Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

# Fast emission estimates in China and South Africa constrained by satellite observations

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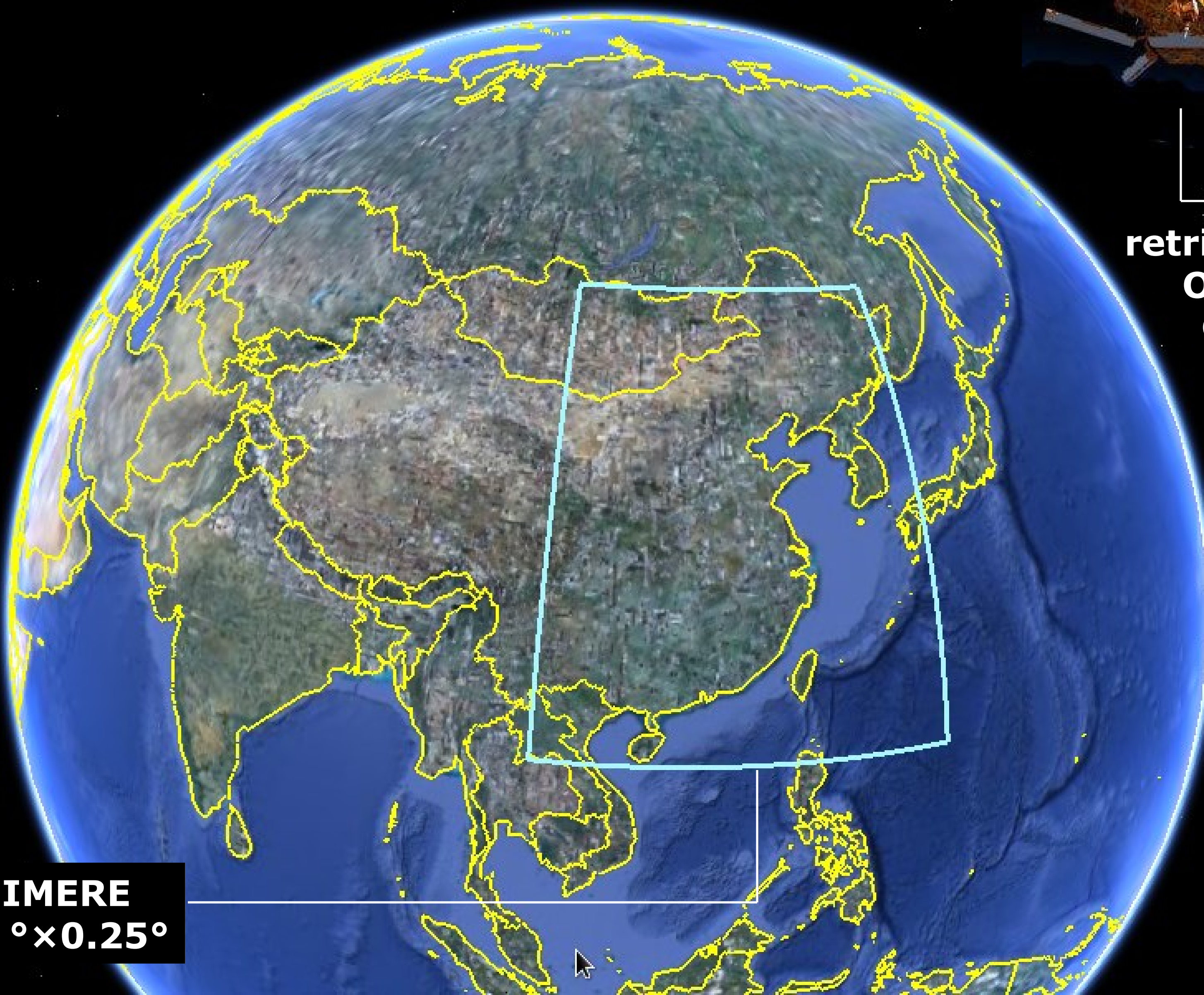
**Ronald van der A**

PRESCRIBE workshop, 16 May 2013

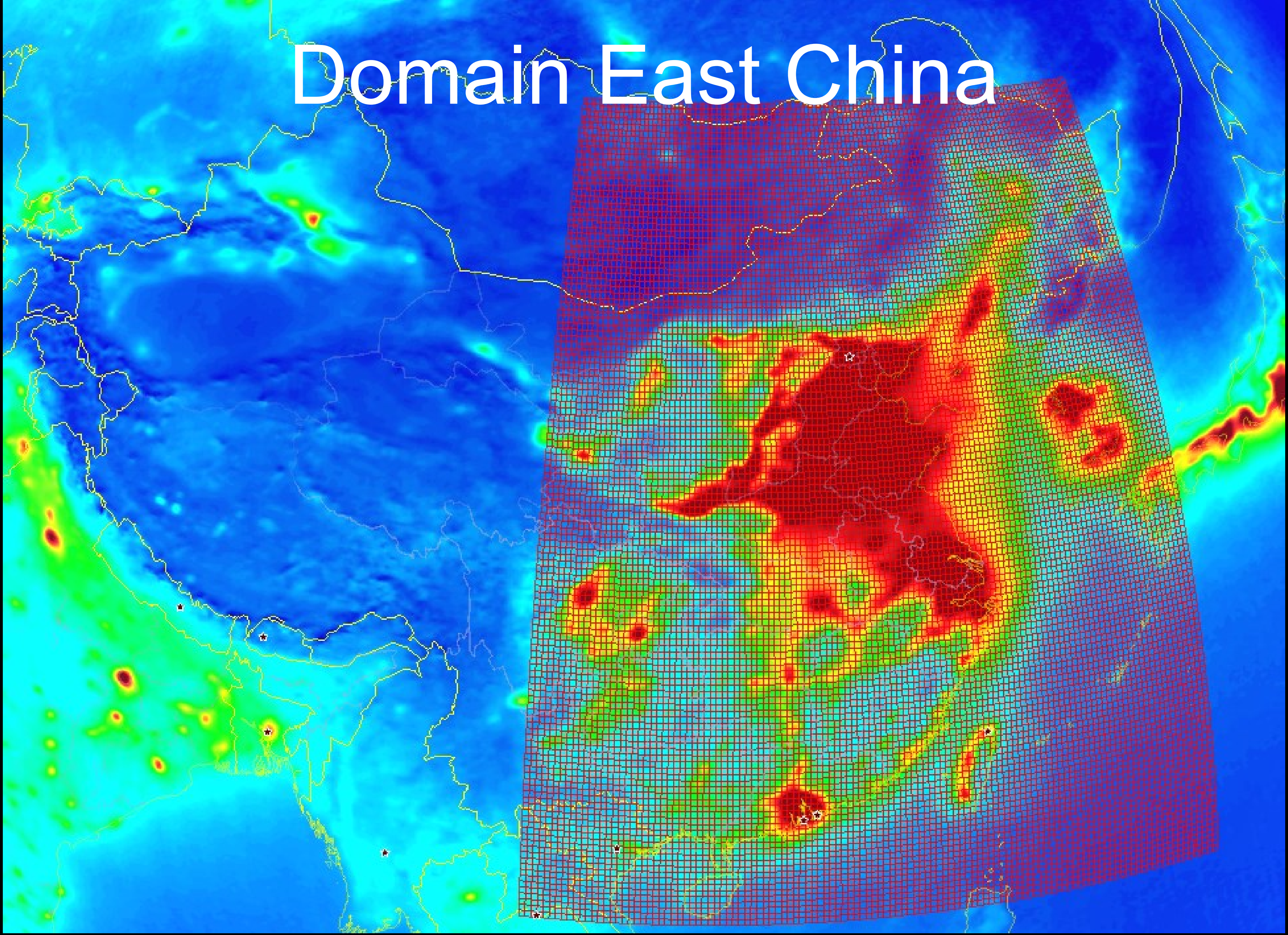
# Overview

- New emission estimation algorithm
- Applied to China
  - $NO_x$ emission trend analysis 2007-2011
- Applied to South Africa
  - First results of $NO_x$ emissions

# Basic tools

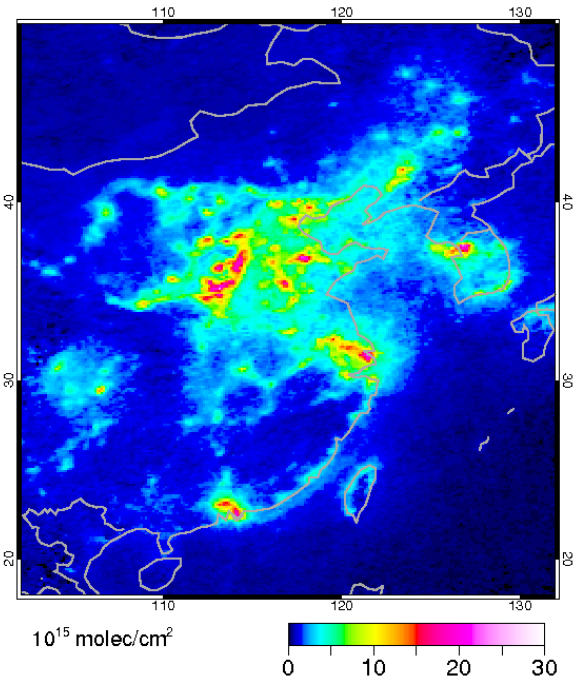
# Domain East China



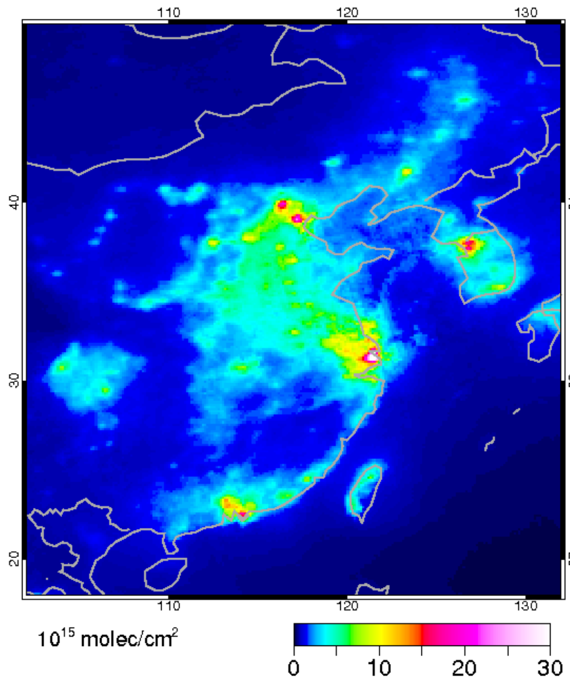
18°N–50°N, 102°E–132°E, 0.25° resolution, 15609 grid cells

# Difference between observations and model

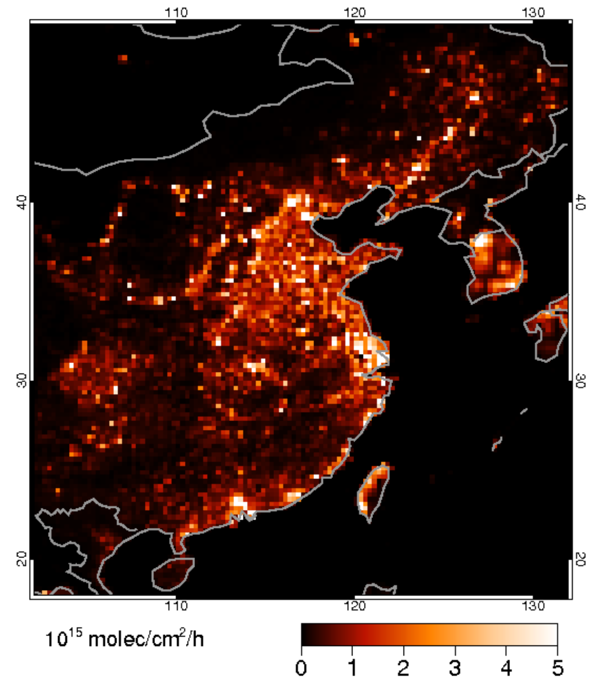
OMI tropospheric $NO_2$




CHIMERE tropospheric $NO_2$




INTEX-B 2006




Average over June−August 2008

# Inversion techniques

*finding the relation between emission changes and concentration changes*

- Adjoint code of CTM
  Not always available.
- Ensemble Kalman Filter
  Multiple forward model runs necessary.
- Local inversion by concentration ratio
  e.g. by Martin et al. (2006). Transport from source neglected.
- **DECSO** algorithm *(Mijling and Van der A, JGR, 2012)*
  **D**aily **E**mission estimates **C**onstrained by **S**atellite **O**bservations

**Only 1 model run necessary:**
Algorithm is relatively fast, enabling daily inversion of observations.

**Transport from source is included:**
Enabling emission estimation on a mesoscale resolution (10-25 km)

Using a simplified 2D transport scheme to approximate CTM run

# *Two concentration contributions*

Consider a time interval $t$=[0,$T$] (24 hrs).

The concentration at $t=T$ is composed of

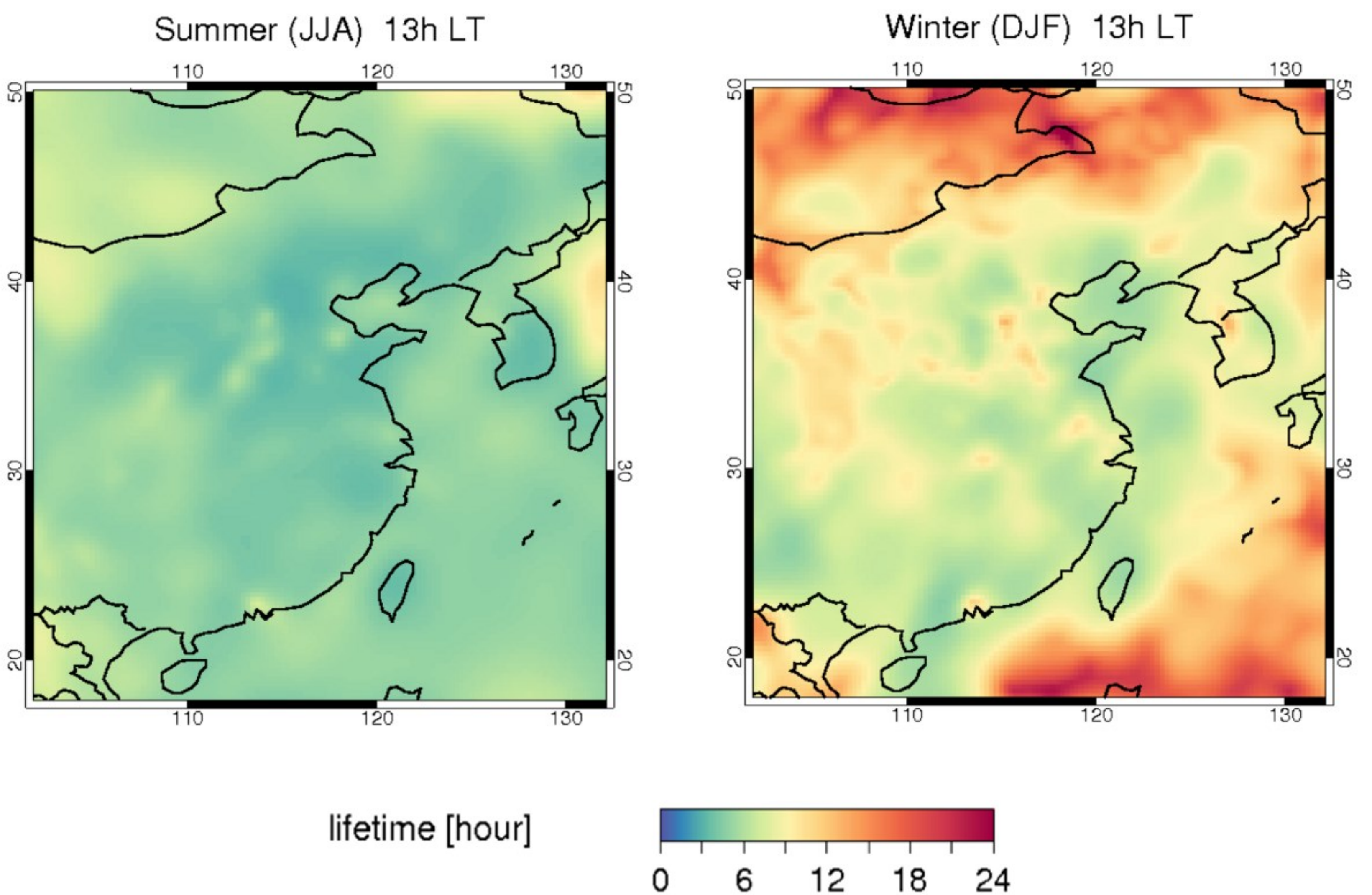
1. Transported and aged background concentration:

$$c_i(T) = \sum_j \exp\left(-T/\tau_j\right)\Omega_{j\to i}(T)c_j(0) \quad \Rightarrow \quad \mathbf{c}(T) = \mathbf{Gc}(0)$$

2. Emitted and transported $NO_x$ during the time interval:

$$c_i(T) = \sum_j \left( \int_0^T \exp\left(-t/\tau_j\right)\Omega_{j\to i}(t) f_j(T-t)\mathrm{d}t \right) e_j \quad \Rightarrow \quad \mathbf{c}(T) = \mathbf{He}$$

# Effective lifetime



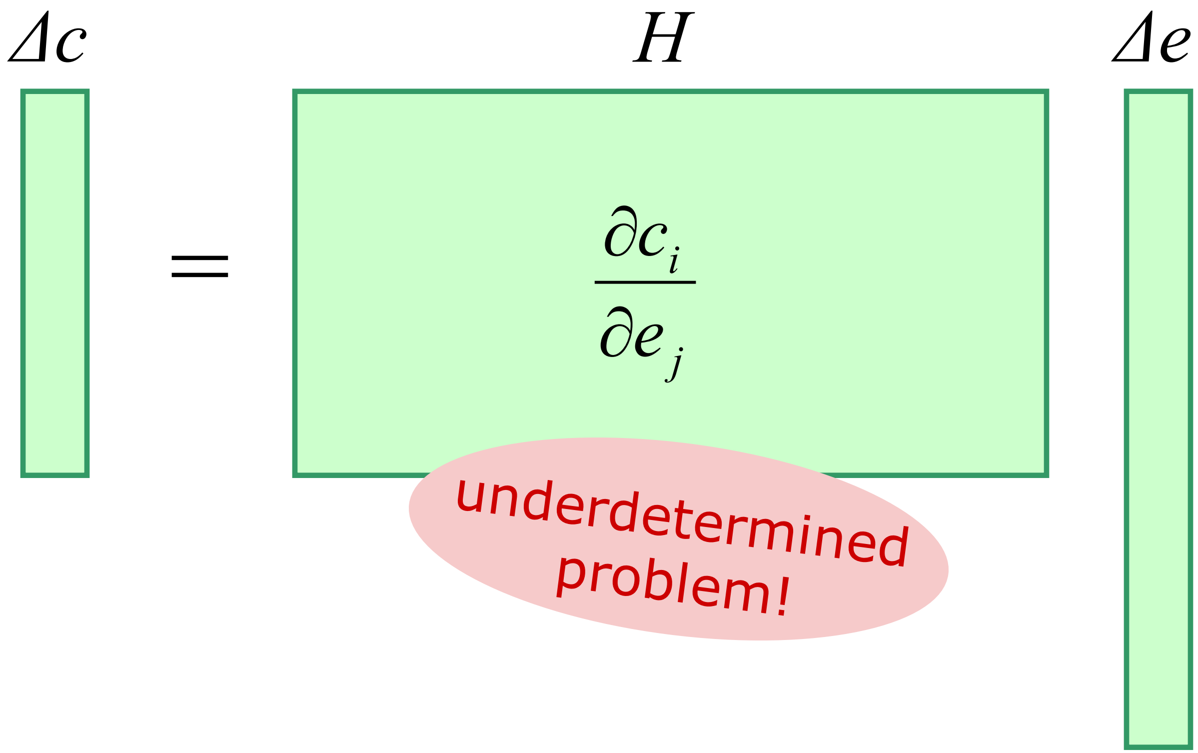
Dependence of $NO_2$ columns in grid cell $i$ on $NO_x$ emission changes in grid cell $j$

$$H_{ij} = \frac{\partial c_i^{NO2}}{\partial e_j^{NOx}} = \gamma_i \frac{a_j}{a_i} \int_0^T e^{-t/\tau_j} \Omega_{ij}(t) f_j(T-t) dt$$

| | |
|---|---|
| $[0,T]$ | 24h time window between two satellite overpasses |
| $f_j(t)$ | diurnal emission modulation |
| $\Omega_{ij}(t)$ | transport of $NO_x$ from cell $j$ to $i$ during $[t,T]$ |
| $\tau_j$ | effective lifetime of NOx |
| $a_j/a_i$ | ratio grid cell area |
| $\gamma_i$ | $NO_2/NO_x$ ratio |

The sensitivities $\mathbf{H}$ are interpolated to the satellite footprints and are corrected for by the averaging kernel of the retrieval method.

# Inversion problem




Difference satellite observation and model simulation over East China

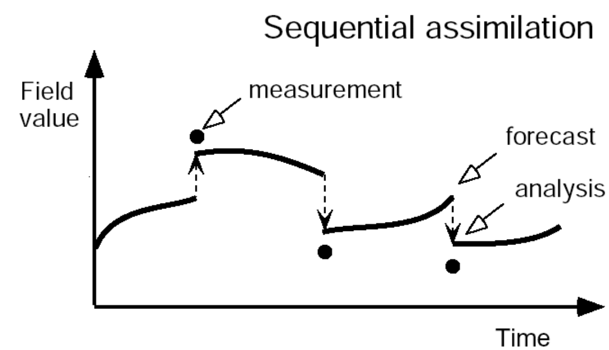
Sensitivity matrix ~ 2000×15000

Update emission inventory (0.25°) over East China

# **Inversion:** The Kalman Filter

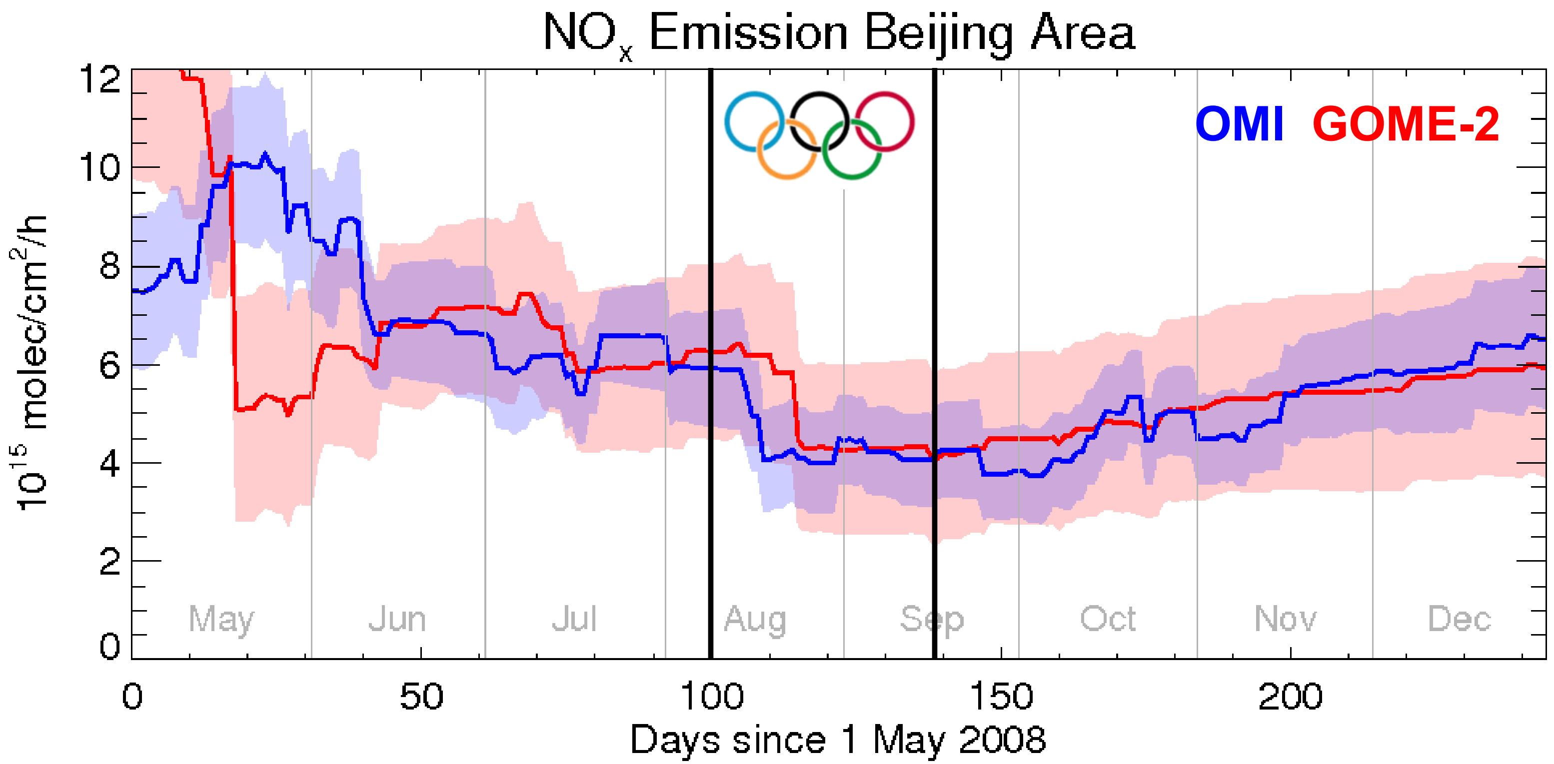
| | |
|---|---|
| State vector forecast | $\mathbf{x}^{f}(t_{i+1}) = M_i\,[\mathbf{x}^{a}(t_i)]$ |
| Error covariance forecast | $\mathbf{P}^{f}(t_{i+1}) = \mathbf{M}_i\mathbf{P}^{a}(t_i)\mathbf{M}_i^{T} + \mathbf{Q}(t_i)$ |
| Kalman gain matrix | $\mathbf{K}_i = \mathbf{P}^{f}(t_i)\mathbf{H}_i^{T}[\mathbf{H}_i\mathbf{P}^{f}(t_i)\mathbf{H}_i^{T} + \mathbf{R}_i]^{-1}$ |
| State vector analysis | $\mathbf{x}^{a}(t_i) = \mathbf{x}^{f}(t_i) + \mathbf{K}_i(\mathbf{y}_i^{o} - H_i\,[\mathbf{x}^{f}(t_i)])$ |
| Error covariance analysis | $\mathbf{P}^{a}(t_i) = (\mathbf{I} - \mathbf{K}_i\mathbf{H}_i)\,\mathbf{P}^{f}(t_i)$ |

- Starts from *a priori* information, i.e. the best known bottom-up emission inventory
- Update depends on error in observation and simulation

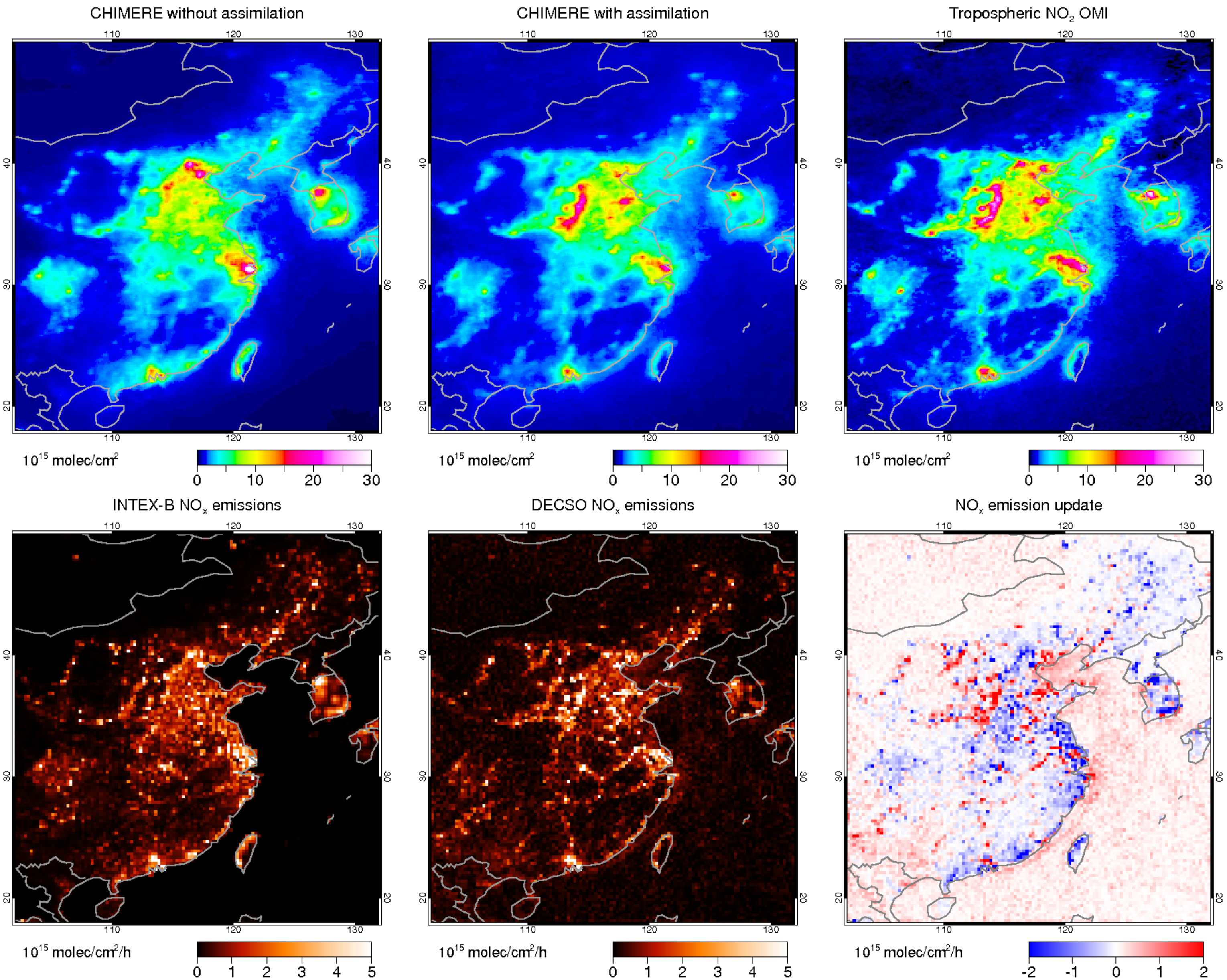



- No update where no information is available
- Emissions are updated by addition instead of scaling
- Error estimation of new emission inventory

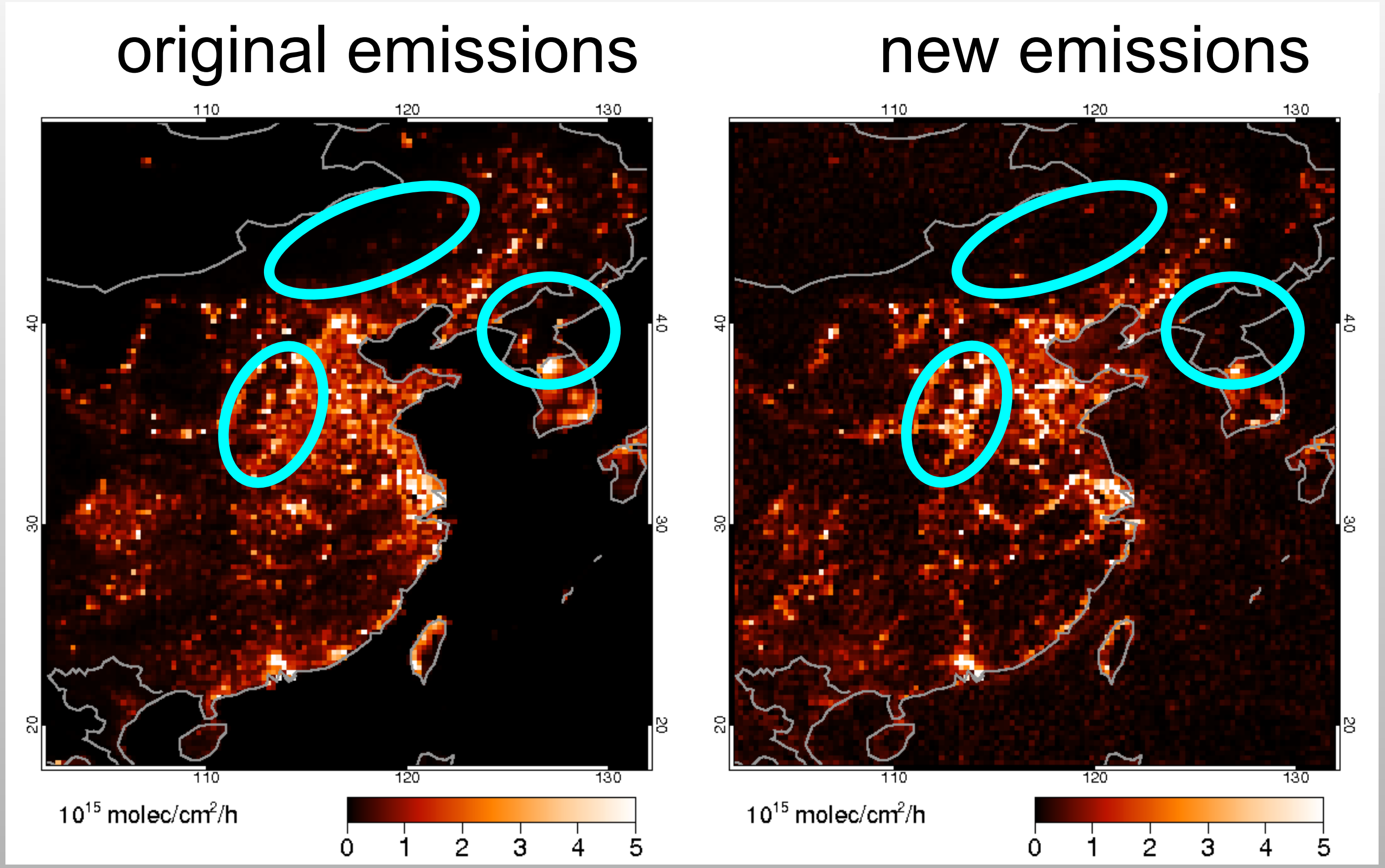
# $NO_x$ emission trend Beijing area



# $NO_x$ emission estimates for East China

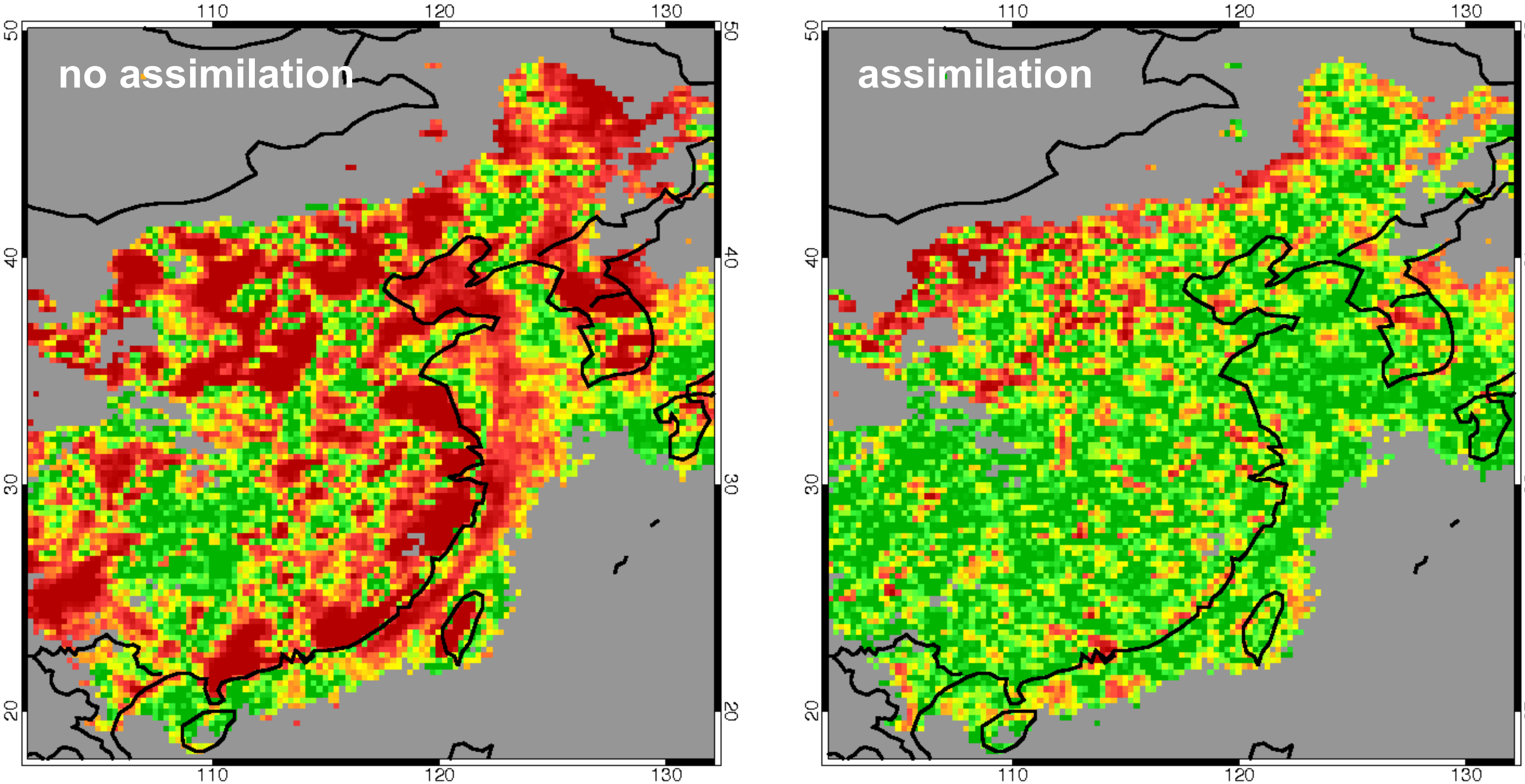


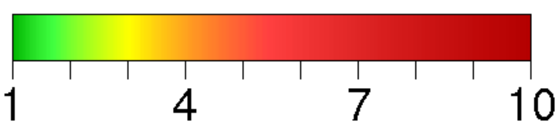
# Emission results China




- New power plants in Inner Mongolia
- Distinct emissions along great rivers
- No emissions in North Korea
- Ship tracks

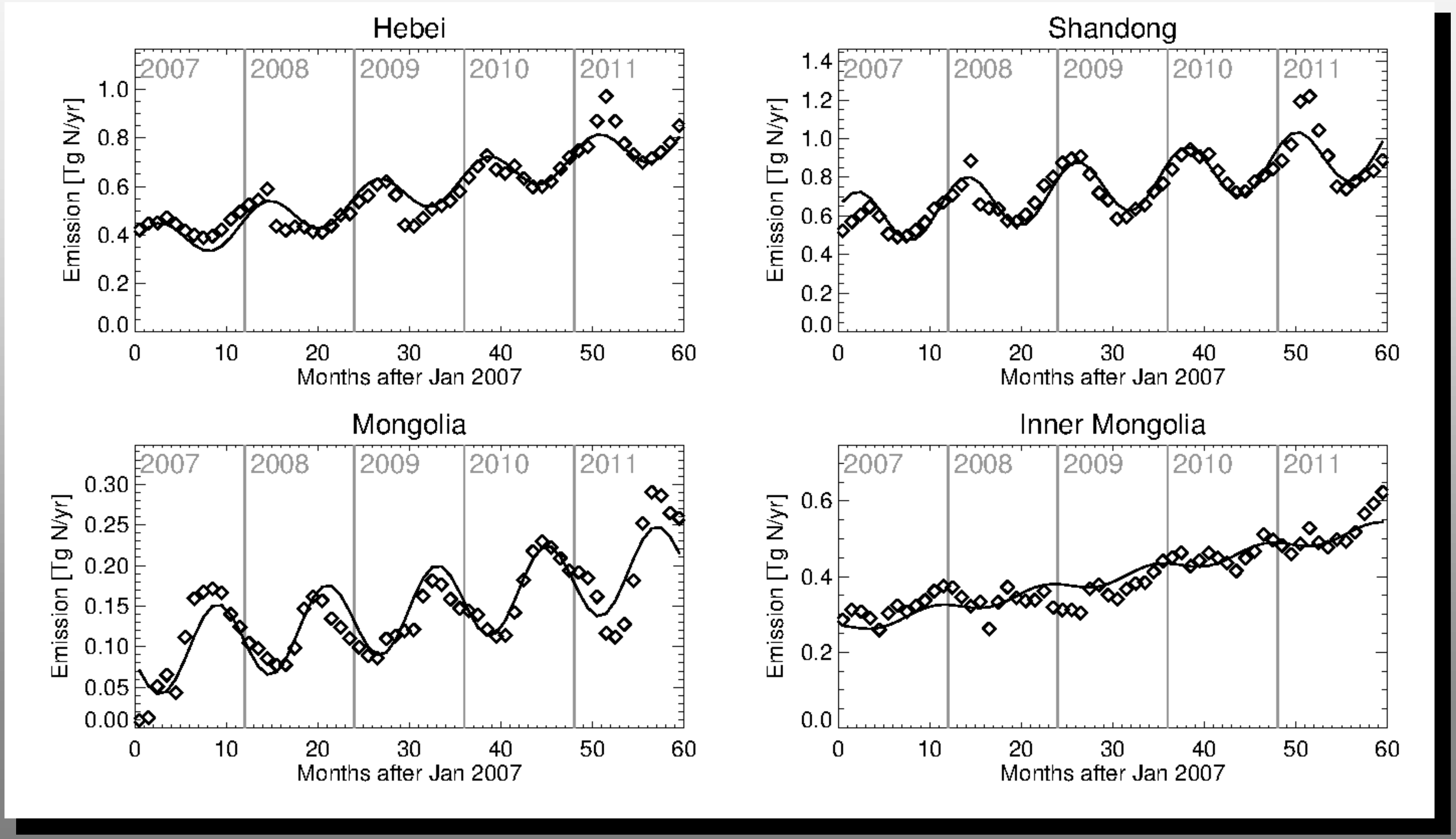
# Agreement between observation and forecast



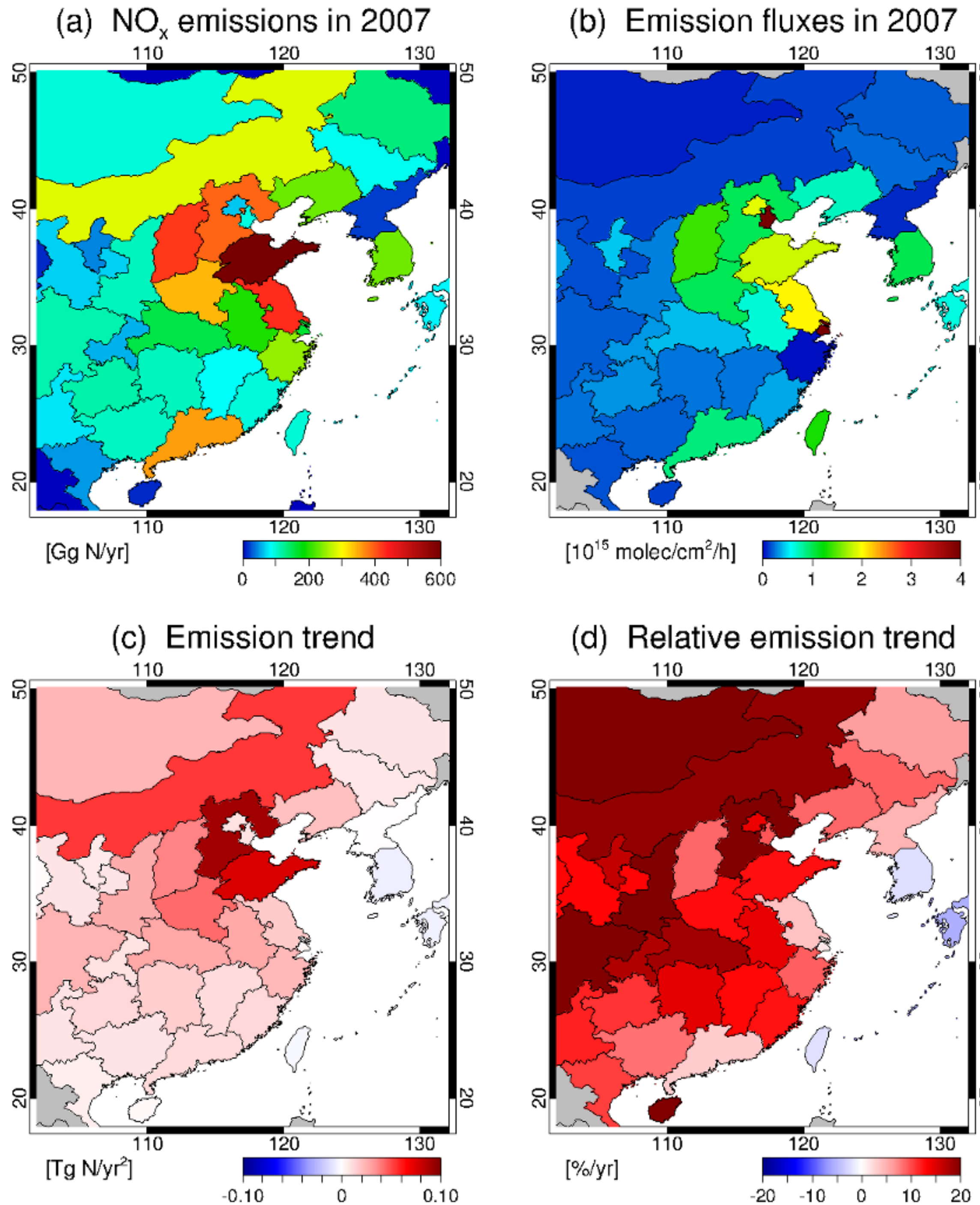



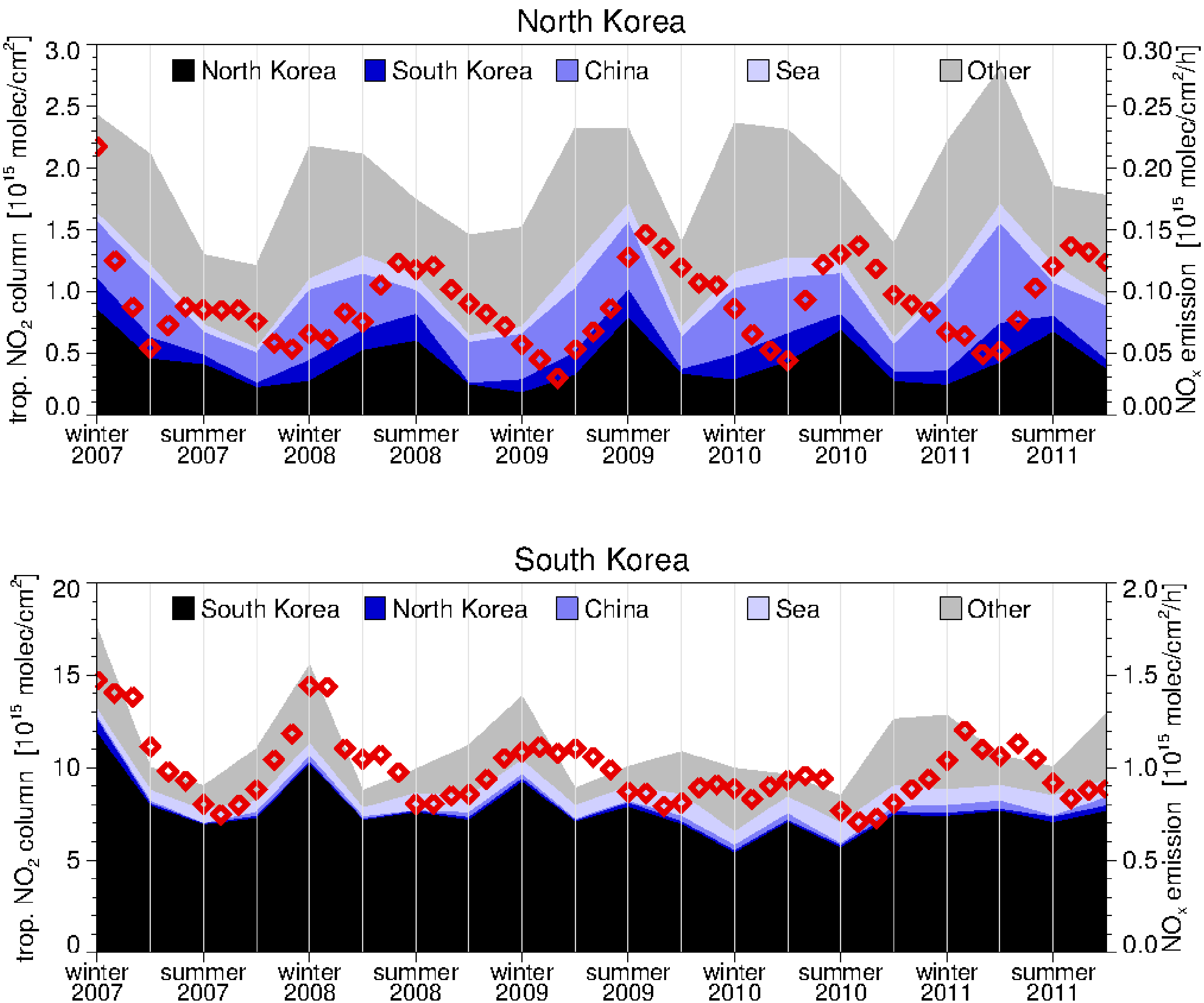

Emission estimates
from OMI data
May-December 2008

# $NO_x$ time series 2007-2011

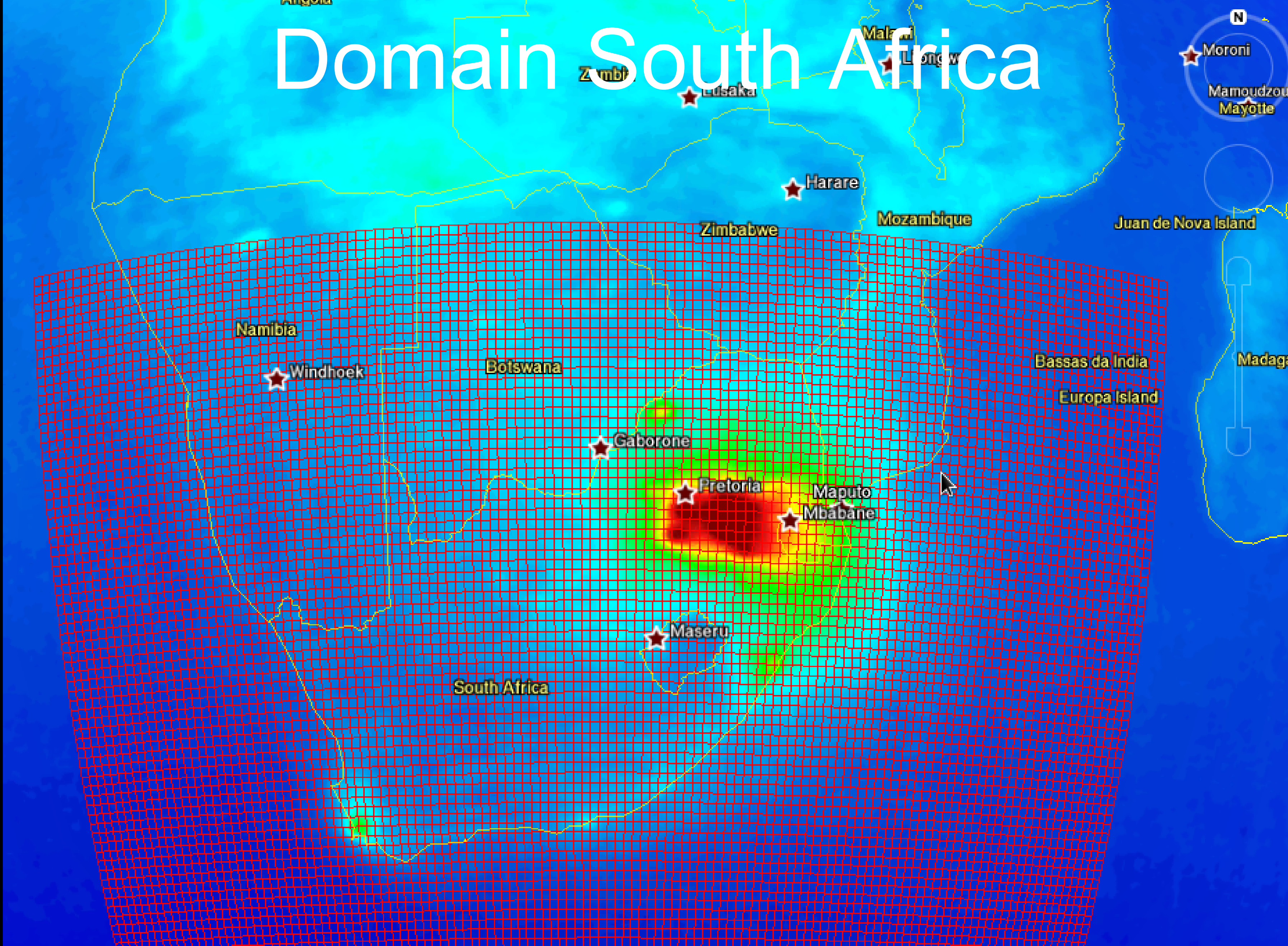


# Emission trends by province




North Korea
North Korea
South Korea
China
Sea
Other
trop. NO2 column [10^15 molec/cm^2]
NOx emission [10^15 molec/cm^2/h]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.30
0.25
0.20
0.15
0.10
0.05
0.00
winter 2007
summer 2007
winter 2008
summer 2008
winter 2009
summer 2009
winter 2010
summer 2010
winter 2011
summer 2011
South Korea
South Korea
North Korea
China
Sea
Other
trop. NO2 column [10^15 molec/cm^2]
NOx emission [10^15 molec/cm^2/h]
20
15
10
5
0
2.0
1.5
1.0
0.5
0.0
winter 2007
summer 2007
winter 2008
summer 2008
winter 2009
summer 2009
winter 2010
summer 2010
winter 2011
summer 2011

# Domain South Africa




19°S–37°S, 10°E–42°E, 0.25° resolution, 9417 grid cells

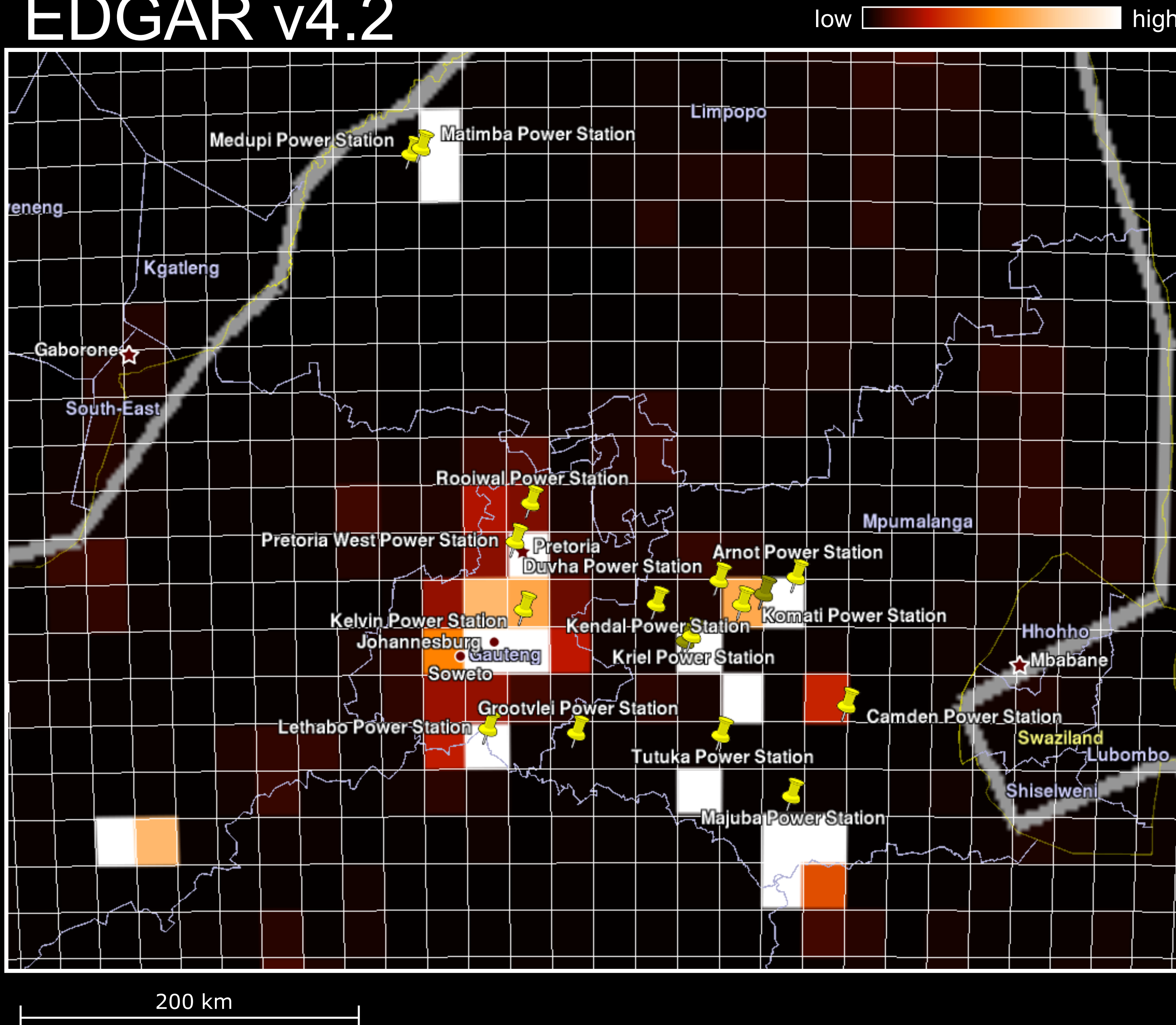
# South Africa:

Emissions characterized by few hot spots (power plants, heavy industry)

Apriori emissions taken from **EDGAR v4.2**

- Total emissions too low
- Location and strength of hot spots generally wrong

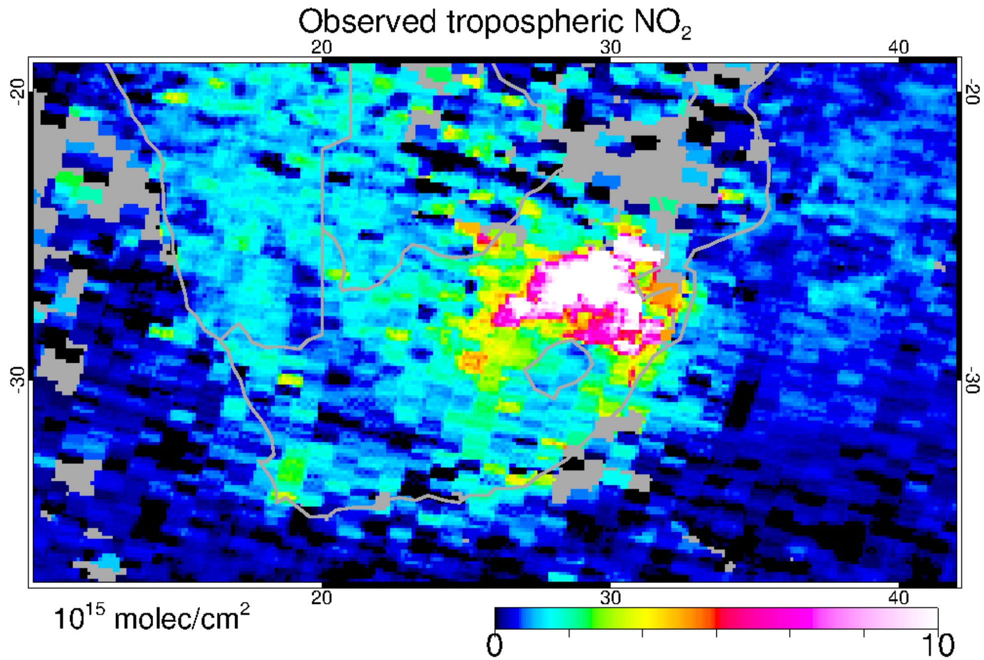
# EDGAR v4.2



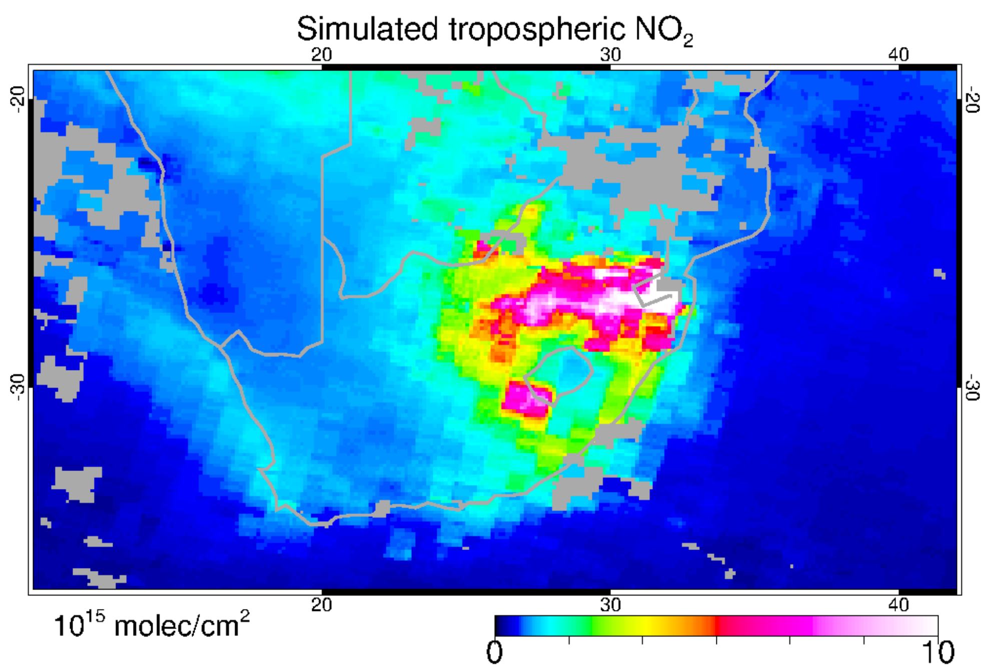
low
high
Medupi Power Station
Matimba Power Station
Limpopo
eneng
Kgatleng
Gaborone
South-East
Rooiwal Power Station
Mpumalanga
Pretoria West Power Station
Pretoria
Arnot Power Station
Duvha Power Station
Kelvin Power Station
Kendal Power Station
Komati Power Station
Hhohho
Johannesburg
Gauteng
Kriel Power Station
Mbabane
Soweto
Grootvlei Power Station
Camden Power Station
Lethabo Power Station
Swaziland
Tutuka Power Station
Lubombo
Shiselweni
Majuba Power Station
200 km

# First results

**GOME-2 observations**
January 2008

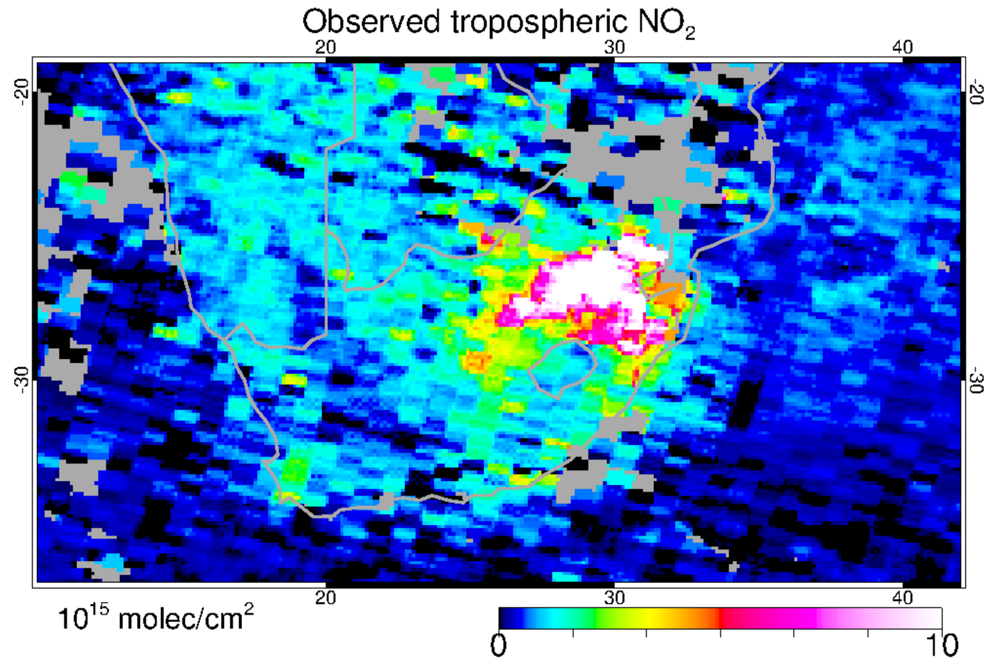



**Colocated simulations**
Based on EDGAR v4.2
No assimilation

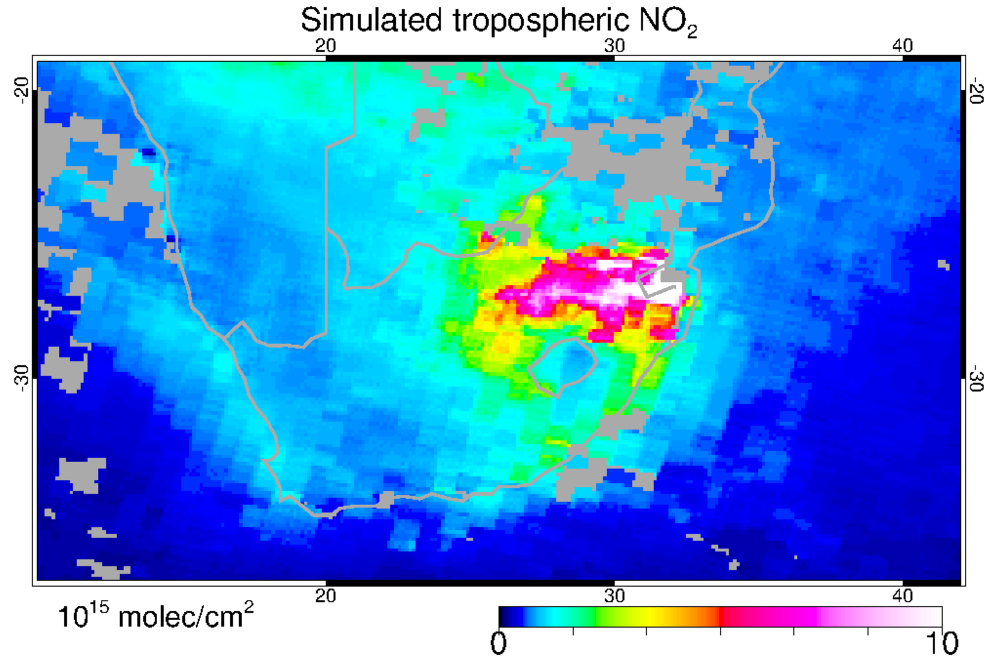


# First results

**GOME-2 observations**
January 2008

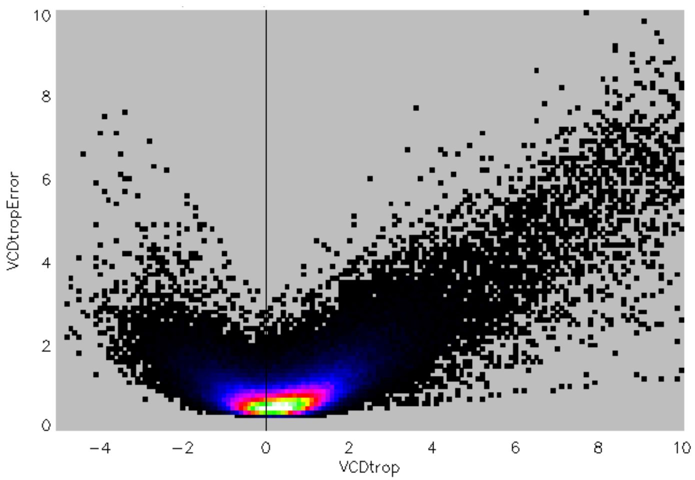



**Colocated simulations**
Assimilated observations

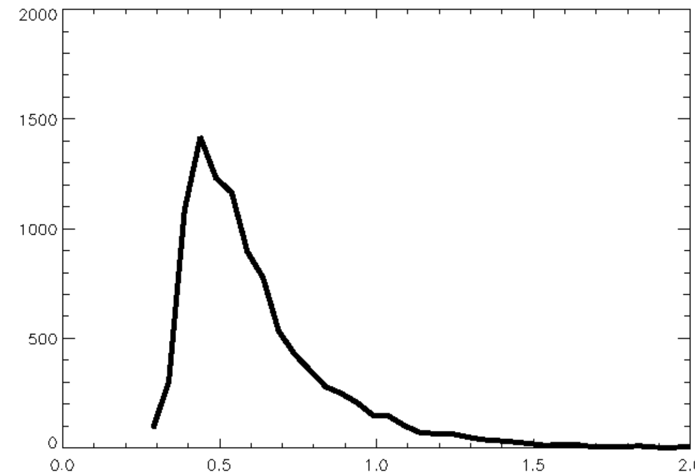


# Observation error (tropospheric $NO_2$)

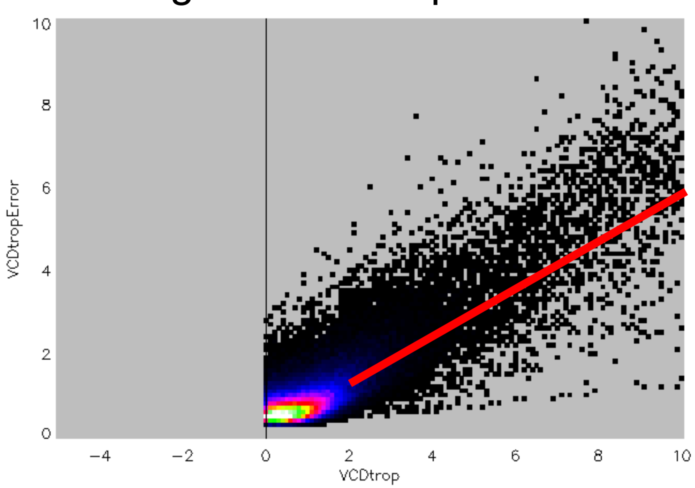
Retrieved column and error



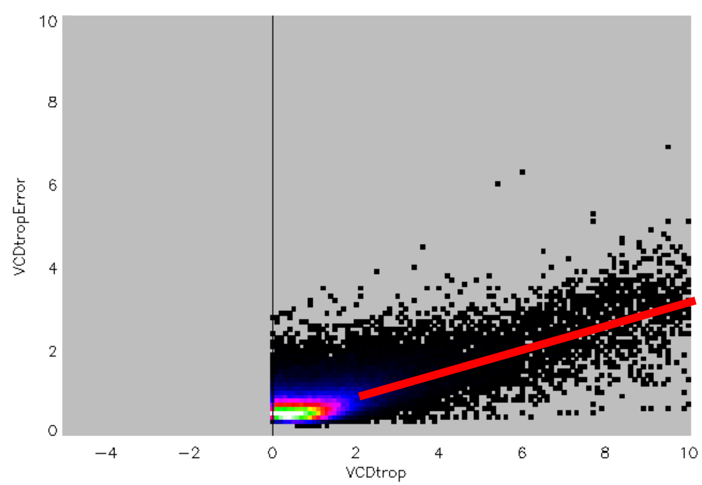

Error distribution around 0




Negative values put to zero

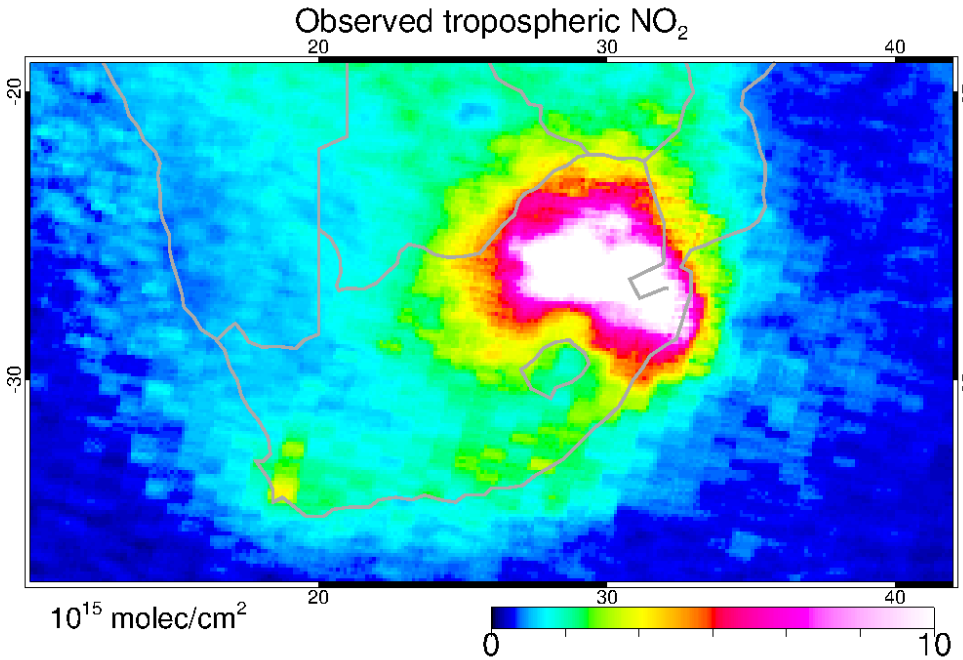



Reduction of relative error



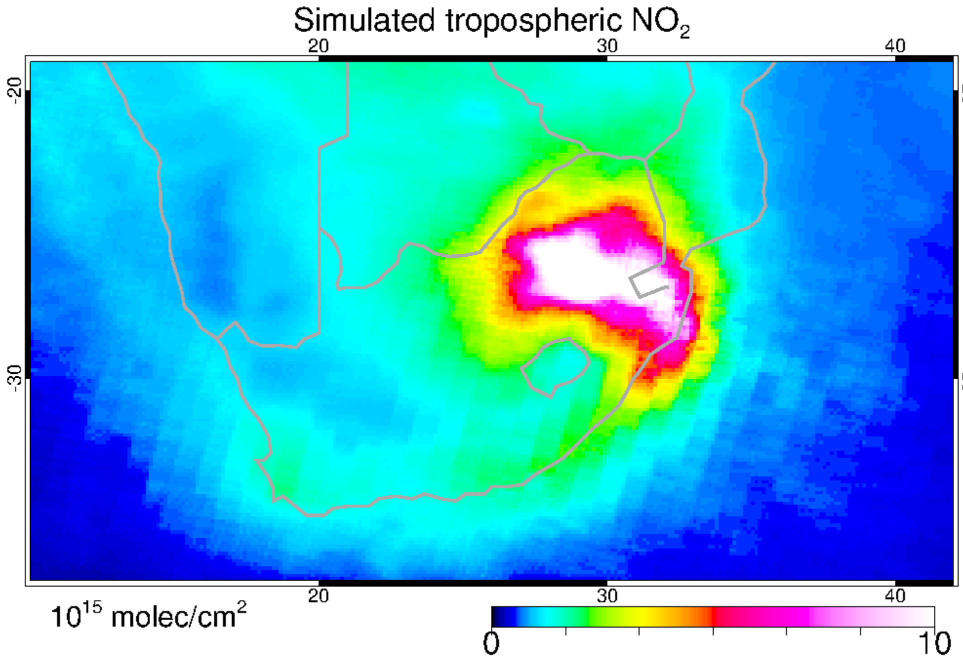
# New results

GOME-2 observations
2010




**Concentration simulation**
Emission injection height according to sector

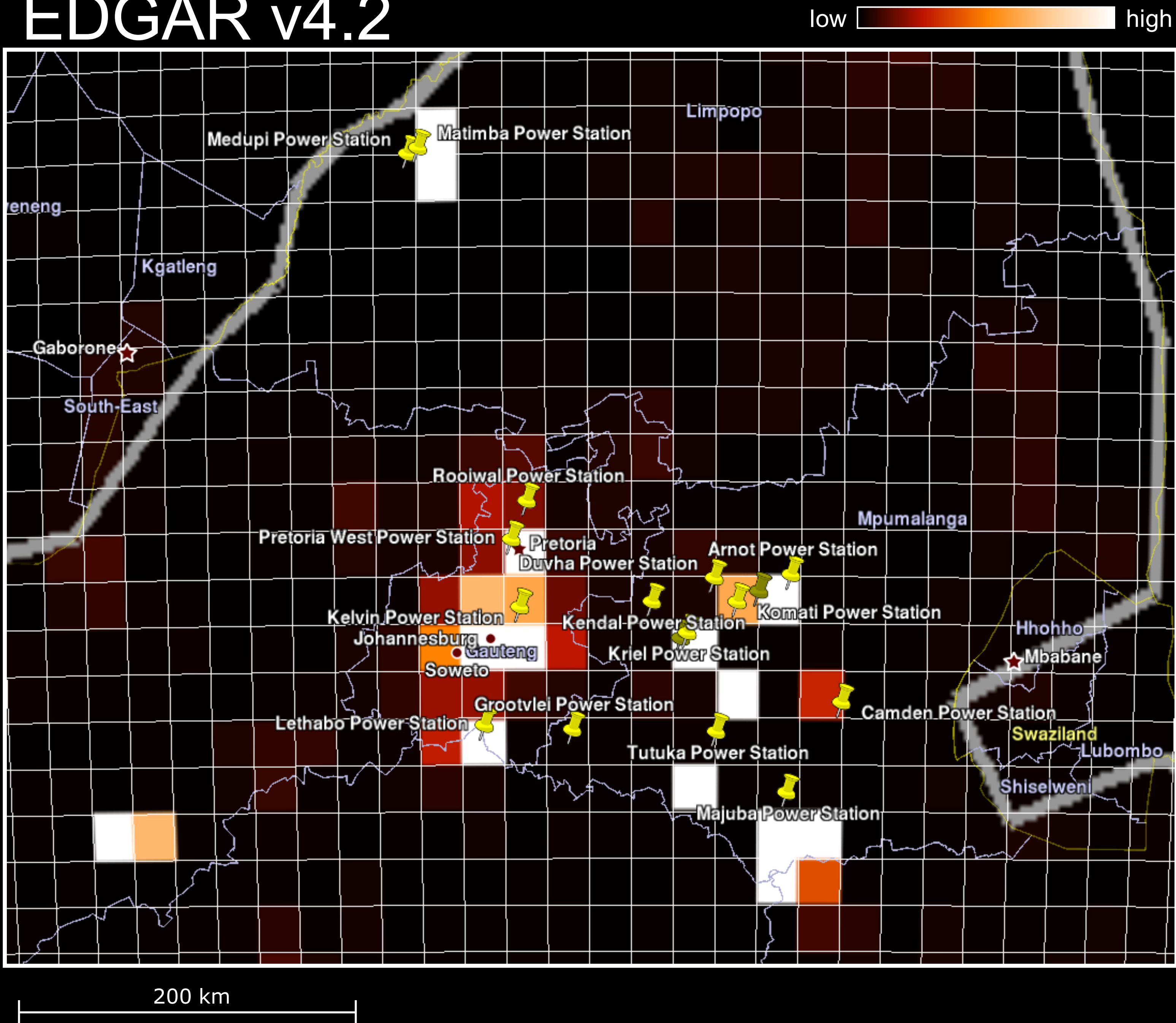
**Source-receptor (sensitivity) calculation**
Backward trajectory calculation




**Emission update**

- Update $NO_x$-correlated pollutants
- Noise and bias reduction over remote areas

# EDGAR v4.2



low
high
Limpopo
Medupi Power Station
Matimba Power Station
eneng
Kgatleng
Gaborone
South-East
Mpumalanga
Rooiwal Power Station
Pretoria West Power Station
Pretoria
Duvha Power Station
Arnot Power Station
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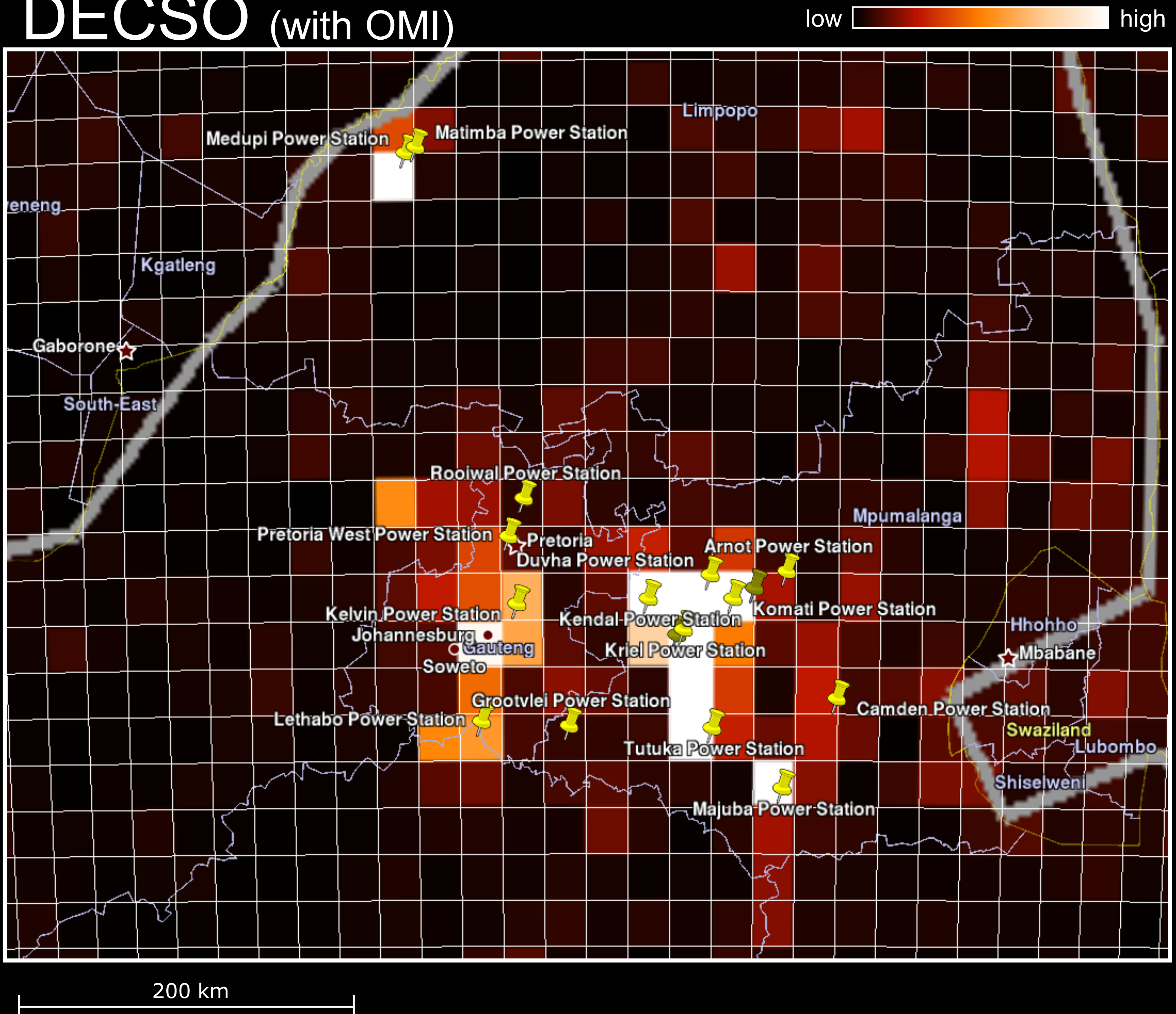
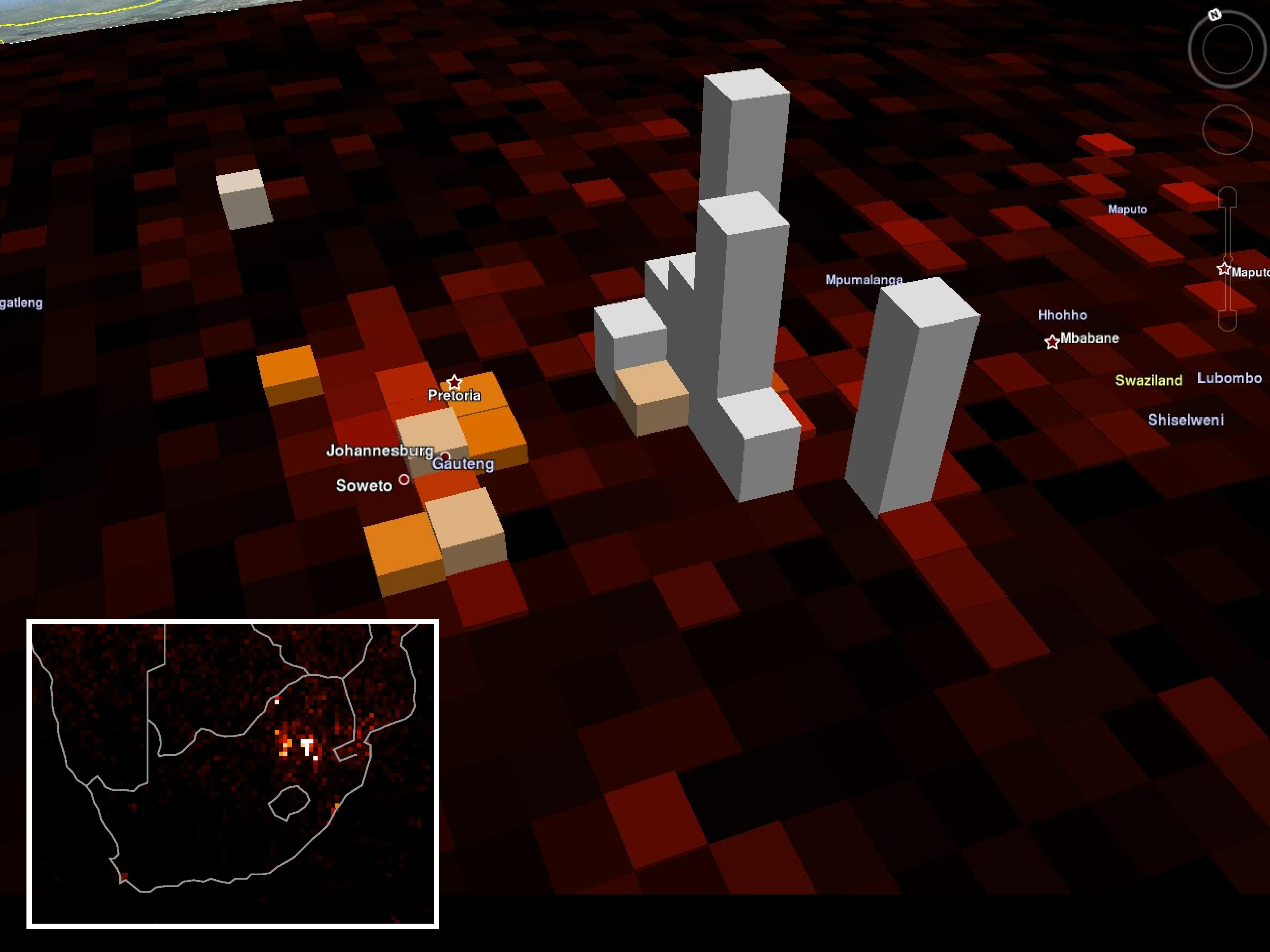
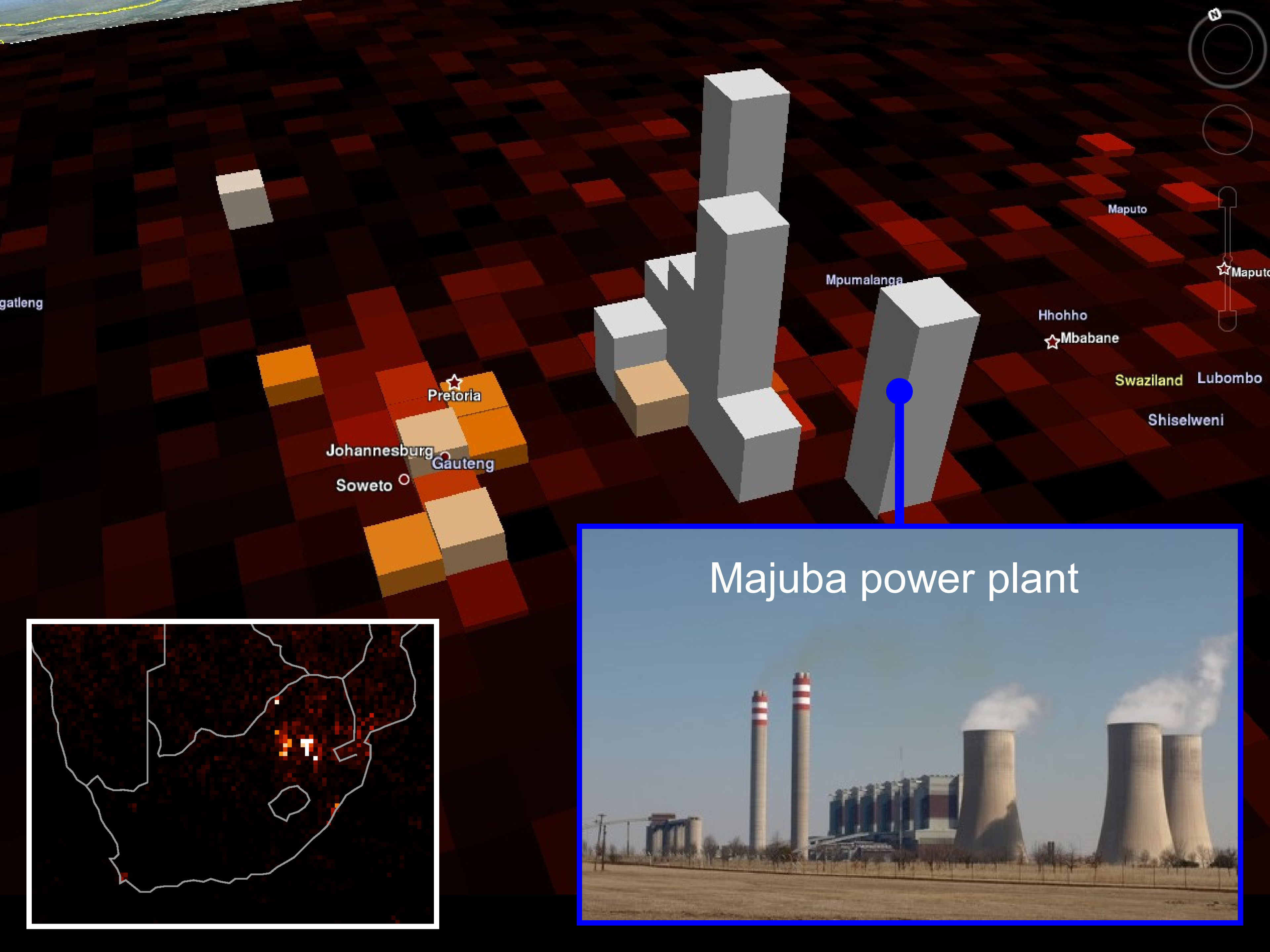
Kelvin Power Station
Kendal Power Station
Johannesburg
Gauteng
Soweto
Kriel Power Station
Hhohho
Mbabane
Grootvlei Power Station
Lethabo Power Station
Camden Power Station
Swaziland
Tutuka Power Station
Lubombo
Shiselweni
Majuba Power Station
200 km

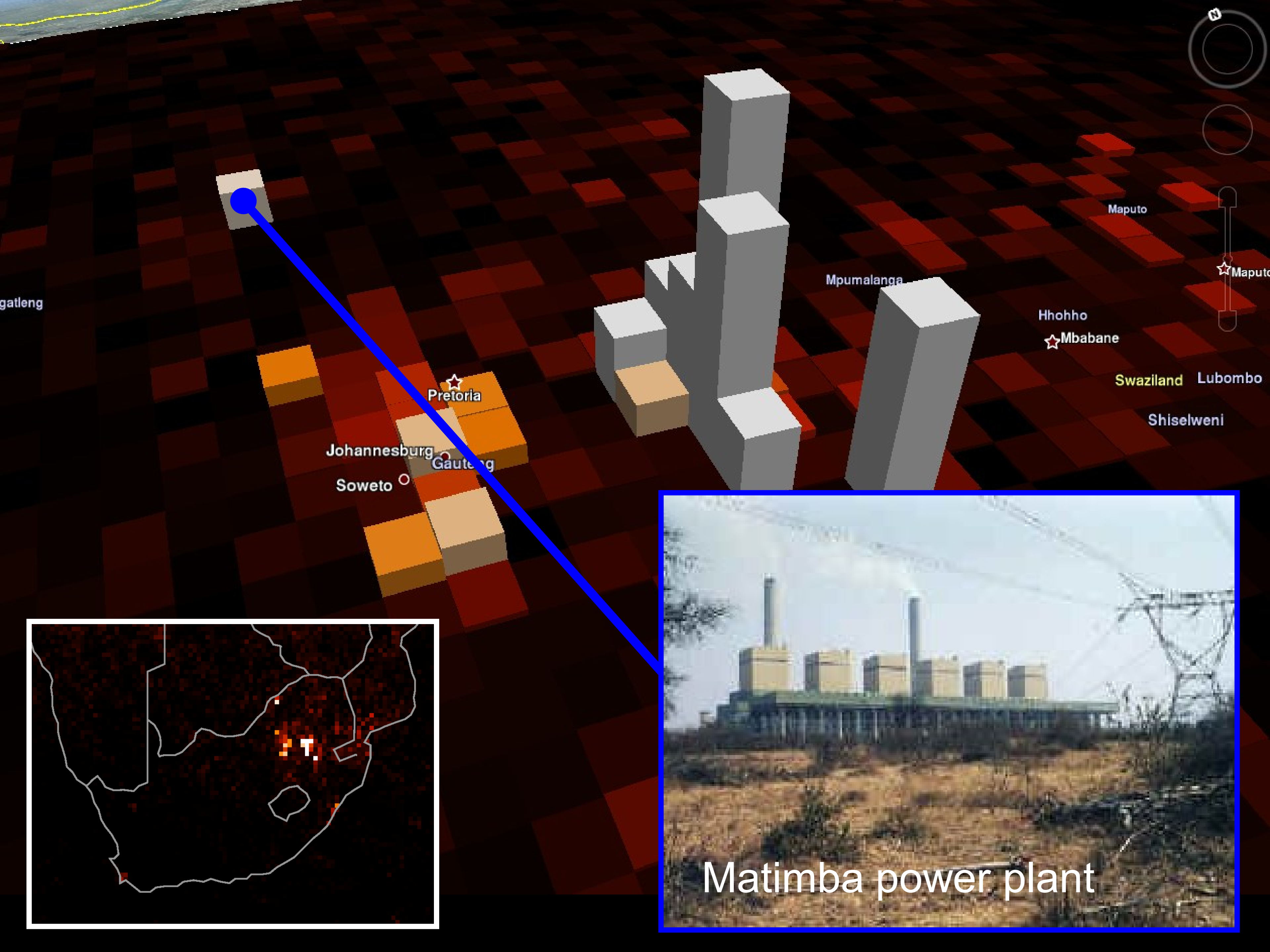
# DECSO (with OMI)

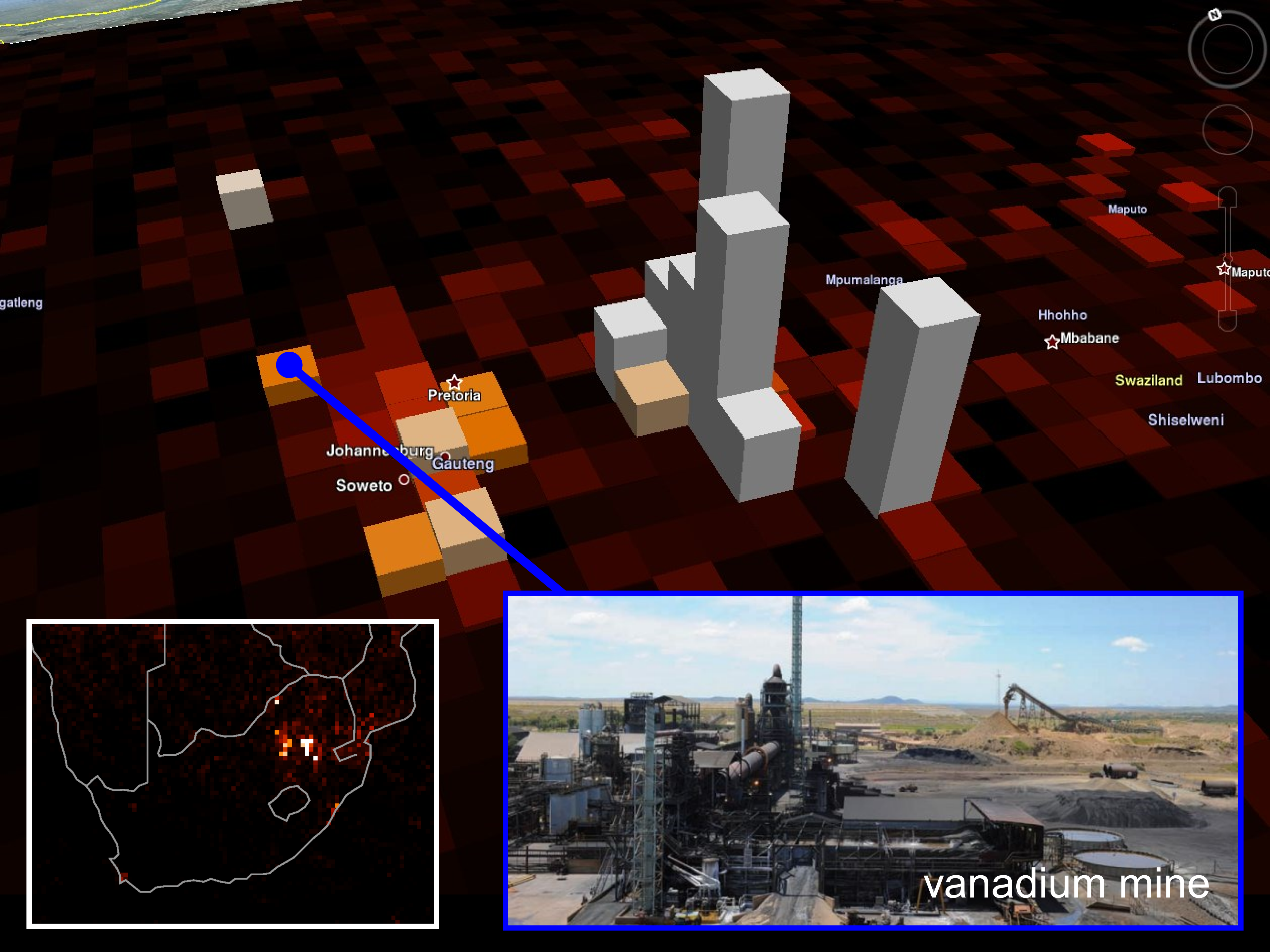


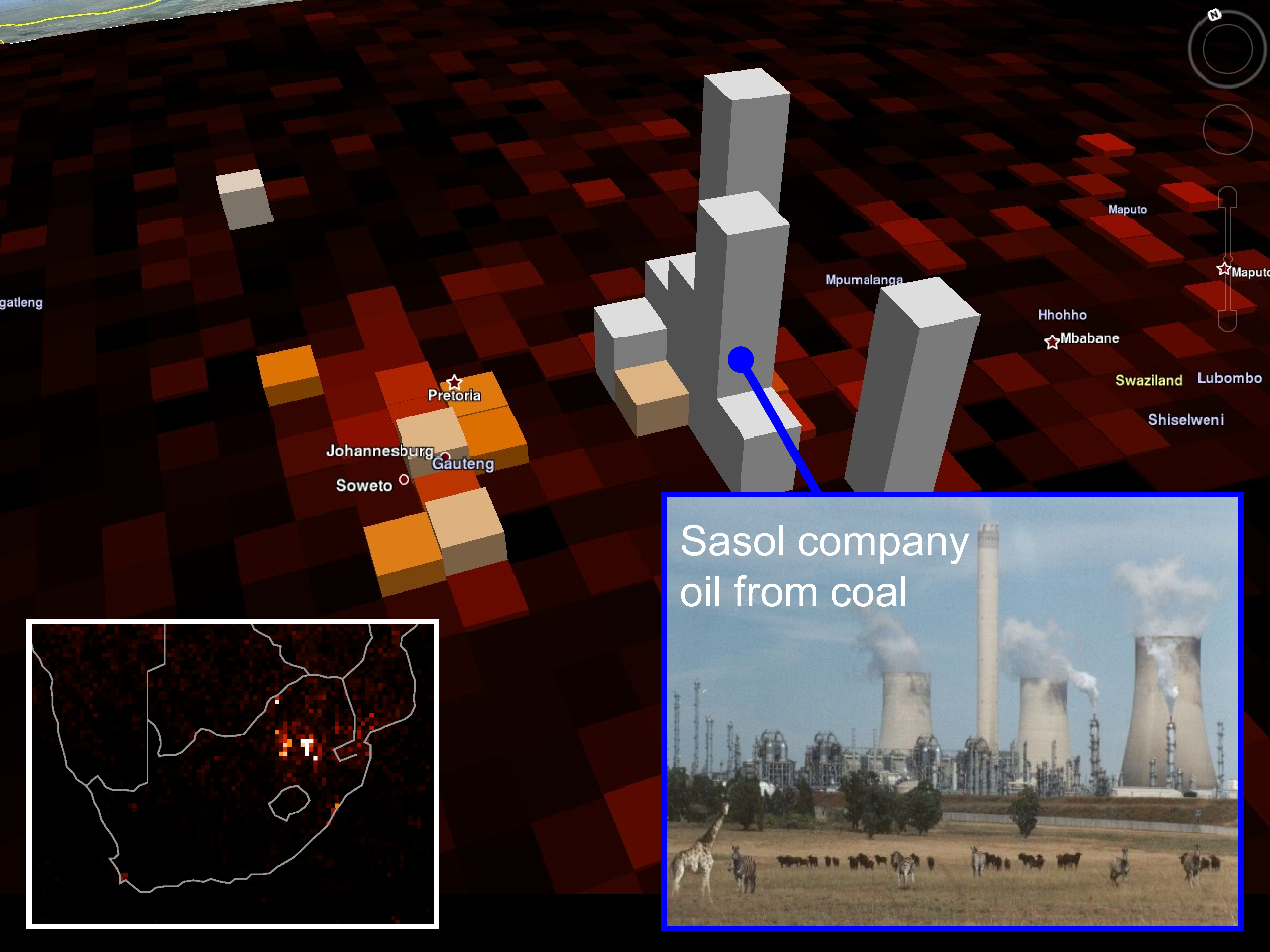


gatleng
Pretoria
Johannesburg
Gauteng
Soweto
Mpumalanga
Maputo
Maputo
Hhohho
Mbabane
Swaziland
Lubombo
Shiselweni

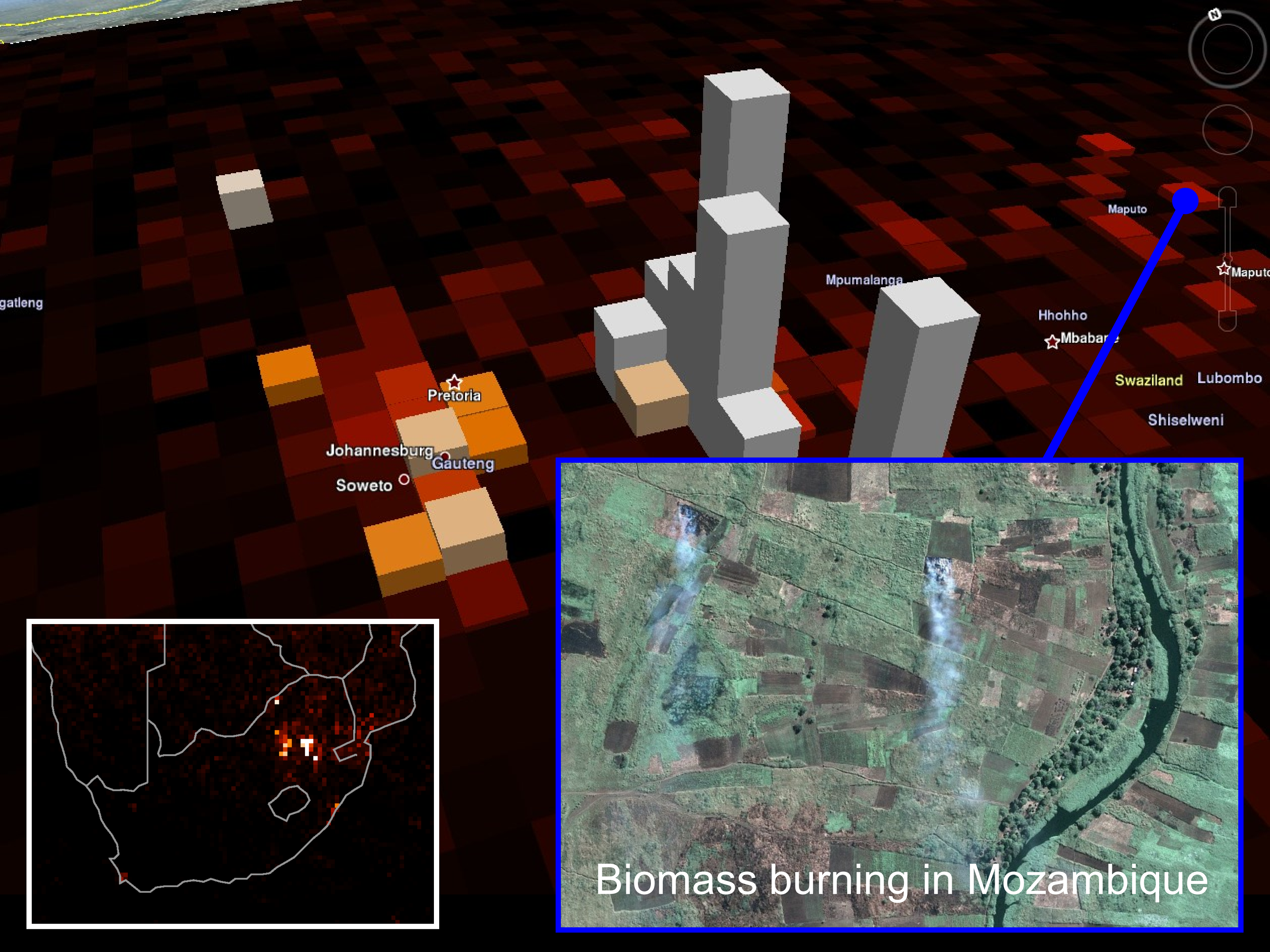

Maputo
Mpumalanga
Hhohho
Mbabane
Swaziland
Lubombo
Shiselweni
Pretoria
Johannesburg
Gauteng
Soweto
Majuba power plant


gatleng
Pretoria
Johannesburg
Gauteng
Soweto
Mpumalanga
Maputo
Maputo
Hhohho
Mbabane
Swaziland
Lubombo
Shiselweni
Matimba power plant


Maputo
Mpumalanga
Hhohho
Mbabane
Swaziland
Lubombo
Shiselweni
Pretoria
Gauteng
Soweto
vanadium mine



Sasol company
oil from coal
Pretoria
Johannesburg
Gauteng
Soweto
Mpumalanga
Maputo
Maputo
Hhohho
Mbabane
Swaziland
Lubombo
Shiselweni
gatleng



gatleng
Pretoria
Johannesburg
Gauteng
Soweto
Mpumalanga
Hhohho
Mbabane
Maputo
Maputo
Swaziland
Lubombo
Shiselweni
Biomass burning in Mozambique

# Algorithm summary

- The presented method is a promising new technique for top-down emission estimates
  from satellite observations.
- The algorithm is fast (<1h), enabling daily assimilation of satellite data.
- The algorithm only needs a forward CTM run; CTM is treated as a black box.

# Results and Outlook (1)

- Successfully applied to China and South Africa.
- Better and up-to-date estimates of location and strength of $NO_x$ emission sources.
- More validation necessary, e.g. with power plant emission data.
- Application to other regions (India, Middle East).
- Application to other species (e.g. $SO_2$).

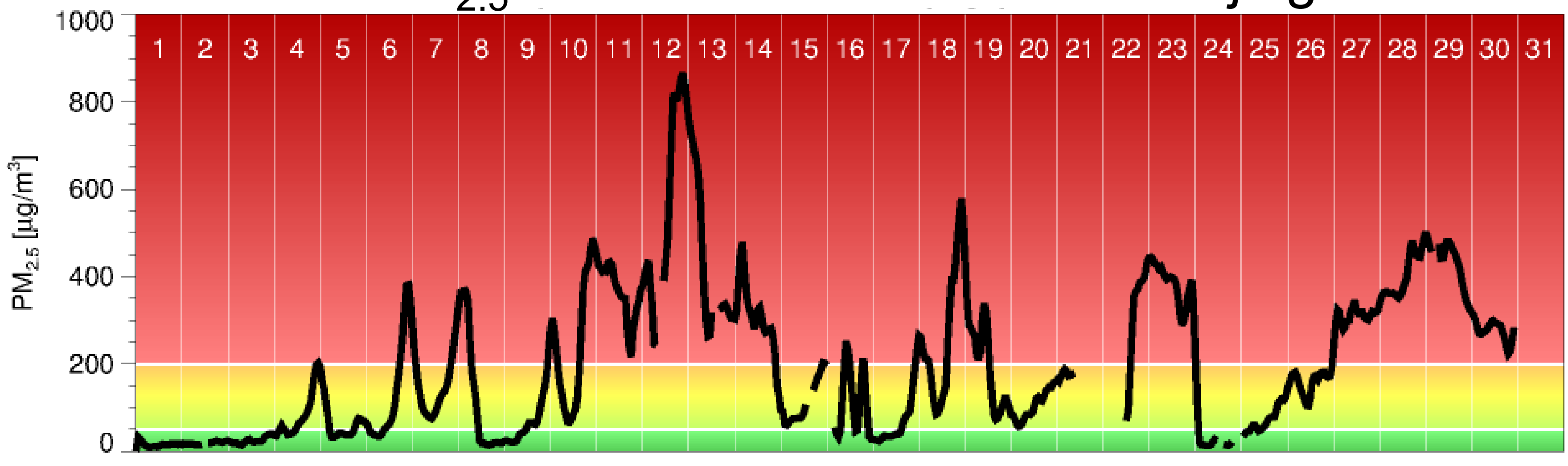
# Outlook (2)

- Improve error estimation.
  (Kalman formalism, autocorrelation of timeseries)
- Influence of satellite resolution on emission resolution.
  (Smaller footprint of TROPOMI will improve results)
- Ingression of combined data sets.
  (e.g. GOME-2 **and** OMI)

# Air pollution in Beijing January 2013

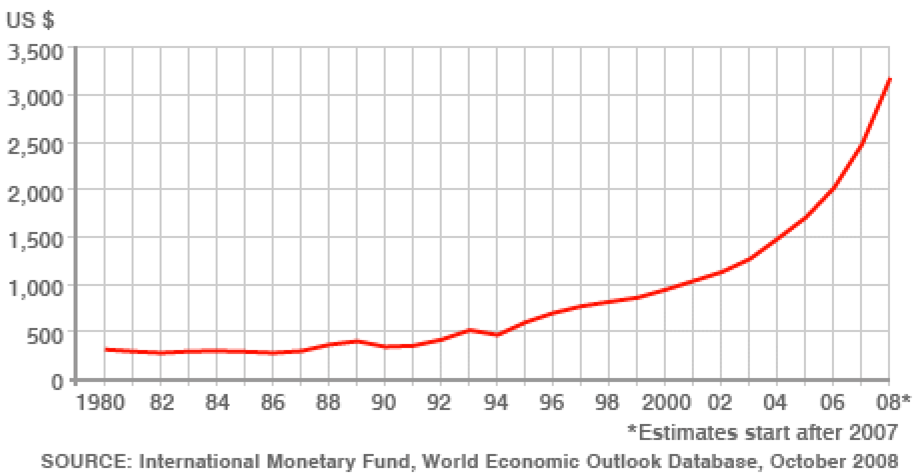


$PM_{2.5}$ surface concentration in Beijing

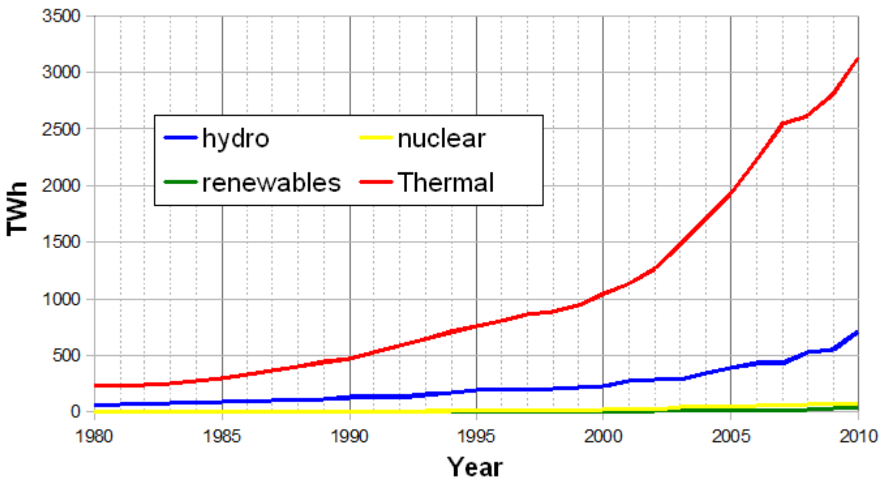


# China: Economic indicators

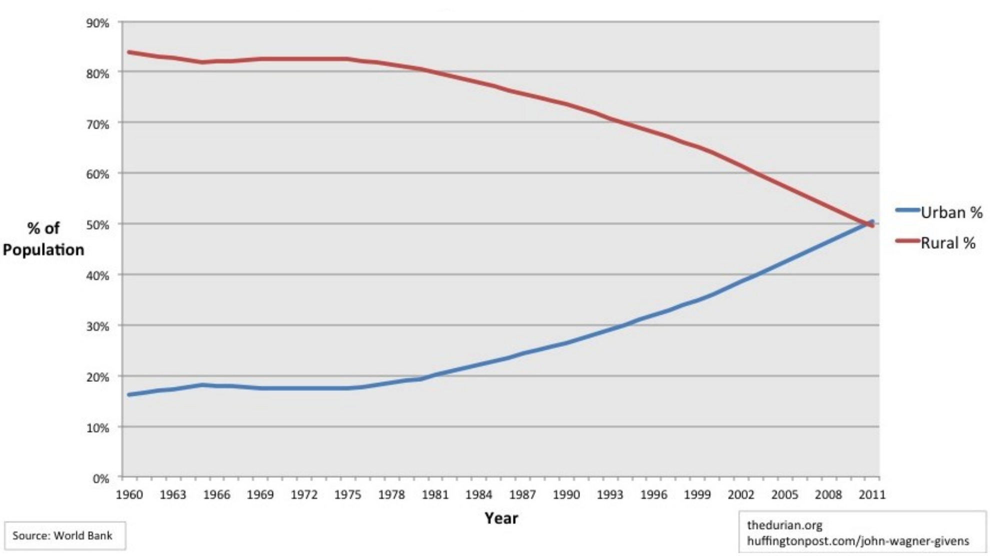
Average annual income per capita, 1980-2008



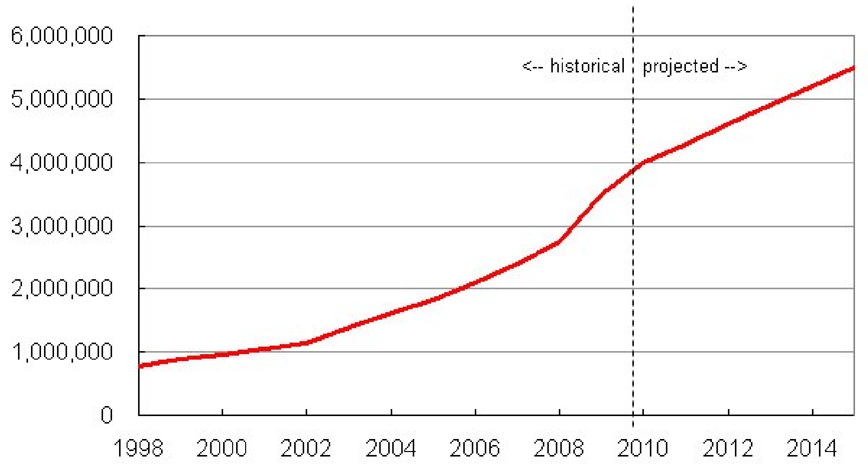

China's electricity production, 1980-2010




China's urbanization, 1980-2011

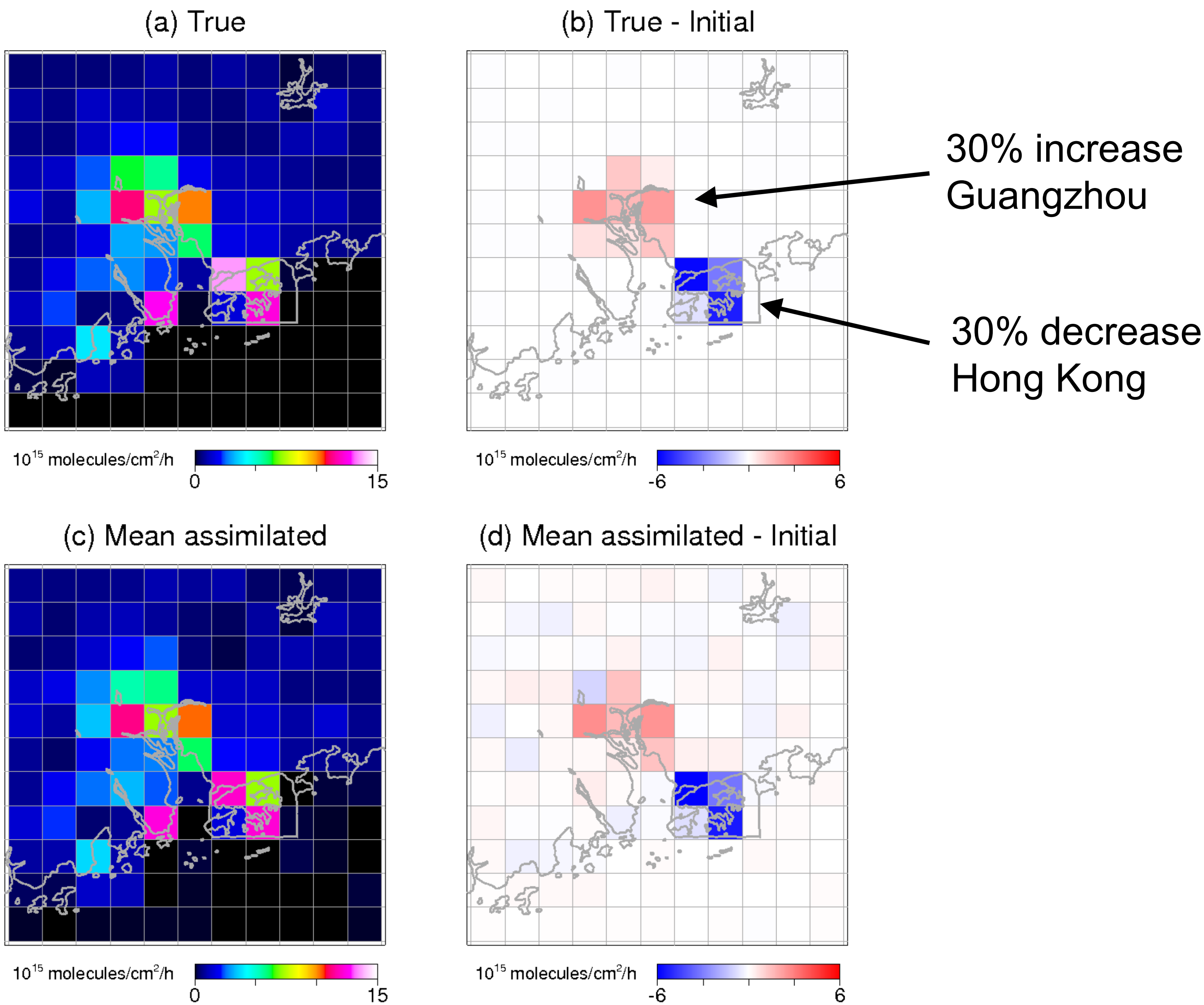



Number of vehicles in Beijing, 1998-2015




Source: China Statistical Yearbook, China Daily (17/2/09)

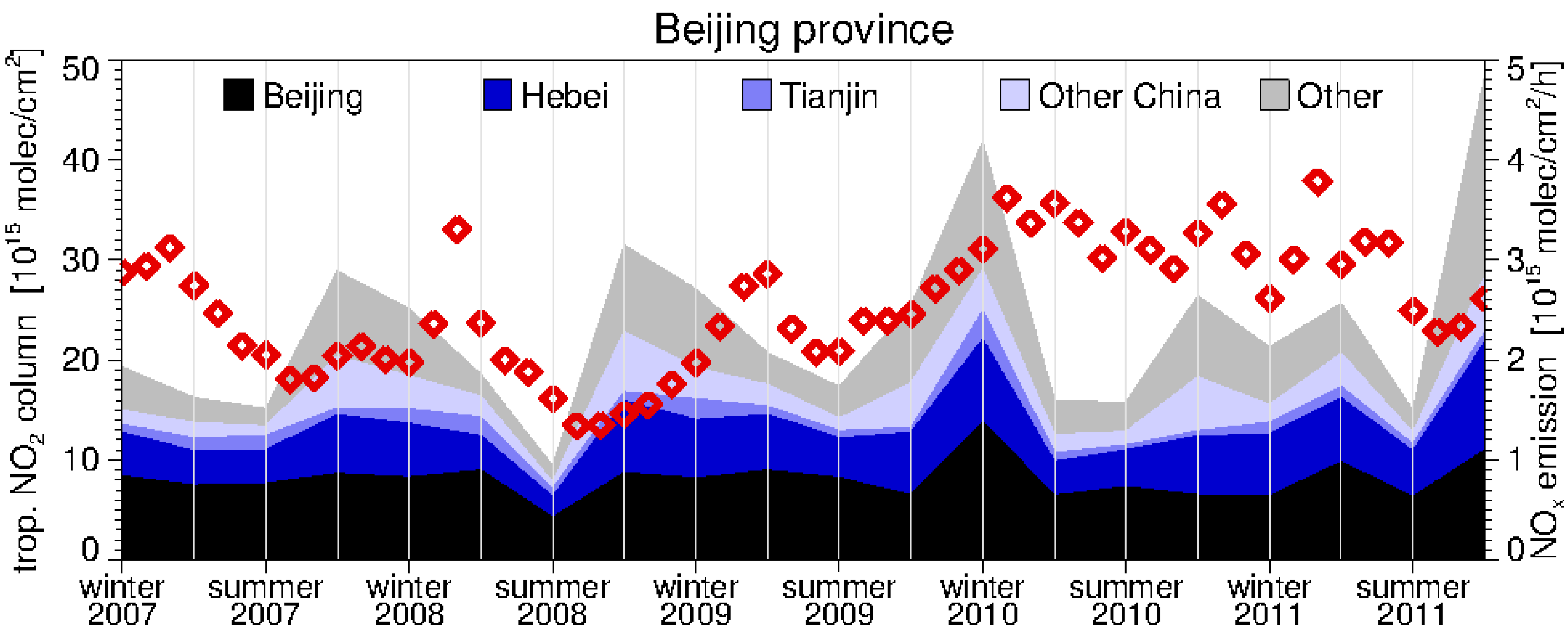
# Closed loop test: Pearl River Delta region



## Comparison of yearly $NO_x$ emission totals for East China

in Tg N/yr

| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **DECSO** | – | 5.63 | 5.91 | 6.06 | 7.09 | 7.96 |
| **EDGAR v4.2** | 5.03 | 5.34 | 5.93 | – | – | – |
| **INTEX-B** | 6.09 | – | – | – | – | – |
| **MEIC** | – | – | 7.54 | – | 8.28 | – |
| **REAS v1.1** | 4.44 | 4.55 | 4.65 | 4.76 | 4.86 | – |



Beijing province
Beijing
Hebei
Tianjin
Other China
Other
trop. NO2 column [10^15 molec/cm^2]
NOx emission [10^15 molec/cm^2/h]
0
10
20
30
40
50
0
1
2
3
4
5
winter 2007
summer 2007
winter 2008
summer 2008
winter 2009
summer 2009
winter 2010
summer 2010
winter 2011
summer 2011