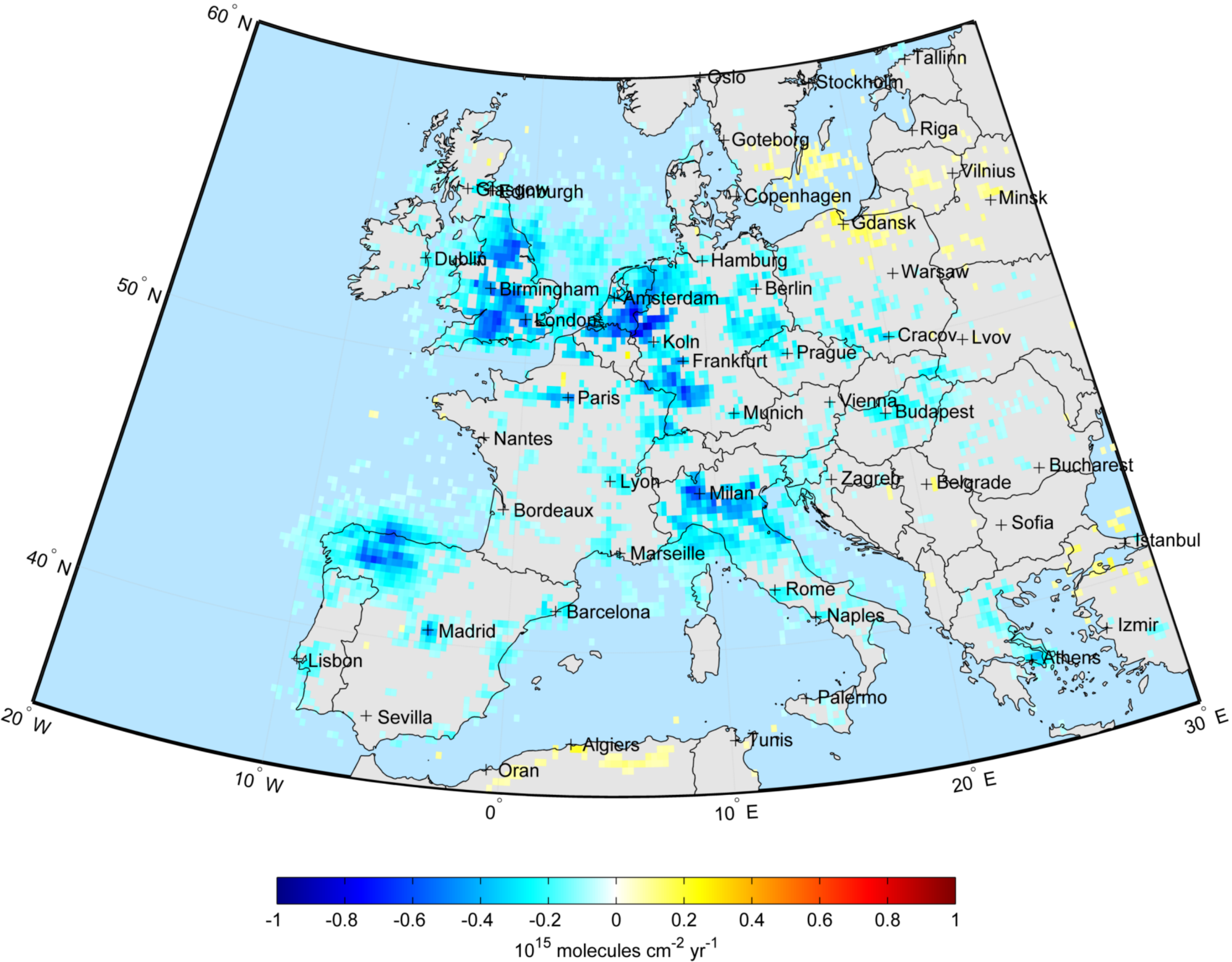
Guilin, January 12 2013

Guilin, January 12 2013

Wuhan, January 11 2013

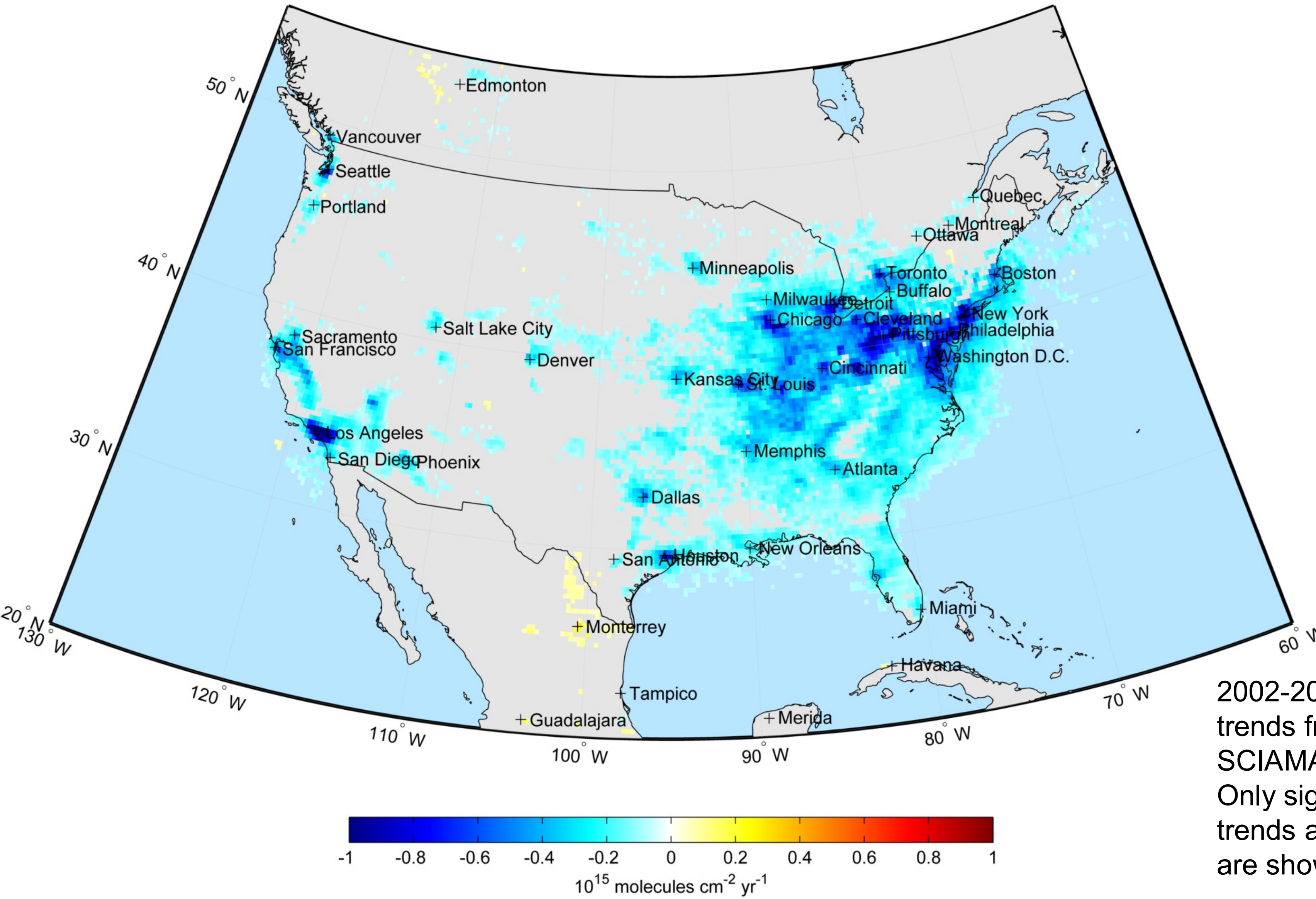
Extra slides

Europe: Absolute Trends



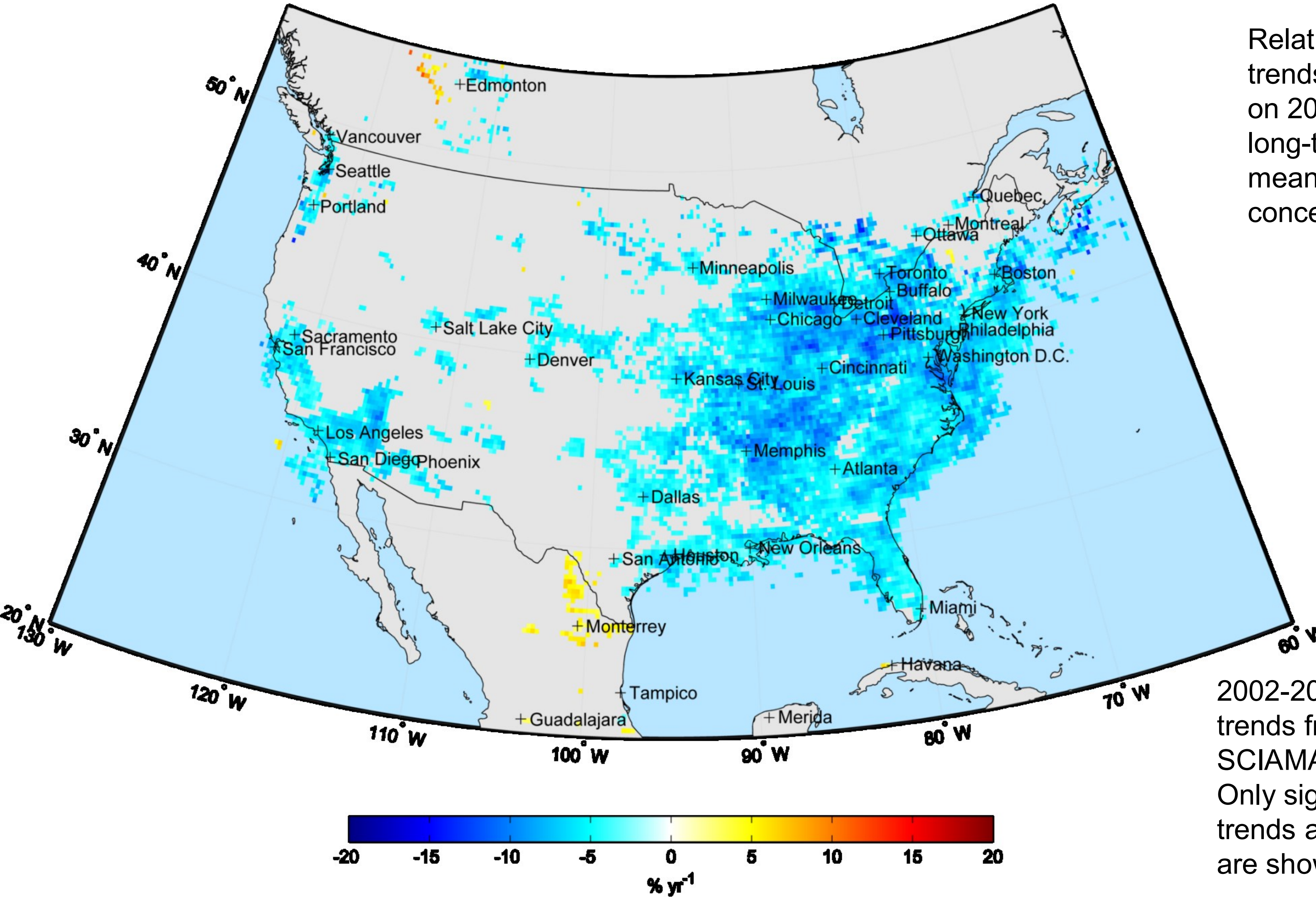
2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at α=0.05 are shown.

North America: Absolute Trends



2002-2011 NO2 trends from SCIAMACHY. Only significant trends at α=0.05 are shown.

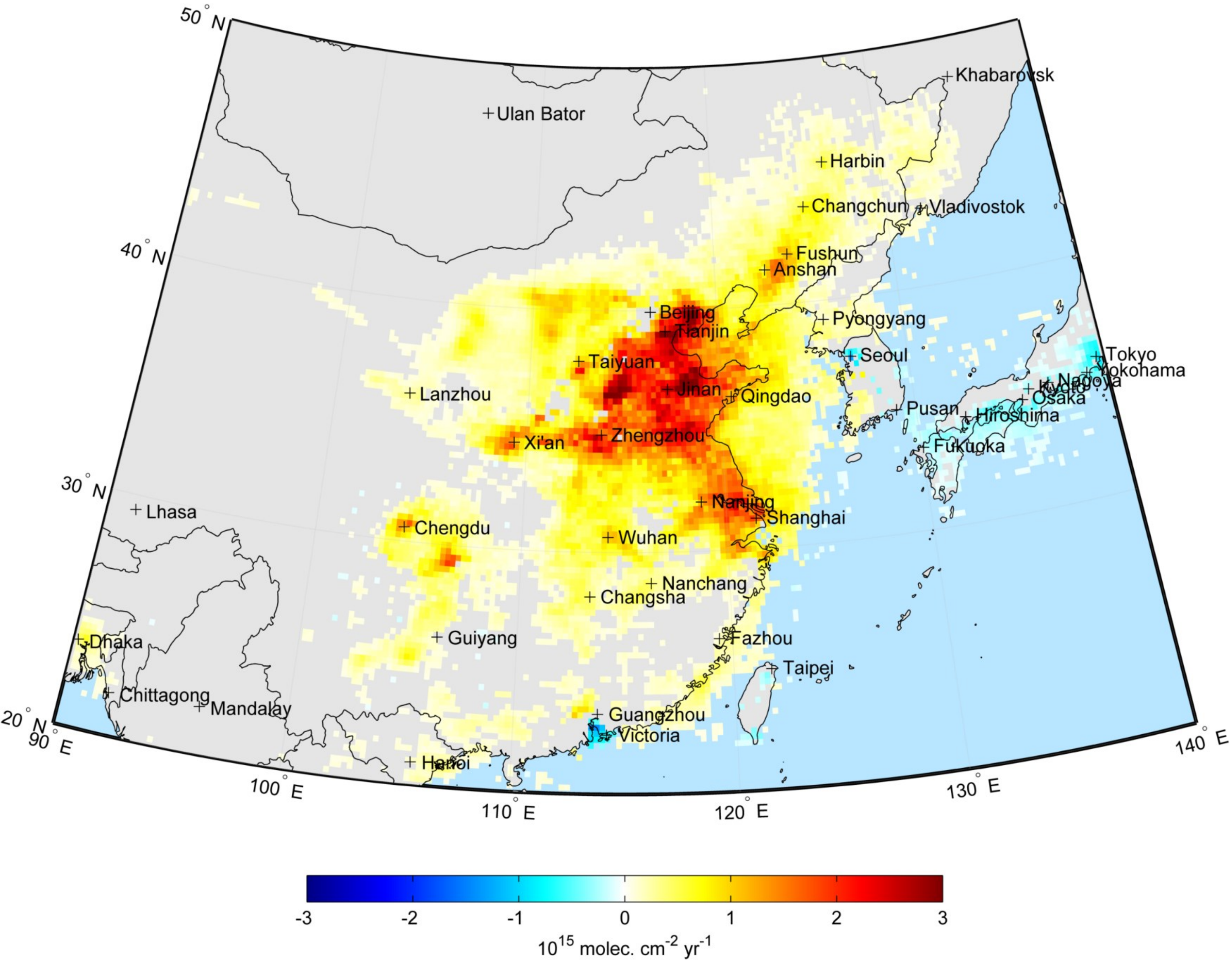
North America: Relative Trends



Relative trends based on 2002-2011 long-term mean concentration

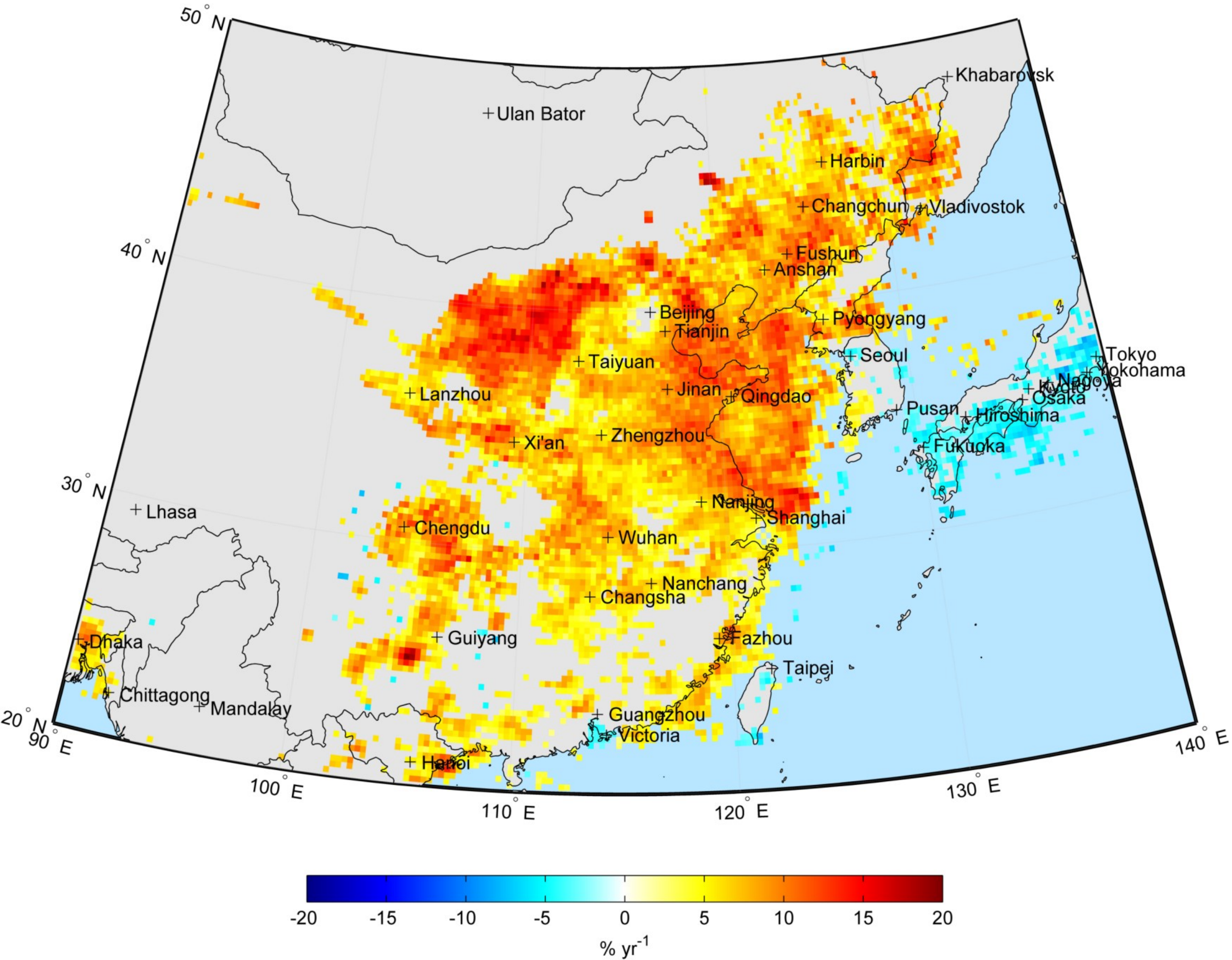
2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at $\alpha=0.05$ are shown.

China: Absolute Trends



2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at $p<0.05$ are shown.

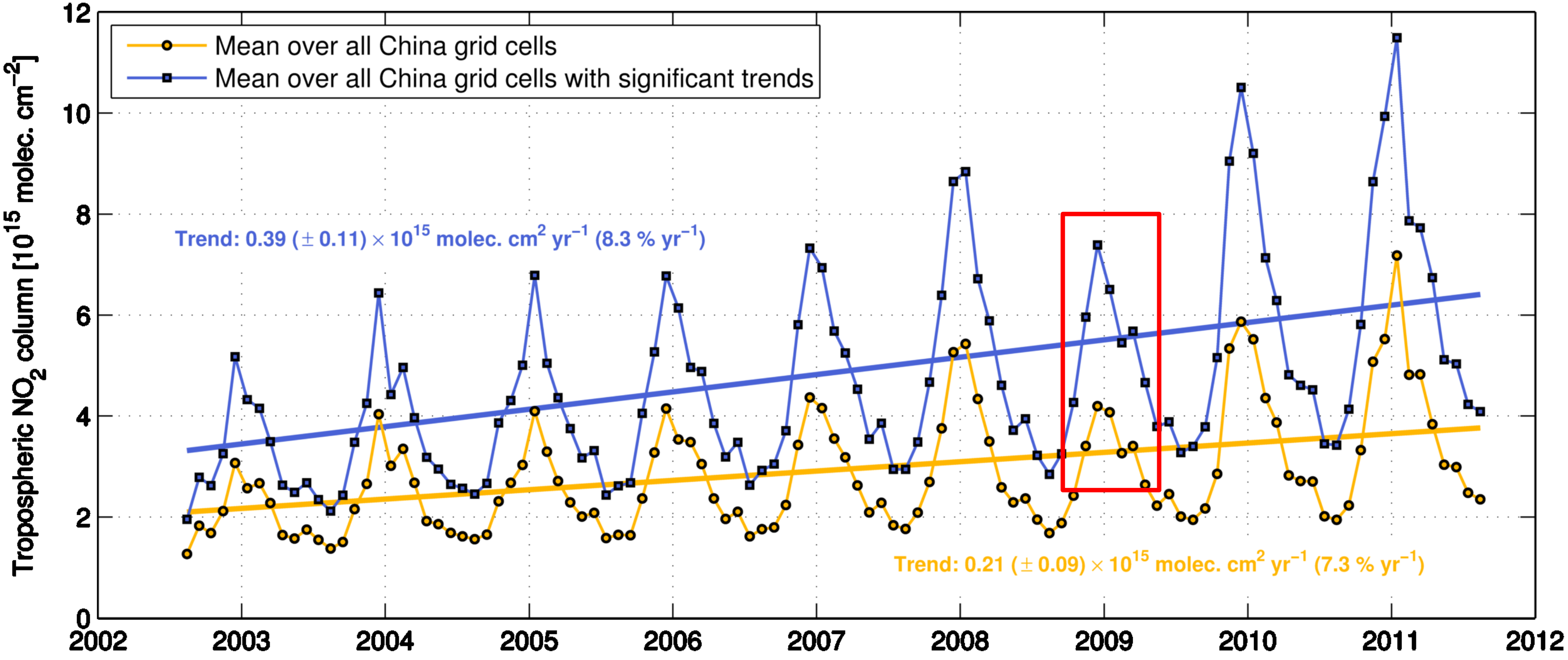
China: Relative Trends



Relative trends based on 2002-2011 long-term mean concentration

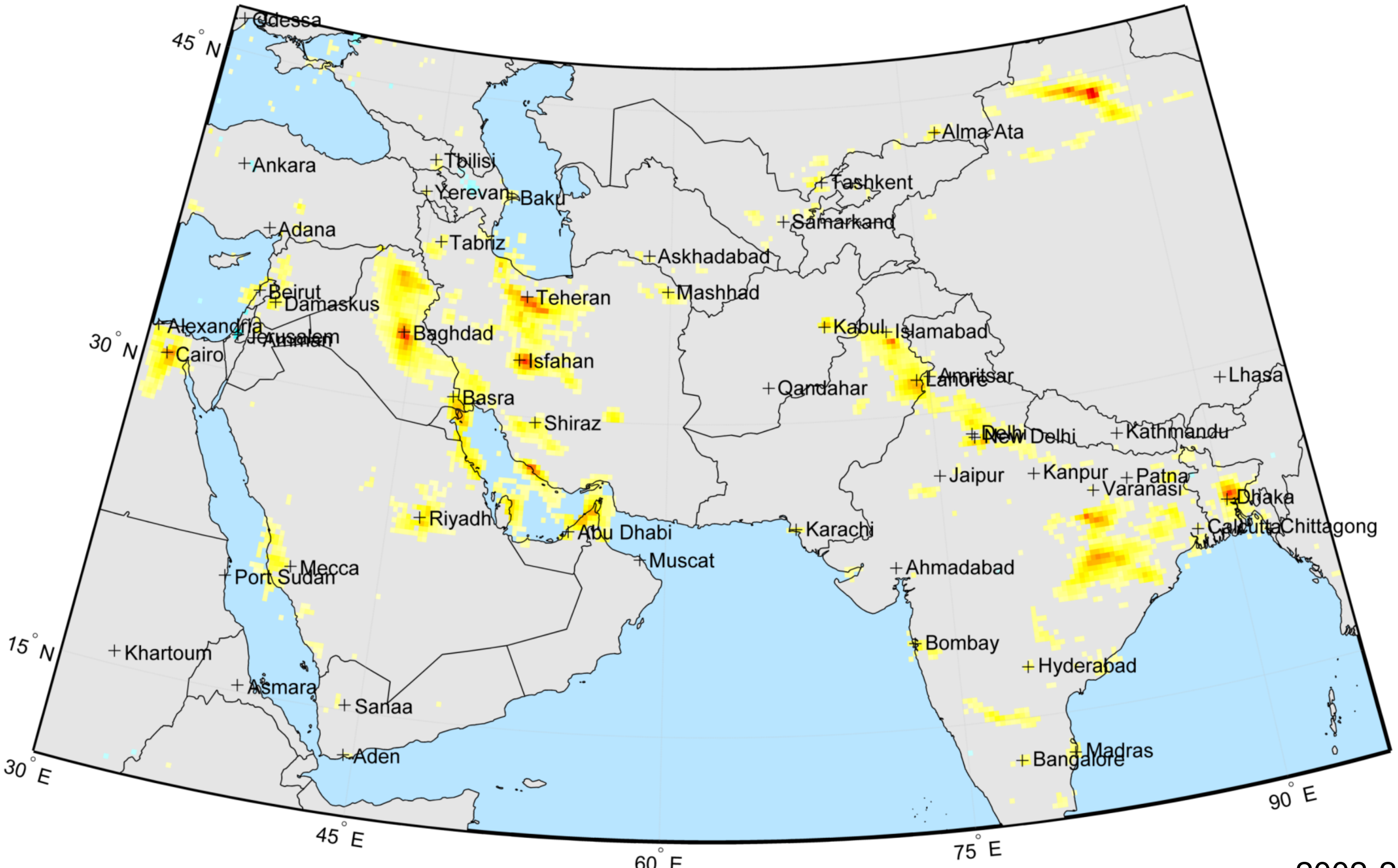
2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at $p<0.05$ are shown.

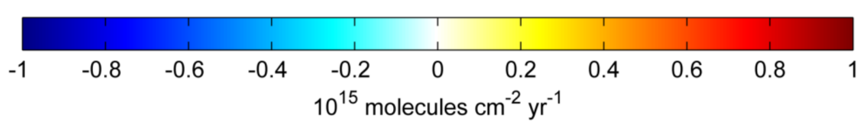
Time Series: China



Schneider P. and R. van der A: A global SCIAMACHY-based trend analysis of tropospheric NO2 over megacities. PRESCRIBE workshop, Bremen, May 15 2013.

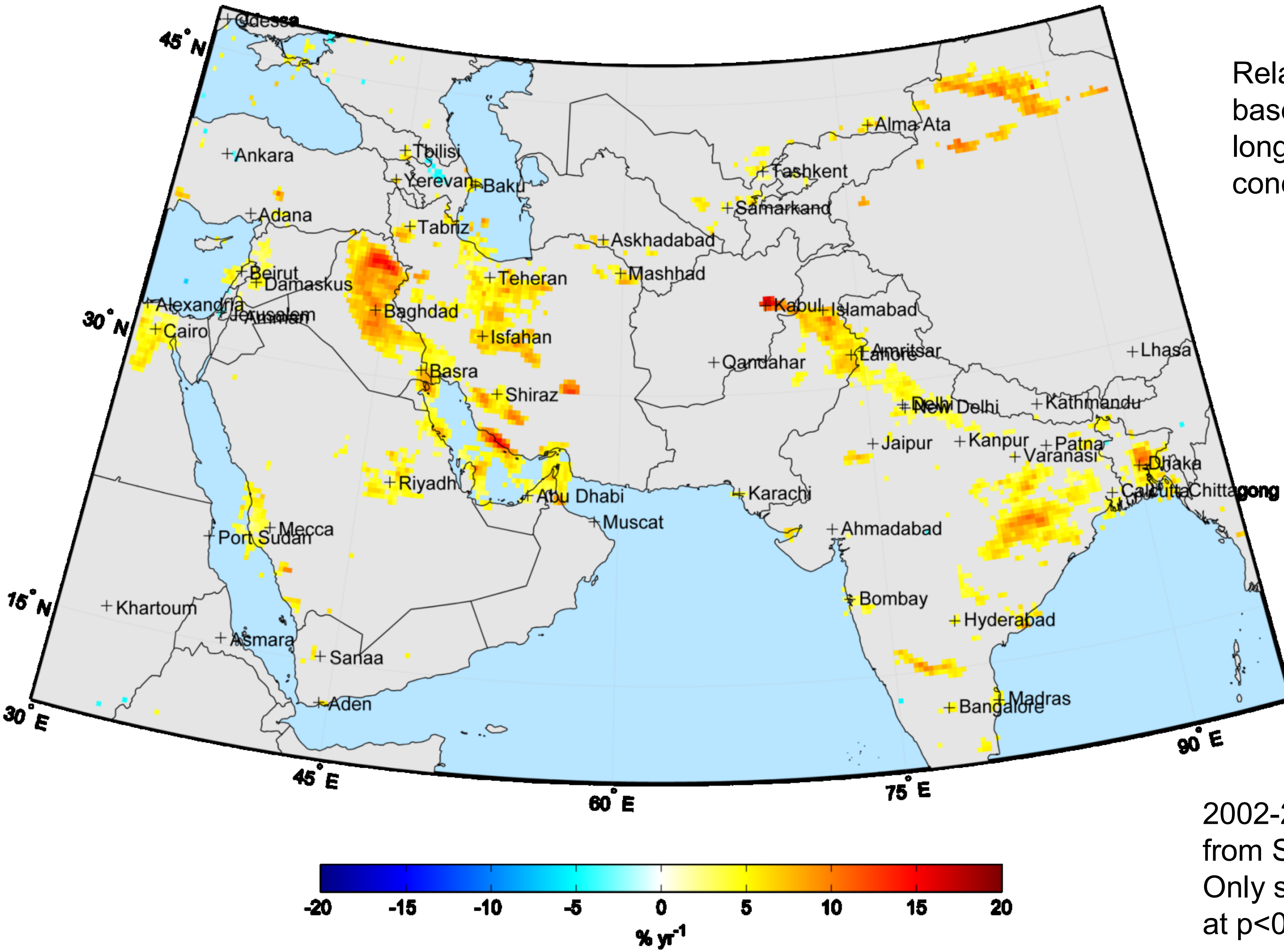
South Asia and M. East: Absol. Trends





2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at $p<0.05$ are shown.

South Asia and Middle East

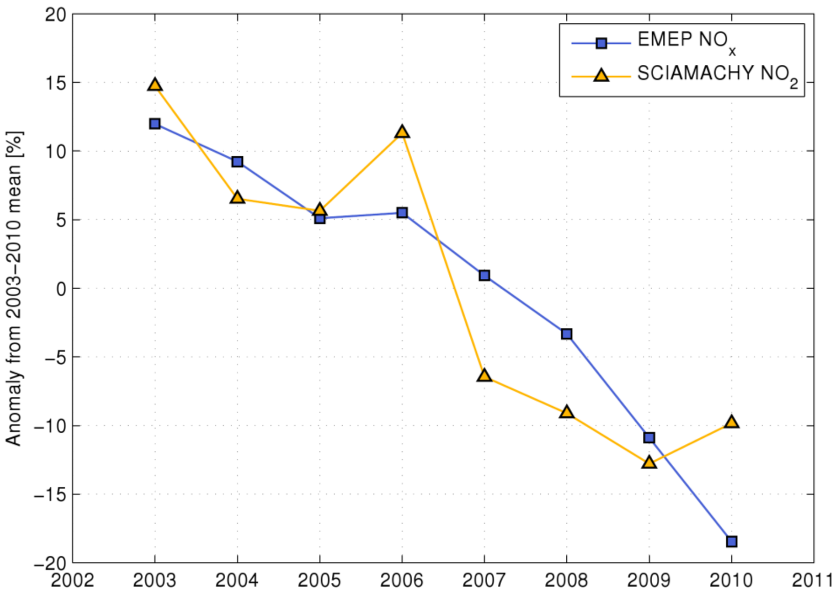


Relative trends based on 2002-2011 long-term mean concentration

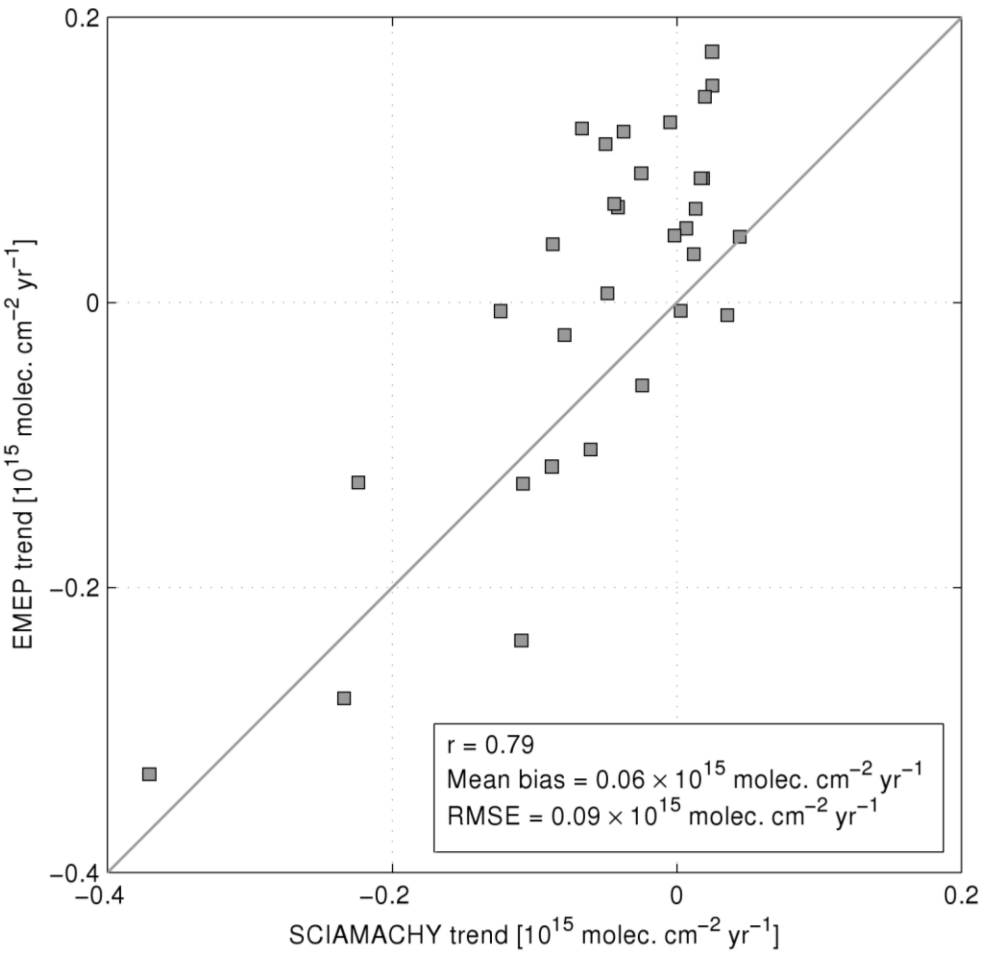
2002-2011 NO_2 trends from SCIAMACHY. Only significant trends at $p<0.05$ are shown.

SCIAMACHY vs. EMEP

Average anomaly of EMEP NO_x emissions vs. SCIAMACHY NO_2 in Germany



2002 – 2009 country-level average trends in tropospheric NO2 column



Conclusions

- 10-year archive of SCIAMACHY data offers the possibility to study global NO_2 trends at a previously unachievable resolution
- Fitting a statistical model with seasonal component is a robust way to extract linear trends from monthly data
- Global and regional analysis shows moderately decreasing NO_2 concentrations in Europe and the US, but rapid increases in Eastern China and many megacities
- Comparison with in situ trends challenging at individual station level, but promising in terms of larger spatial patterns
- Comparison with EMEP model trends shows similarities in western Europe but discrepancies in Eastern Europe
- Upcoming instruments such a Sentinel-5 precursor (TROPOMI, launch ~2015) will provide vastly improved datasets: Daily global coverage at a spatial resolution of 7 km x 7 km