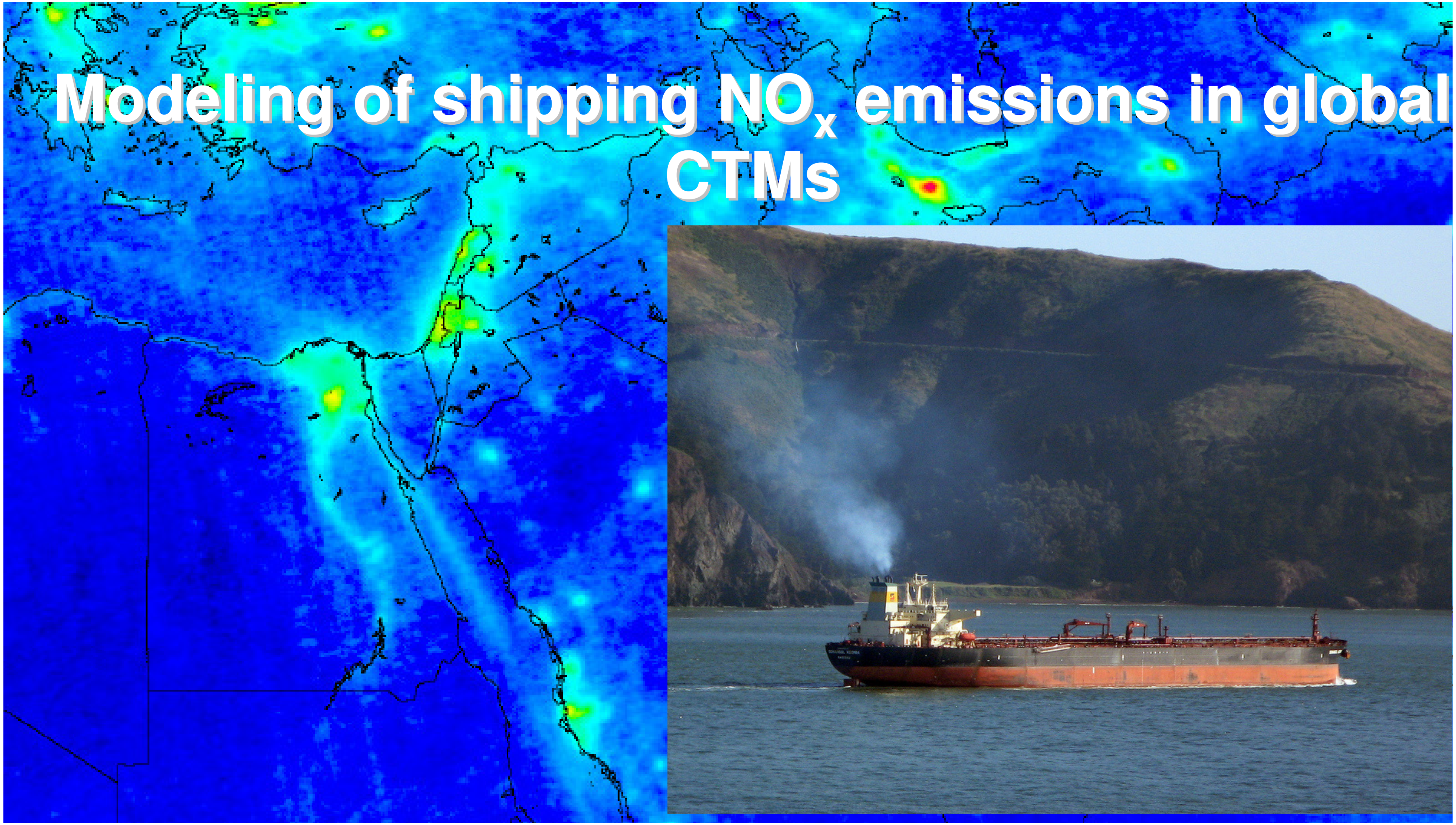
Modeling of shipping NO_x emissions in global CTMs

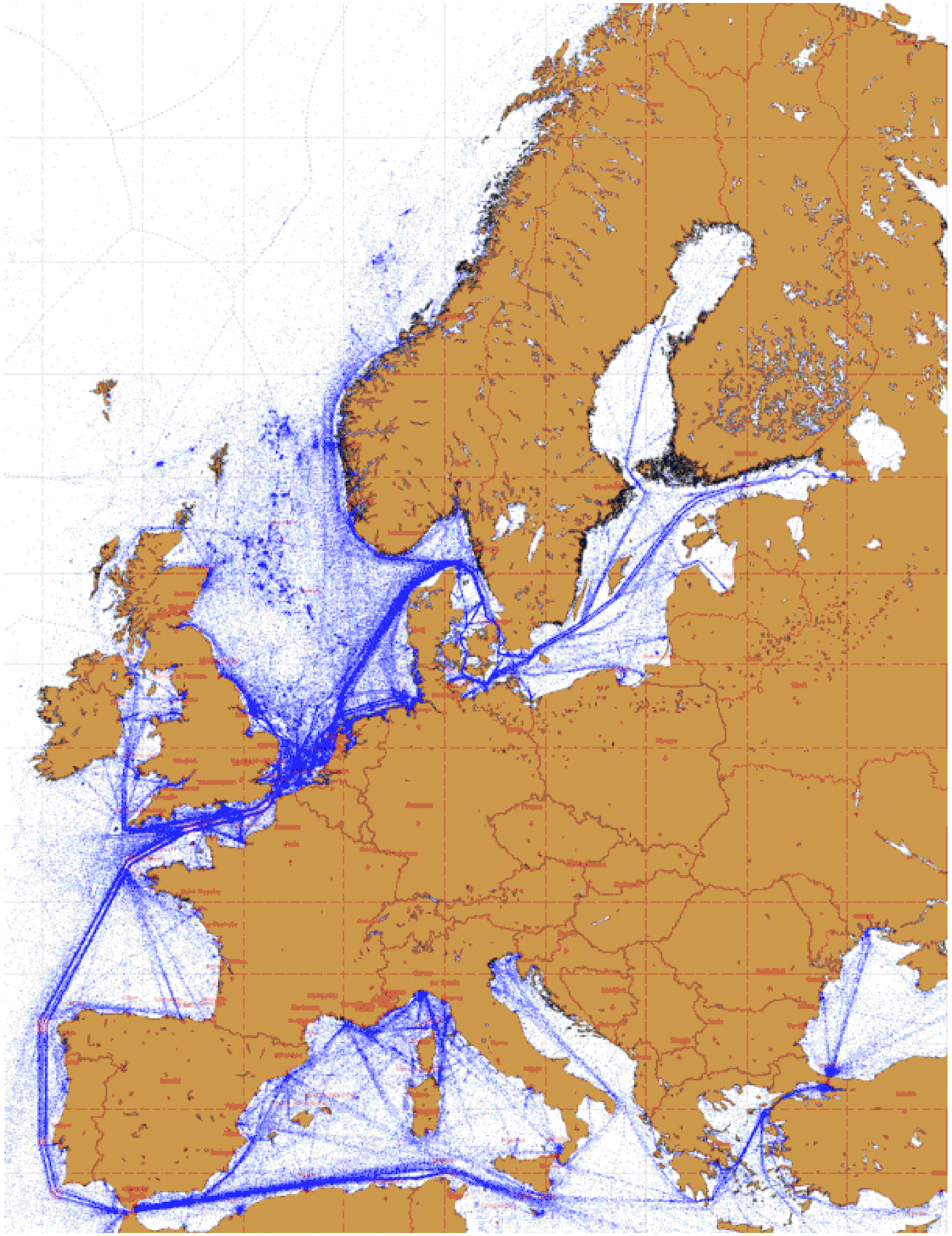


Geert Vinken[1], Folkert Boersma[2], and Daniel J. Jacob[3]

1. Eindhoven University of Technology,
2. KNMI
3. Harvard University

KNMI

ESA map reveals European shipping routes

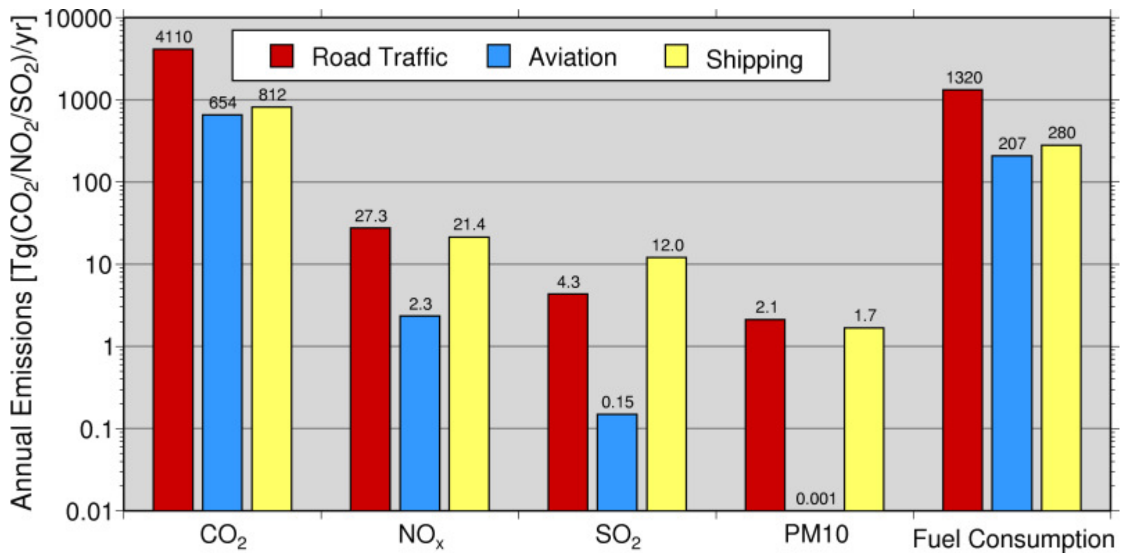


The shipping route map derived from analysis of the Advanced Synthetic Aperture Radar (ASAR) instrument on ESA's Envisat (2002-2009). The NO_2 map shows yearly average tropospheric nitrogen dioxide measurements for 2008 as performed by the Ozone Monitoring Instrument (OMI) on the NASA EOS-Aura satellite. OMI represents the Dutch contribution to the mission.

Source: ESA News, 22 May 2009

OMI NO_2 data: K. F. Boersma & R. J. van der A

Motivation



15 of the world's biggest ships may now emit as much pollution as all the world's 760 million cars [*Guardian*, April 2009]

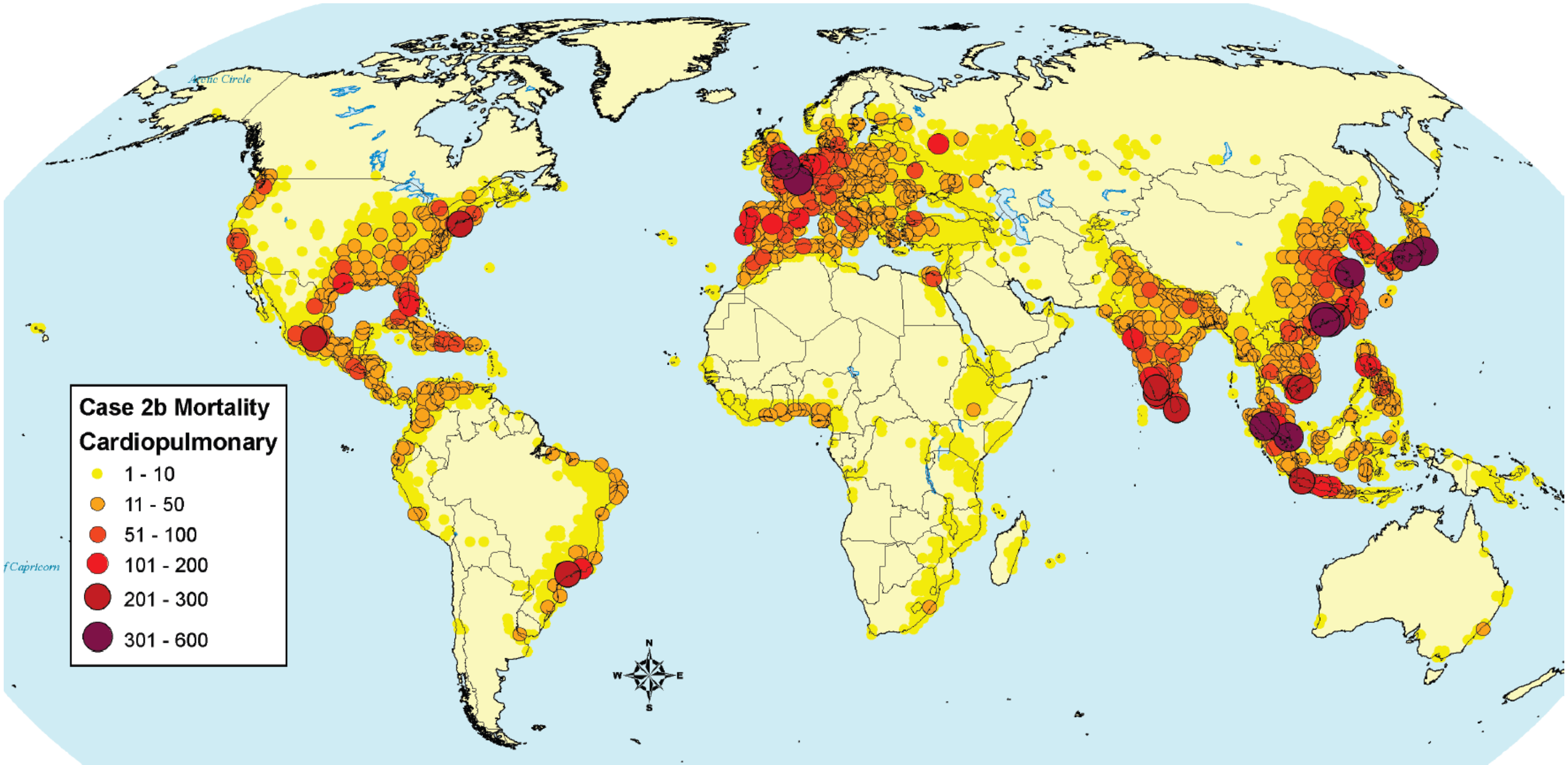
15-30% of global nitrogen oxide (NOx) emissions
5-7% of global sulfur dioxide (SO2) emissions
3-4% of global carbon dioxide (CO2) emissions

Ship fuel has up to 2,000 times the sulphur content of diesel fuel used in US and European automobiles

About 70% of the ship emissions occur within 400 km of land

Only industrial sector not regulated under the Kyoto Protocol.

Cardiopulmonary mortality attributable to ship PM2.5 emissions worldwide



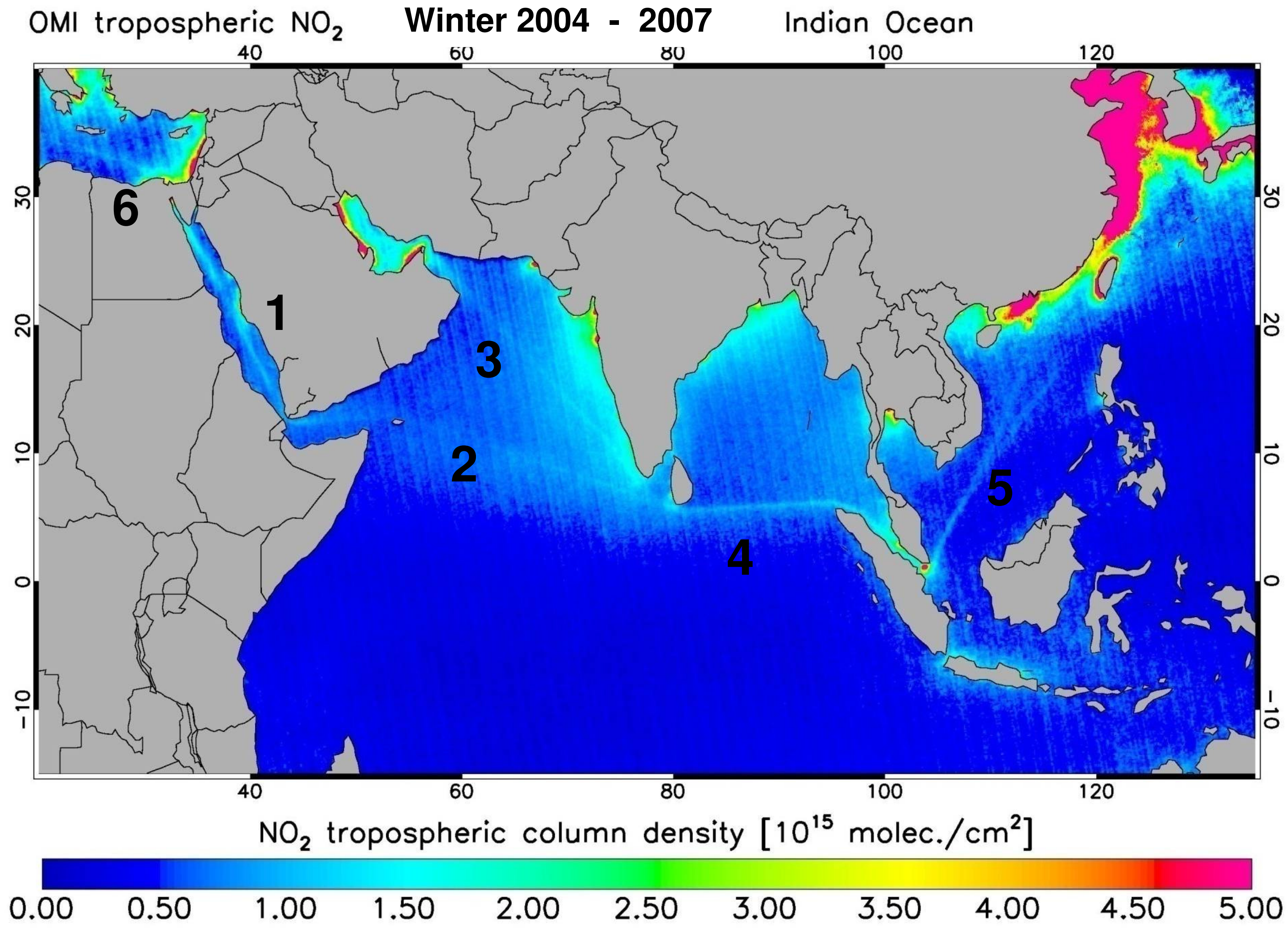
Pollution from the world's 90,000 cargo ships leads to 60,000 deaths a year

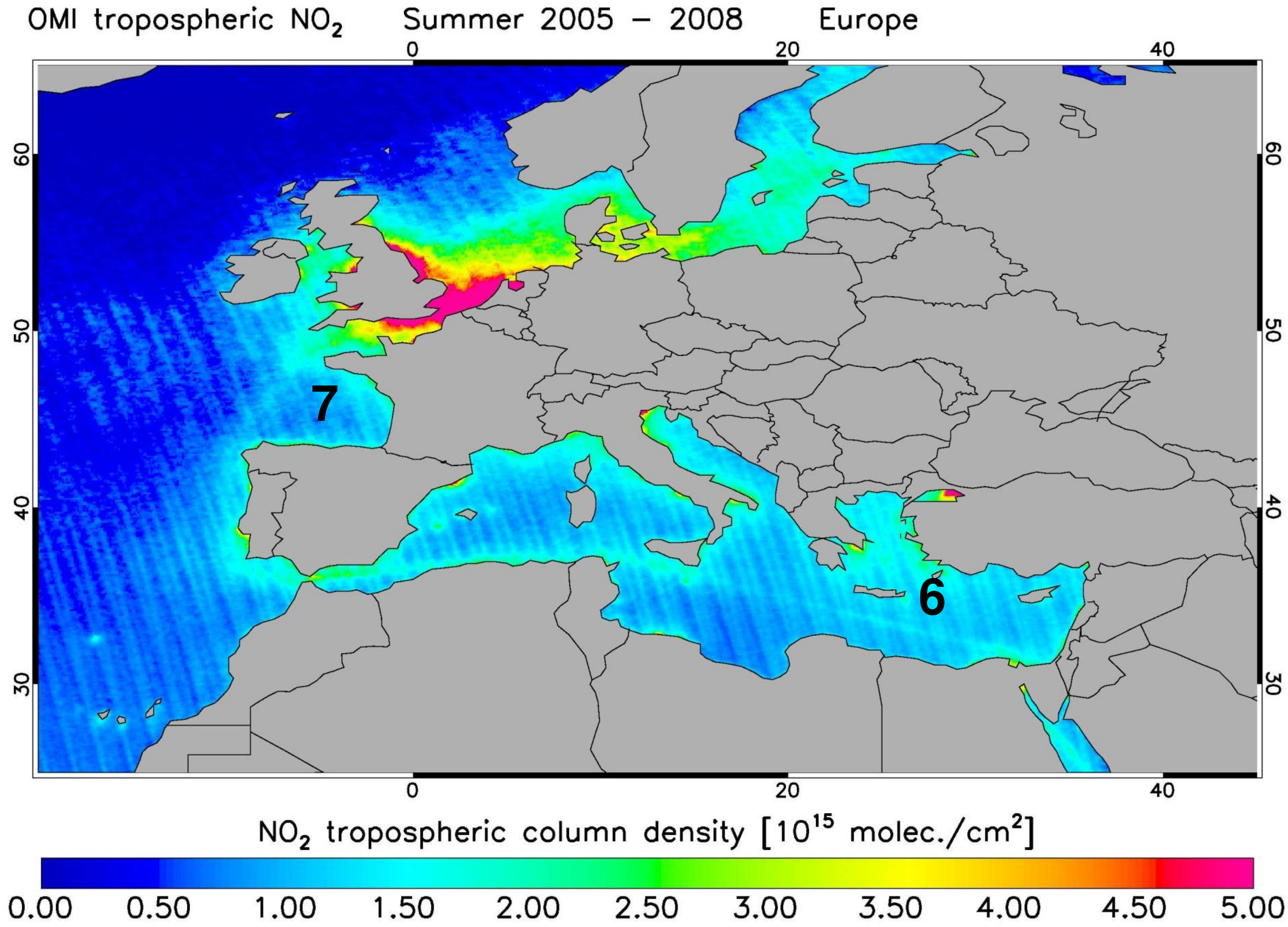
Source: Corbett et al (2007)

Ship emission inventories

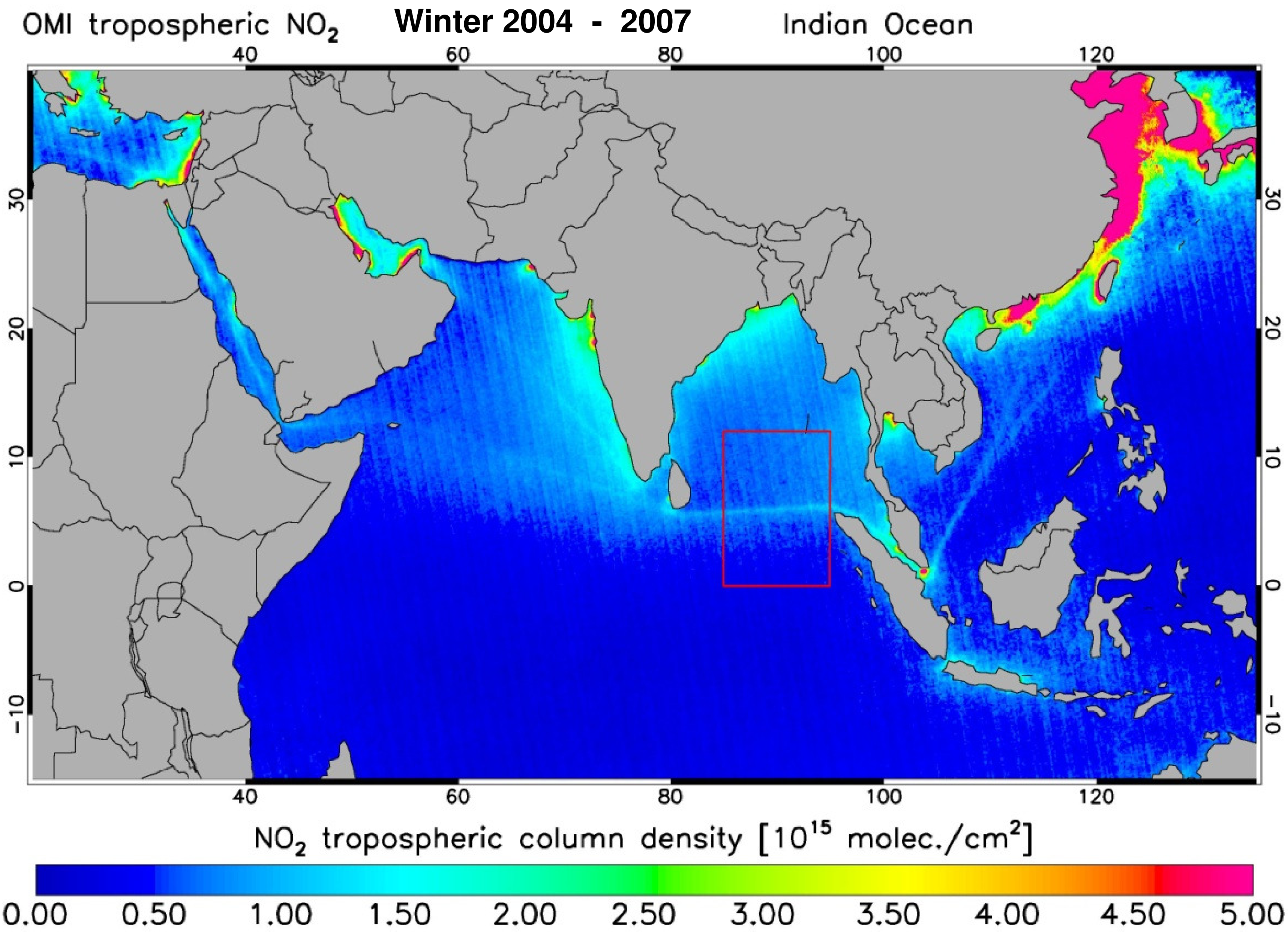
Source	Fuel Consumption (million tonnes)	NOx emissions (Tg N)
Eyring et al. [2005]	**280**	**6.51**
Corbett et al. [2003]	**289**	**4.72**
Endresen et al. [2003]	**165-200**	**3.23**
IMO study [Skjølsvik et al, 2000]	**120-147**	**3.06**
Corbett et al. [1999]	**140-147**	**3.08**

- Lots of estimations -> high uncertainty
- Improve using satellite information


OMI tropospheric NO2
Winter 2004 - 2007
Indian Ocean
40
60
80
100
120
30
20
10
0
−10
1
2
3
4
5
6
NO2 tropospheric column density [10^15 molec./cm^2]
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00



OMI tropospheric NO_2 Summer 2005 – 2008 Europe
0
20
40
60
50
40
30
7
6
NO_2 tropospheric column density [10^{15} molec./cm^2]
0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00



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Winter 2004 - 2007
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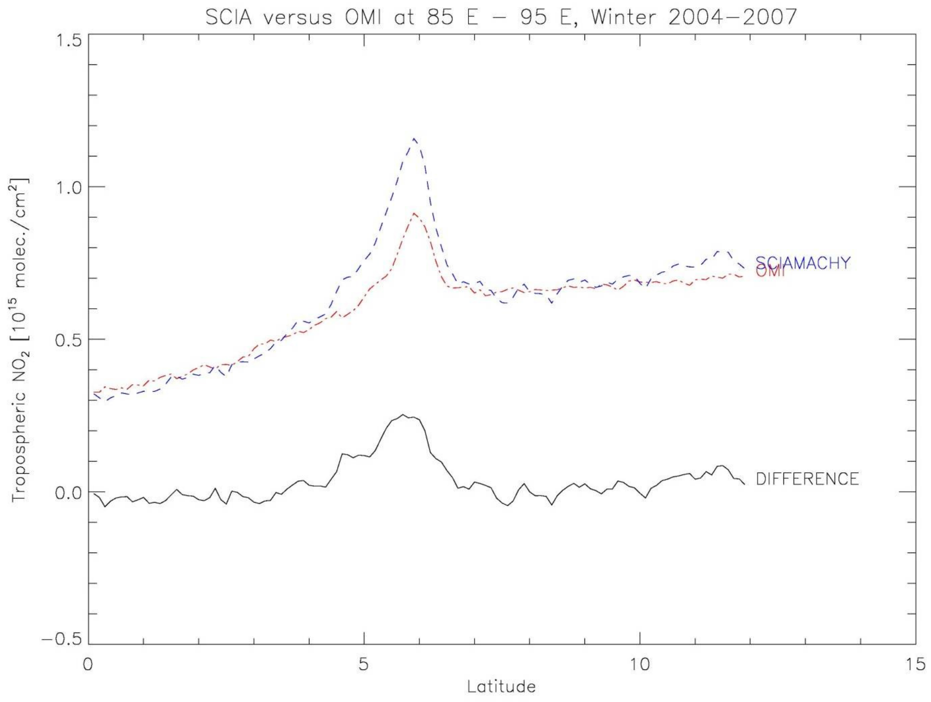
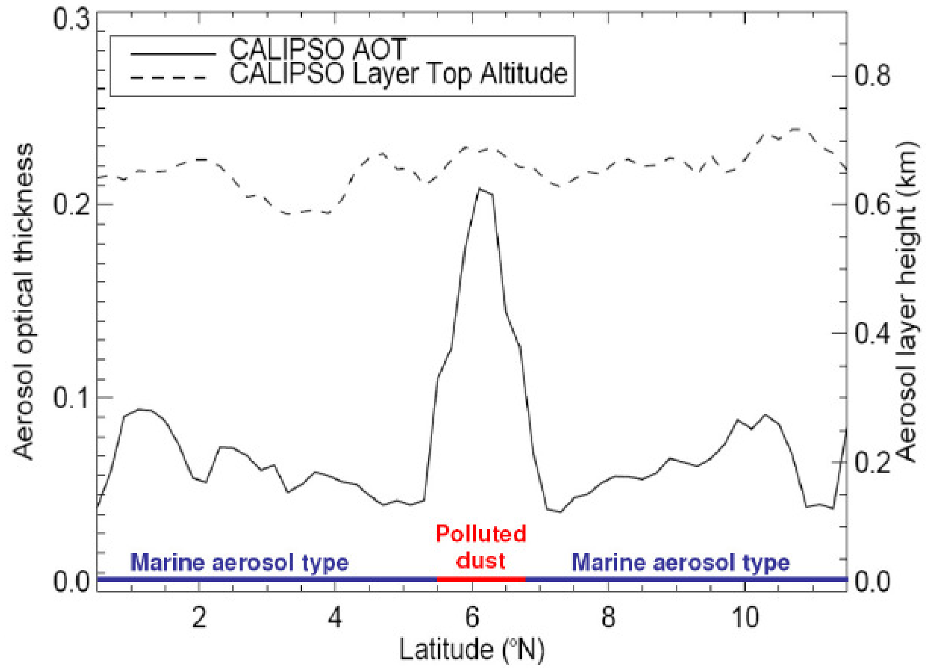




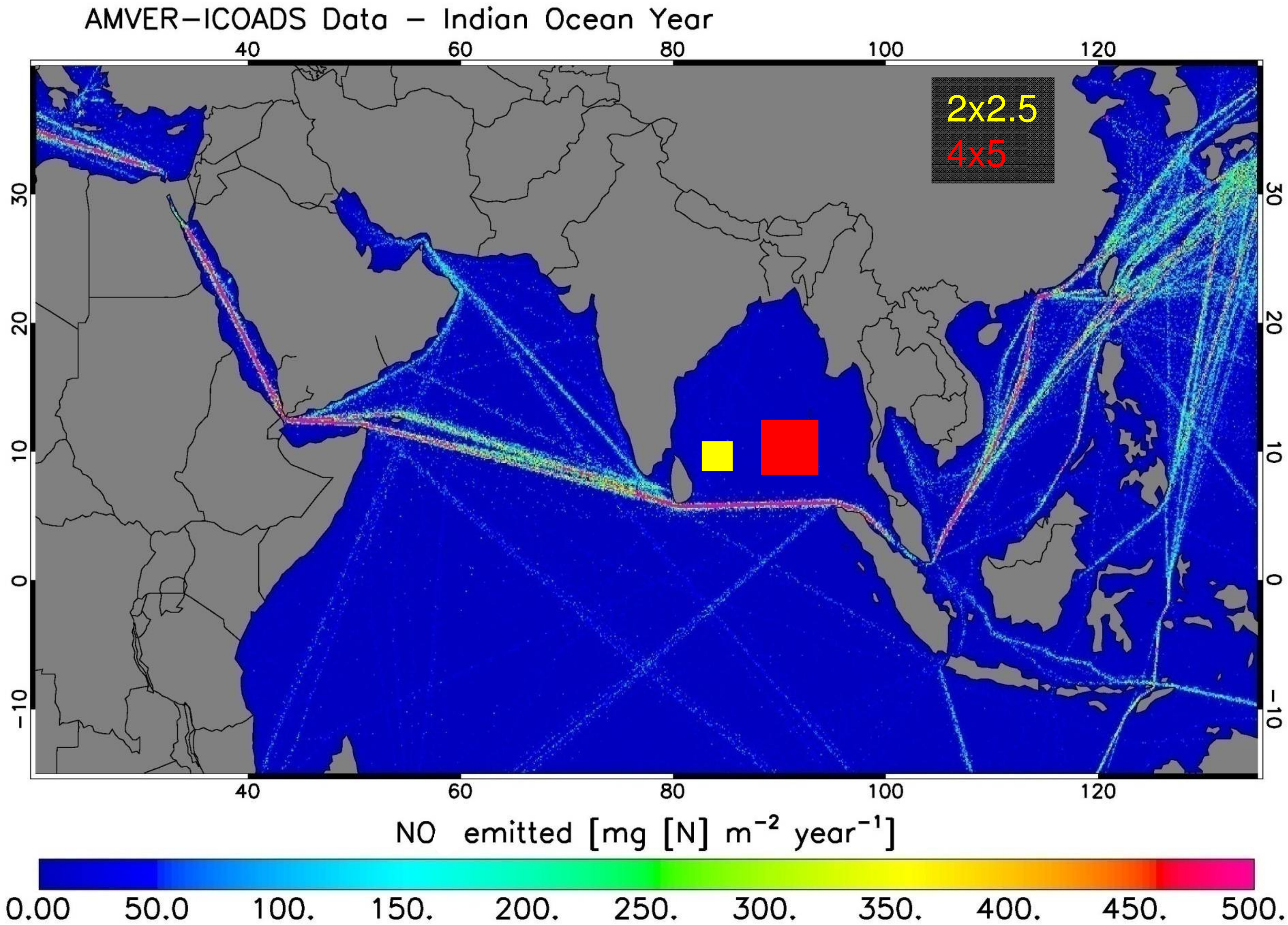
Information on diurnal cycle in SCIAMACHY and OMI observations

Information on aerosol characteristics and vertical distribution from CALIPSO

How satellite observations can help…

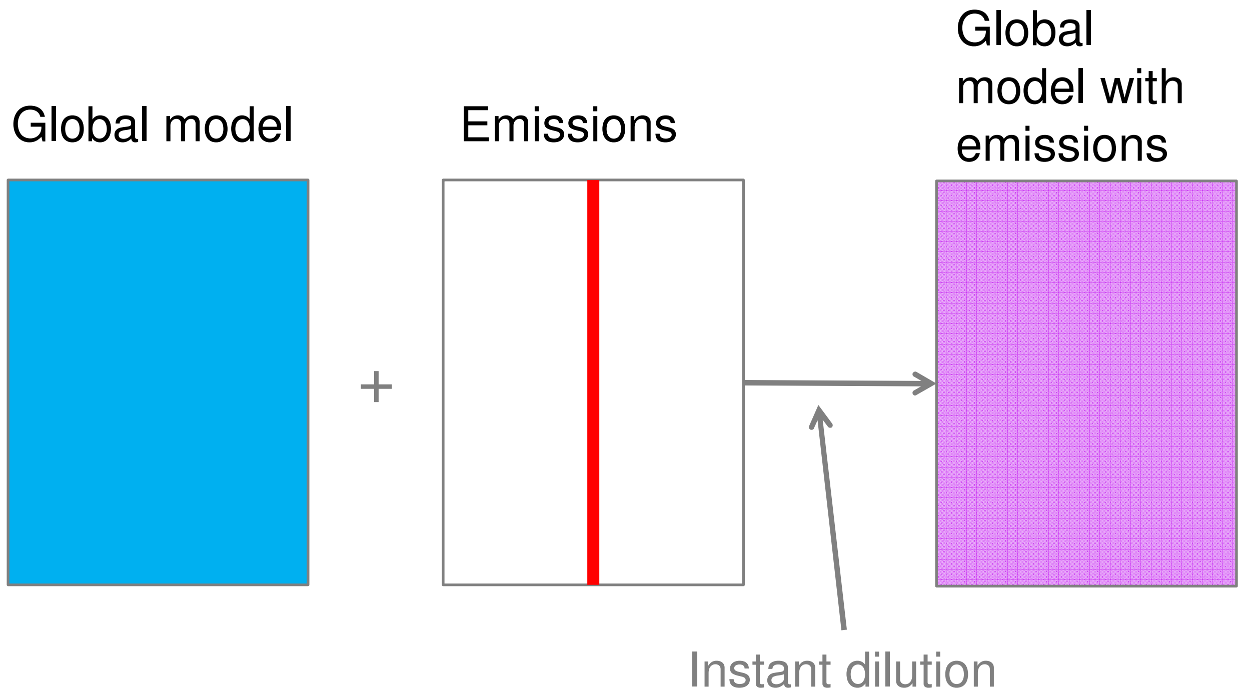
- Simulate NO_2 columns with chemistry transport model (TM5/GEOS-Chem) and use the satellite observations to constrain the emissions
- Problem in models:

  Localized emissions in global models are spread out, neglecting sub-grid processes..



AMVER−ICOADS Data − Indian Ocean Year
40
60
80
100
120
30
20
10
0
−10
2x2.5
4x5
NO emitted [mg [N] m^{-2} year^{-1}]
0.00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.

Ship emissions in global models



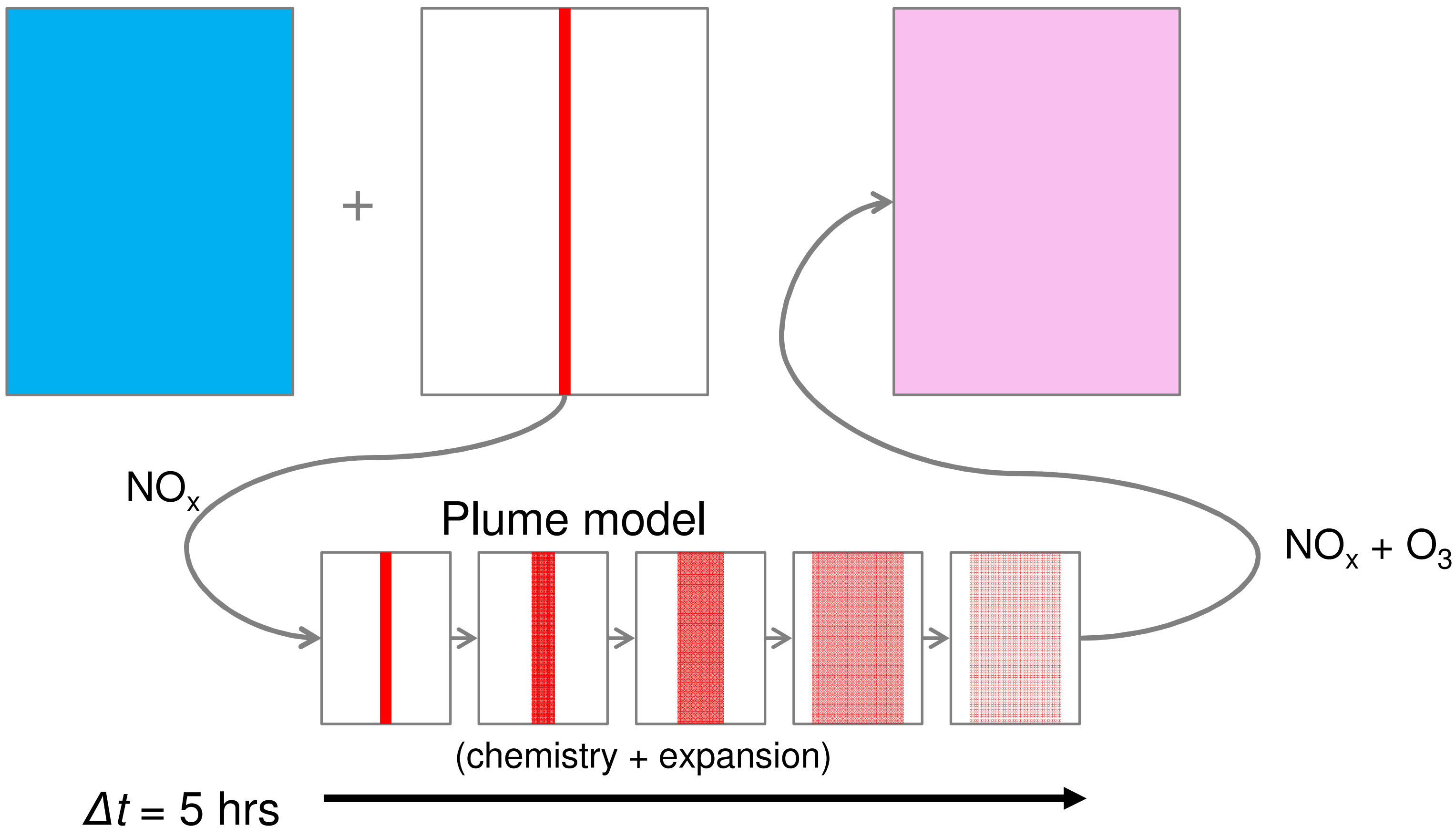
Lifetime of NO_x emitted from ships is overestimated
→ too much NO_y, ozone, …

Ship emissions in global models

- TM5: instant dilution
- GEOS-Chem: ship NO_x emissions emitted as HNO_3 and $10*O_3$, assuming constant OPE 10
- Is better than instant dilution, but neglect the effect of ambient O_3 concentration, temperature, time of day, and no shipping NO_x in model!

Implementation

- Pre-processing ship emissions to improve the modeling of ship emissions in Global Models



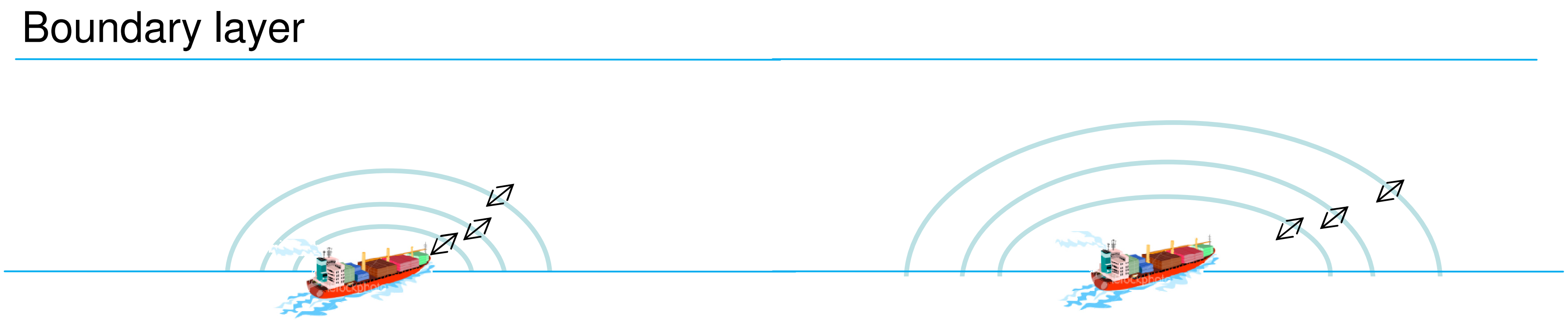
PARANOX model

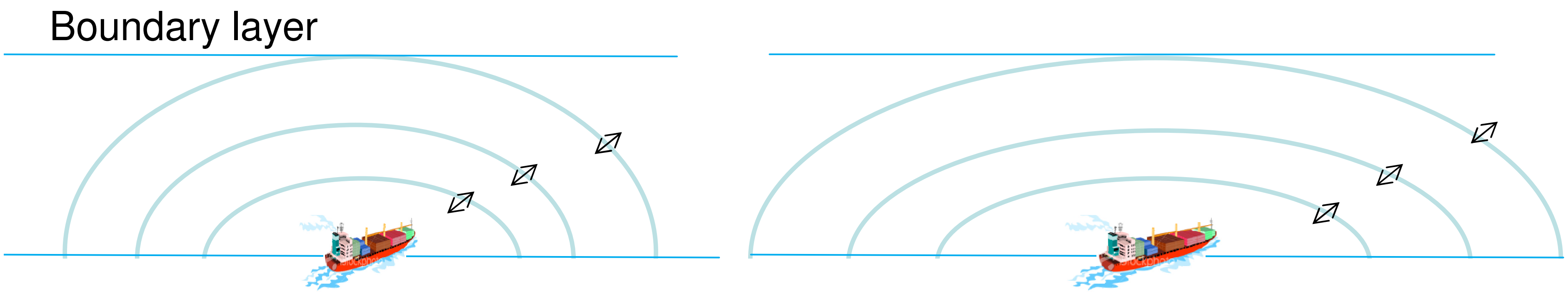
- PARameterization of Aircraft emitted NOX
- Developed by Ernst Meijer, KNMI [Meijer et al, 1997]
- Gaussian dispersion model
- Emits one puff and calculates the remaining nitrogen oxides fractions of the original NO_x emission
- Model with 10 rings; take inner structure of plume into account
- Interaction between rings and entrainment of ambient air in outside ring
- Chemistry mechanism containing 44 species and 103 reactions

Adapting PARANOX

- Describe expansion as function of downwind distance (Song et al. [2003], Franke et al. [2007])
- Account for reflection by image plume at z=0, i.e. doubling initial concentrations in all rings.
- Update photolysis values with GEOS-Chem values for lowest level.
- Stop expanding plume when outer radius of 10th ring reaches boundary layer height.
- Run for (somewhat arbitrary) 5 hours, after which plume chemistry of initial emissions is in ‘equilibrium’.
  - too short: too high fraction of NOx remaining and thus too much ozone production when diluted back into the model
  - too long: increases the computational burden.

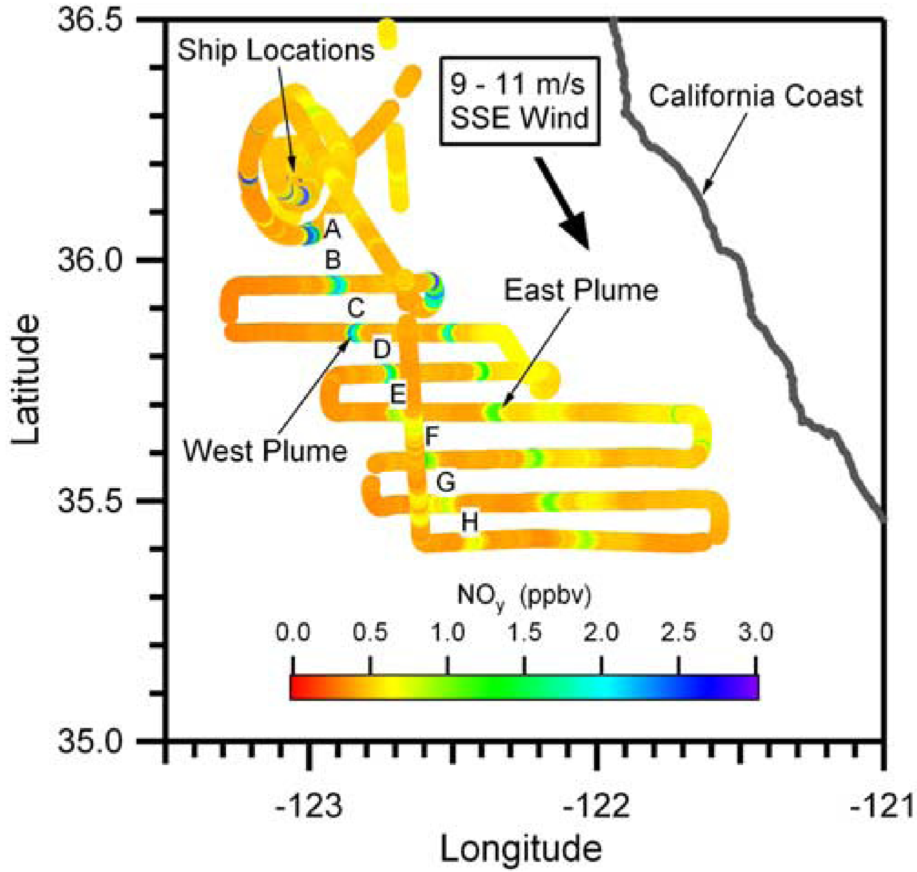
Cartoon



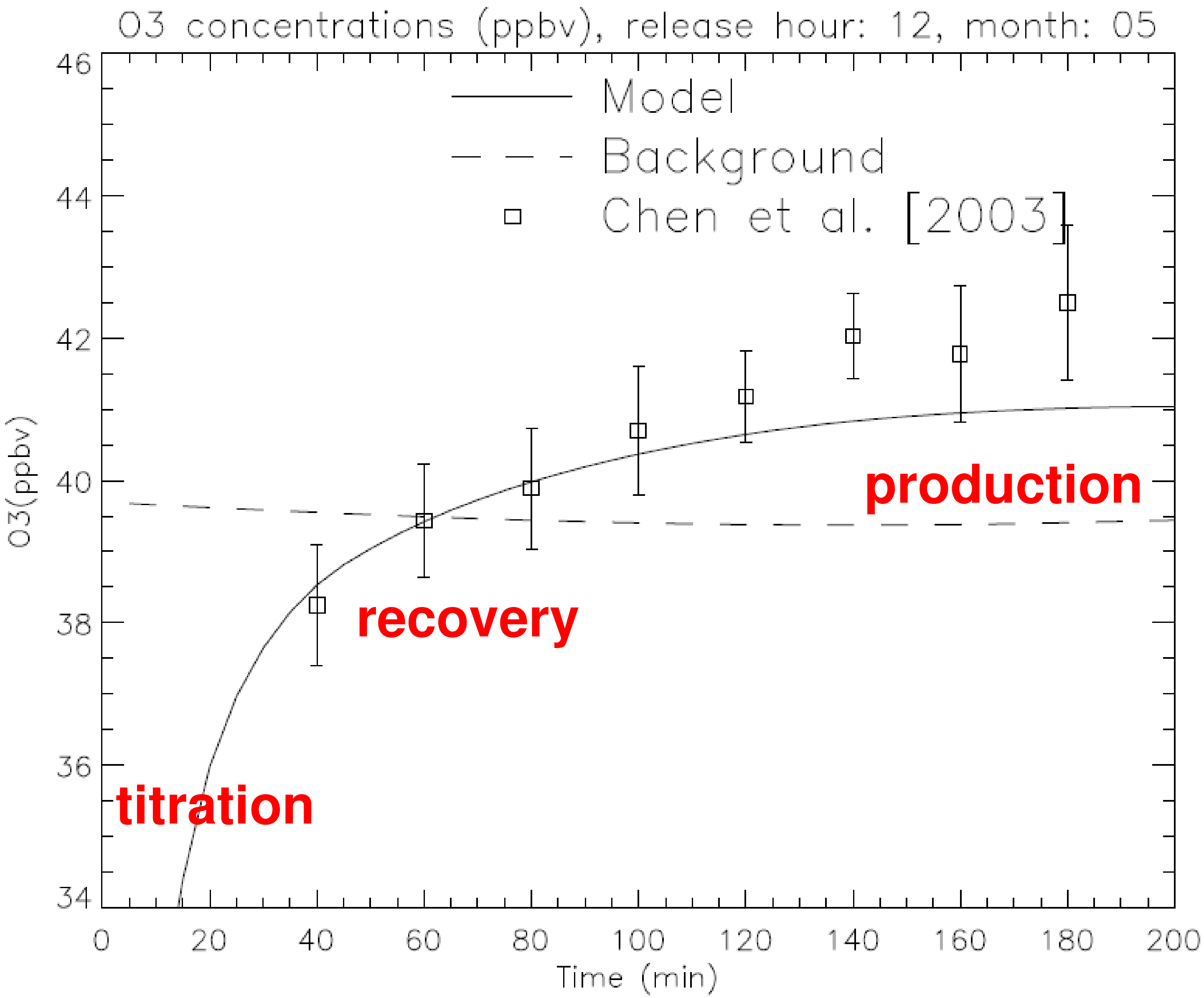


Comparing with observations

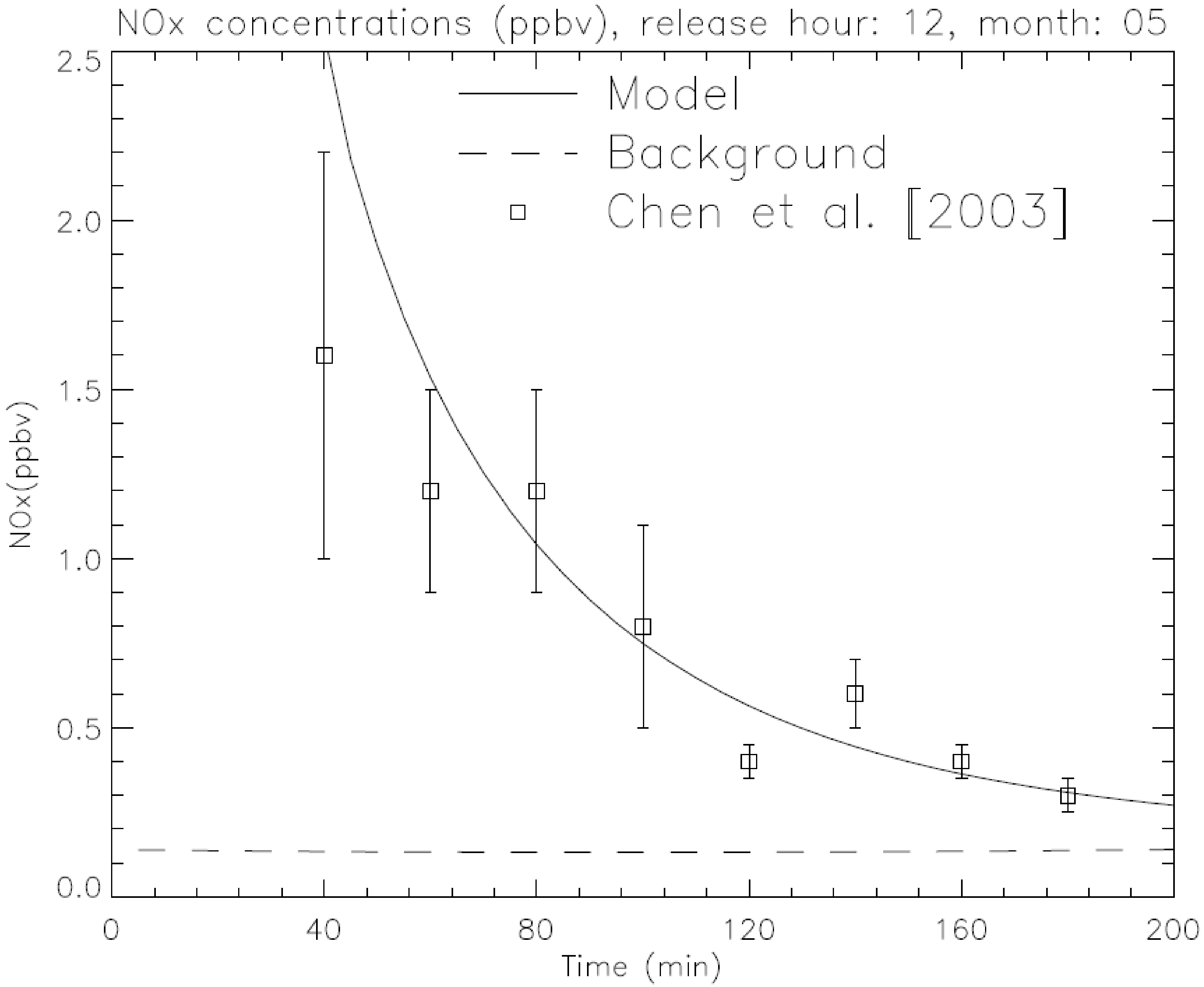
- Comparing to *Chen et al.* [2005]
- Uses observations of the ITCT 2002 airborne field campaign
- Measurements in ship plumes near Monterey, Californian Coast at 8 May 2002
- Moderately polluted background
- Use ambient concentrations provided by *Chen et al.* [2005]



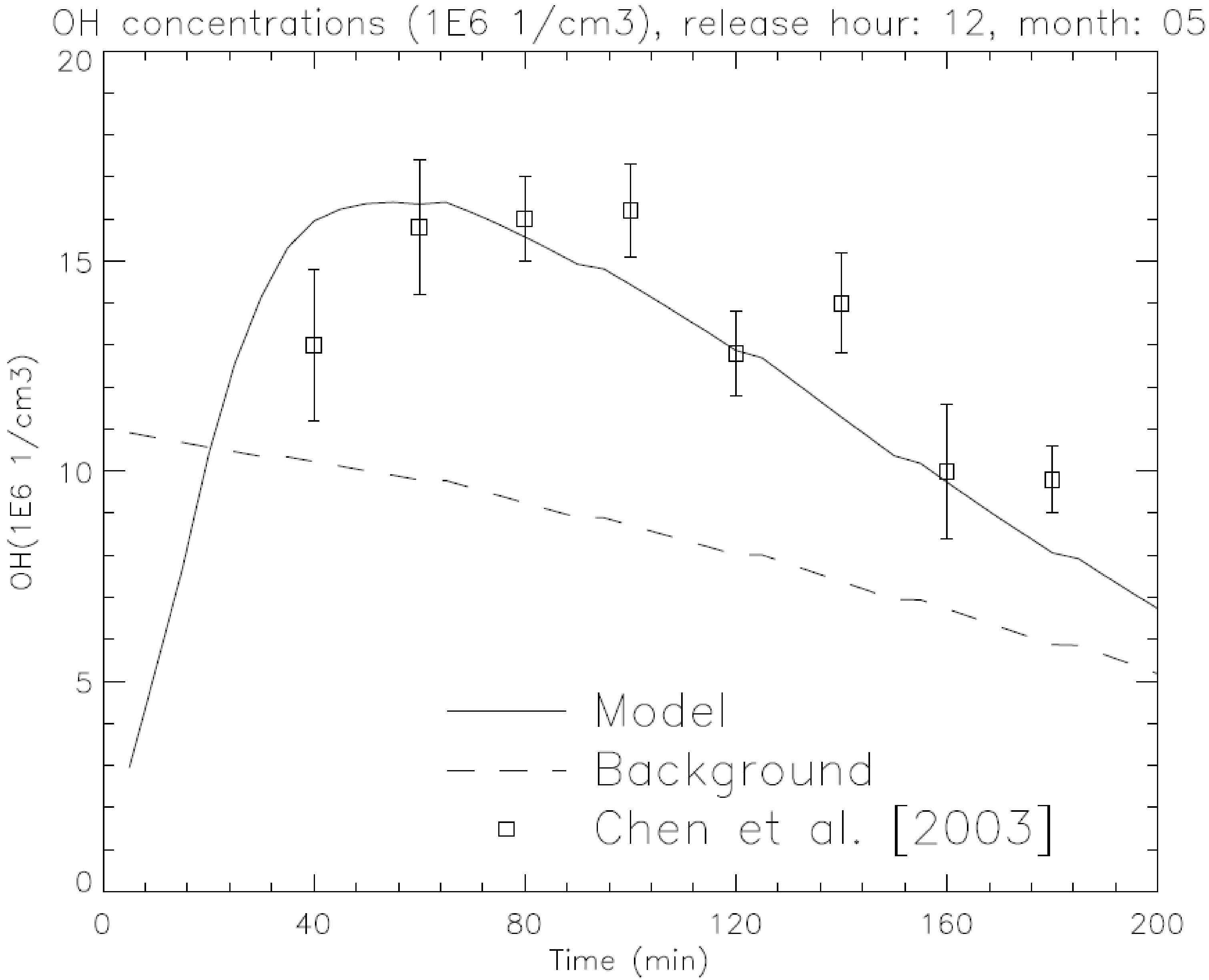
Ozone simulations in the plume



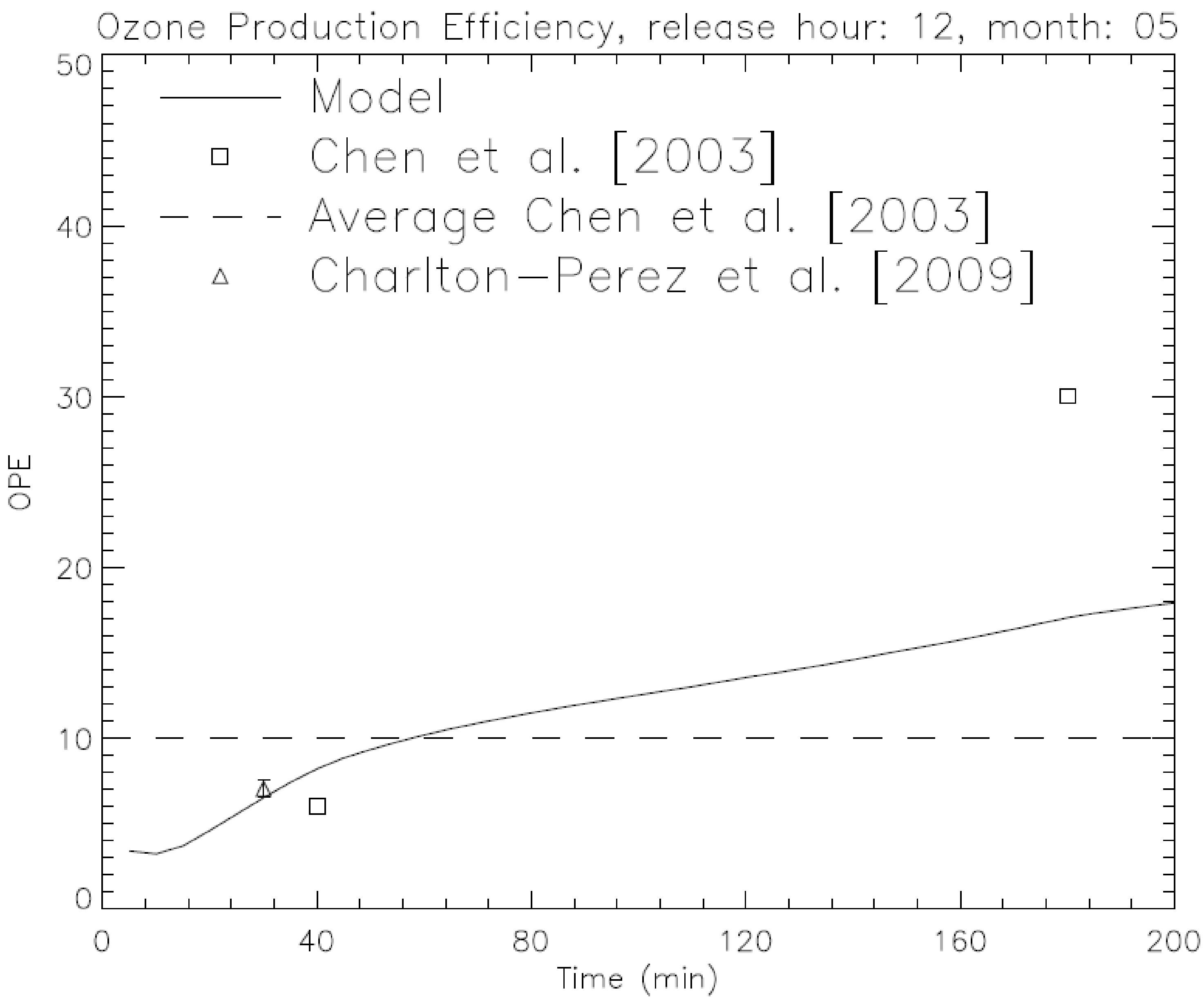
NOx simulations in the plume



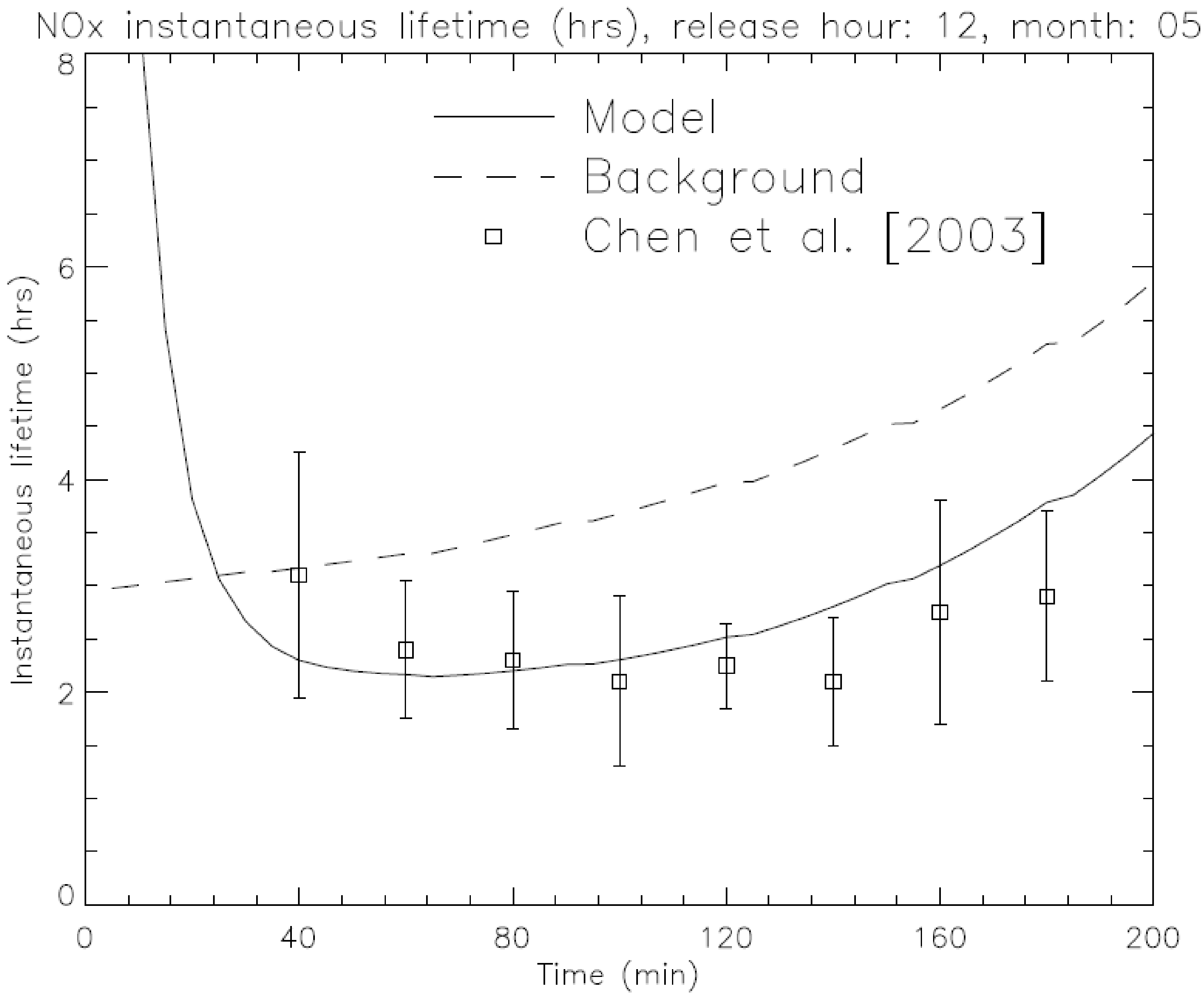
OH simulations in the plume



Ozone production efficiency

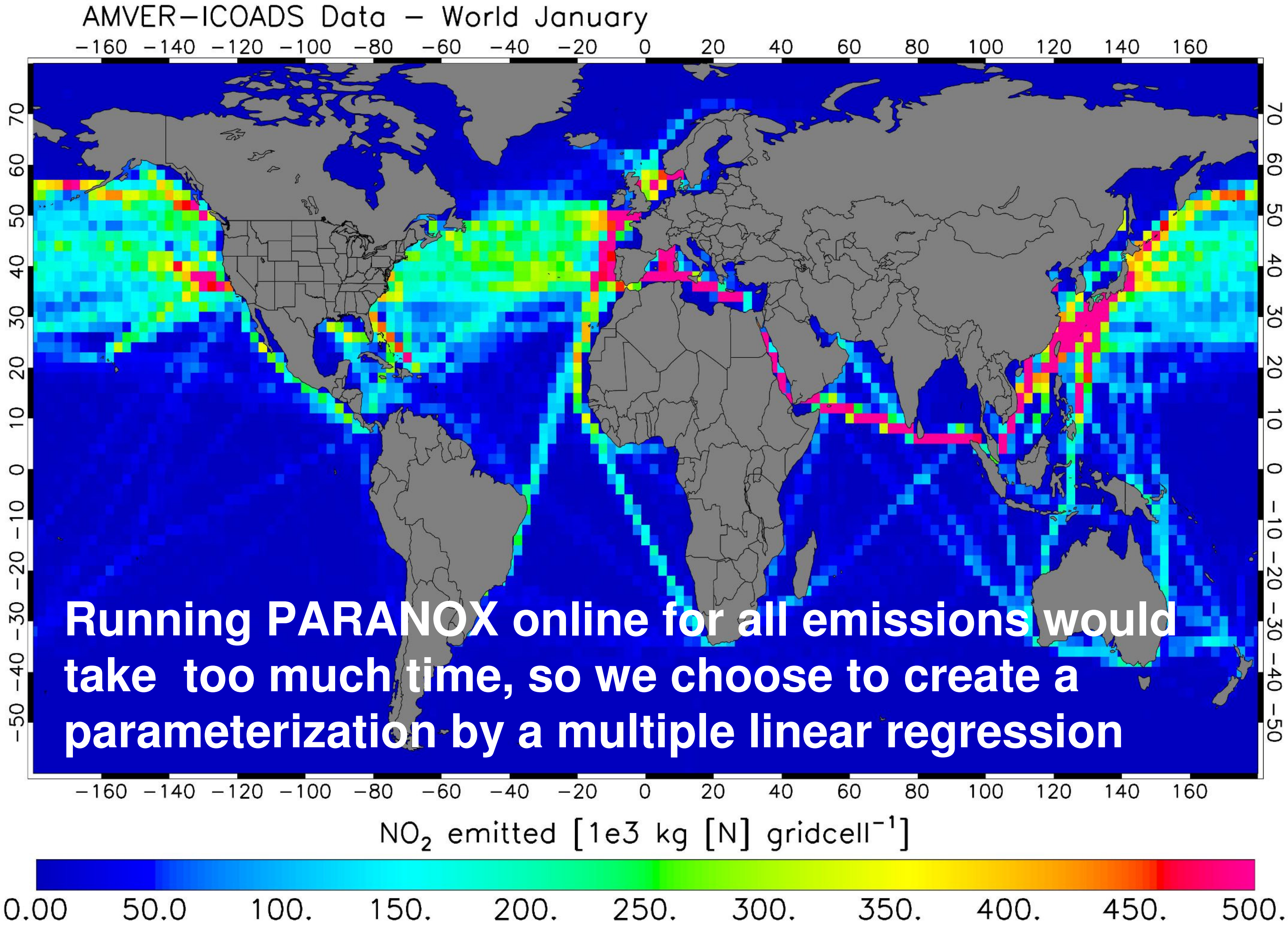


NOx lifetime



Improving global models with ship PARANOX

- Two options:
  - Run PARANOX online for all grid cells with emissions
  - Create parameterization based on model output for a number of conditions
    - Ozone Production Efficiency (OPE)
    - Fraction NO_x remaining
  - Generate look-up table



Running PARANOX online for all emissions would take too much time, so we choose to create a parameterization by a multiple linear regression

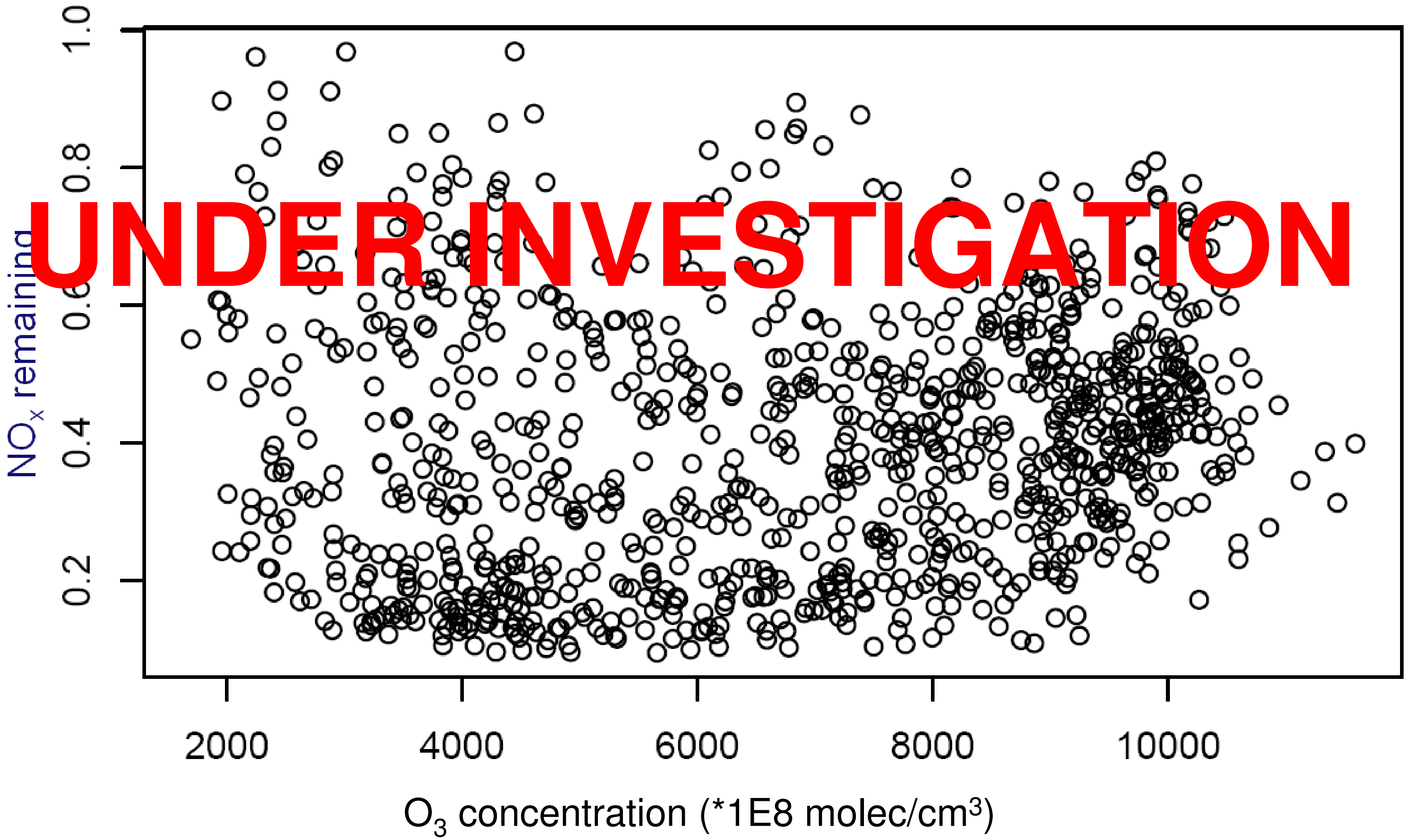
Creating parameterization

- Create hourly output of possible dependent variables from GEOS-Chem at 1/01, 1/04, 1/07, 1/10
- Run ship PARANOX and expand for 5 hours for grid cells with emissions and take GC output at these grid cells as ambient values
- Run for several emission times
- Output independent variables, dependent variables, month, emissions and emission time
- To calculate fraction of NO_x remaining, entrainment of NO_x, PAN and HNO_3 into plume is not allowed

Parameterization variables

- Independent variables: Integrated OPE and fraction of NO_x remaining
- Possible dependent variables:
  - J-values
  - Mixing depth
  - Wind speed
  - Temperature
  - Concentrations (O3 and CO)
  - Solar Declination
  - Emissions

Results



UNDER INVESTIGATION
1.0
0.8
0.6
0.4
0.2
NOx remaining
2000
4000
6000
8000
10000
O3 concentration (*1E8 molec/cm3)