Have US Power Plant NO_x Emission Reductions Had an Impact on Air Quality?

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Motivation

- Electric power generation accounted for about 25% of US NO_x emissions in late 1990's
- Since then, NO_x pollution controls were implemented by utility companies
- Satellite measurements of NO_2 vertical columns have been available since 1995
  - ➢ Do satellite observations reflect these emission changes?

Outline

- CEMS observations of emission control efforts
- Satellite measurement methods
- Model description
- Power plant updates to NEI 1999 using CEMS data
- Results
    - Satellite and model spatial distribution of NO_2 columns
    - Year-to-year trends in NO_2 columns and emissions
    - Seasonal trends in satellite and model NO_2 columns
    - Model predictions of boundary layer NO_2 and O_3 changes

Point Source NO_x Emission Control Programs

- Acid Rain Program
  - 1990 - present
  - part of Title IV of 1990 Clean Air Act Amendments
  - limits annual NO_x emission rate (lb/mmBTU)
  - all US coal-fired power plants

- Ozone Transport Commission NO_x Budget Program
  - 1999 - 2002 ozone seasons (May - Sept)
  - cap-and-trade
  - all point sources in OTC region

- EPA 1998 NO_x State Implementation Plan (SIP) Call
  - states must amend SIPs to decrease downwind O_3
  - caps ozone season E(NO_x) for each state
  - states decide on strategy and sources to control
- NO_x Budget Trading Program
  - 2003 - present ozone seasons
  - cap-and-trade
  - extends OTC program to entire SIP Call region
  - all large point sources in NO_x SIP Call region

EPA Acid Rain Program, 2002 & 2003 Progress Reports
NO_x Budget Trading Program, 2003 Progress and Compliance Report

CEMS Data Analysis

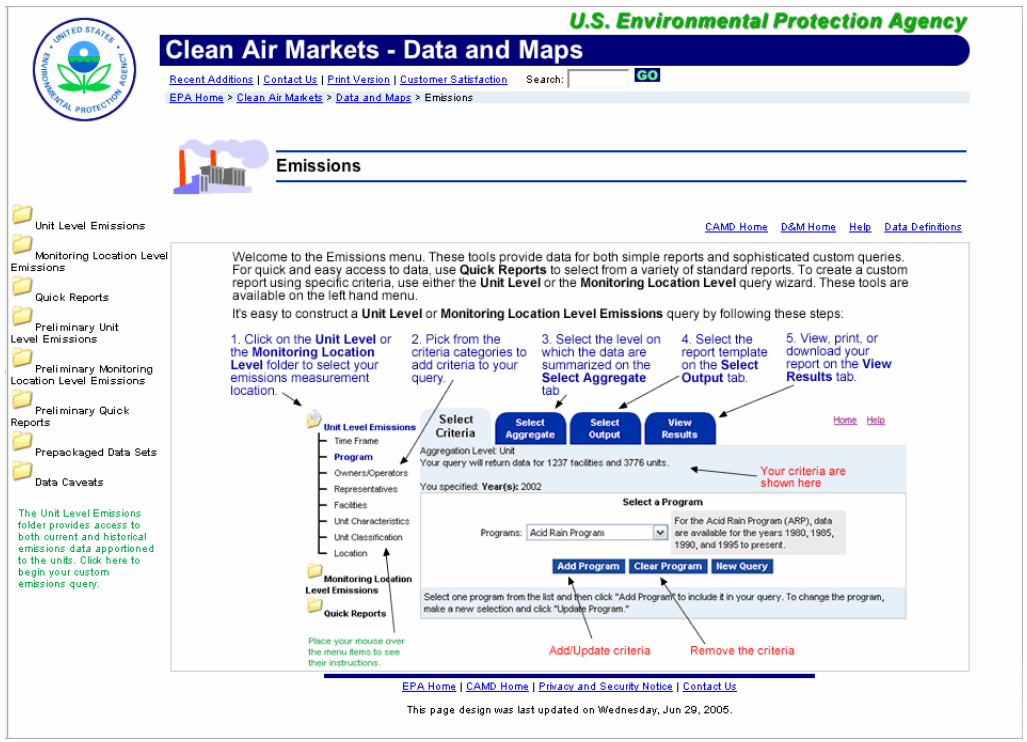
CEMS = Continuous Emission Monitoring Systems

- Direct observations of point source emissions
- Hourly NO_x, SO_2, and CO_2 emissions and heat input
- Reported quarterly to EPA Clean Air Markets Division
- Data for 966 facilities in 1999 and 1427 facilities in 2004
- Most sources: electric power generation, co-generation with other industry

Clean Air Markets Query Wizard

- Very useful web tool to extract and aggregate CEMS data
- User specifies:
  - Unit or monitoring level
  - Time aggregation period
  - Year
  - Emissions aggregation level
  - Output fields
  - View or download reports

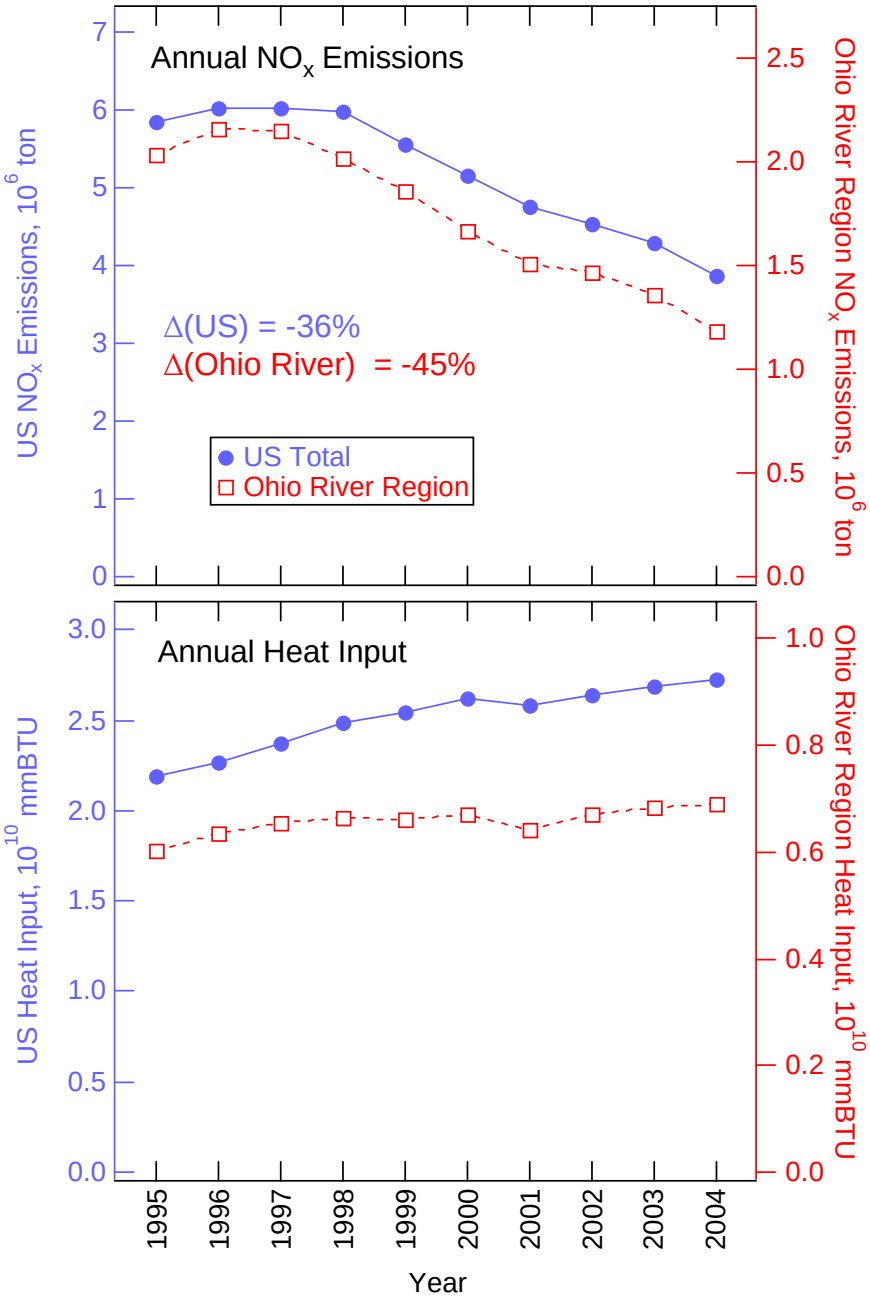
http://cfpub.epa.gov/gdm/index.cfm?fuseaction=emissions.wizard



Annual NO_x CEMS Trends

- US since late 1990's
  - NO_x emissions decreased
  - Heat input increased slightly
- Ohio River region (IL, IN, KY, OH, PA, WV)
  - One-third of US power plant NO_x emissions in late 1990's
  - High density of coal-burning plants
  - High NO_x emissions per unit of electricity generated
  - NO_x emissions decreased even faster than US as a whole
  - Heat input almost constant

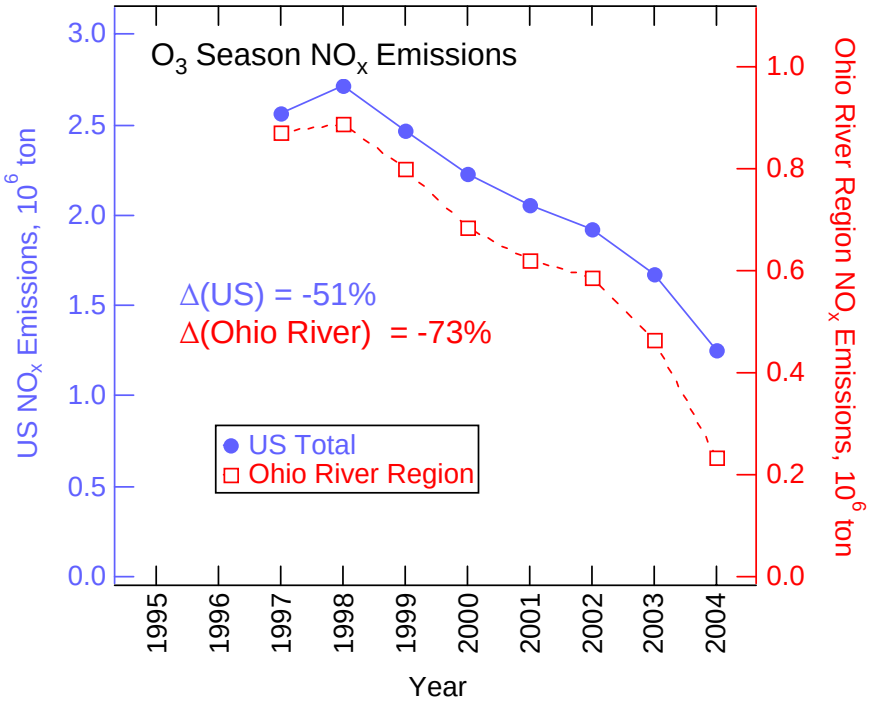
➢ Substantial NO_x emission reductions while maintaining amount of electric power generated

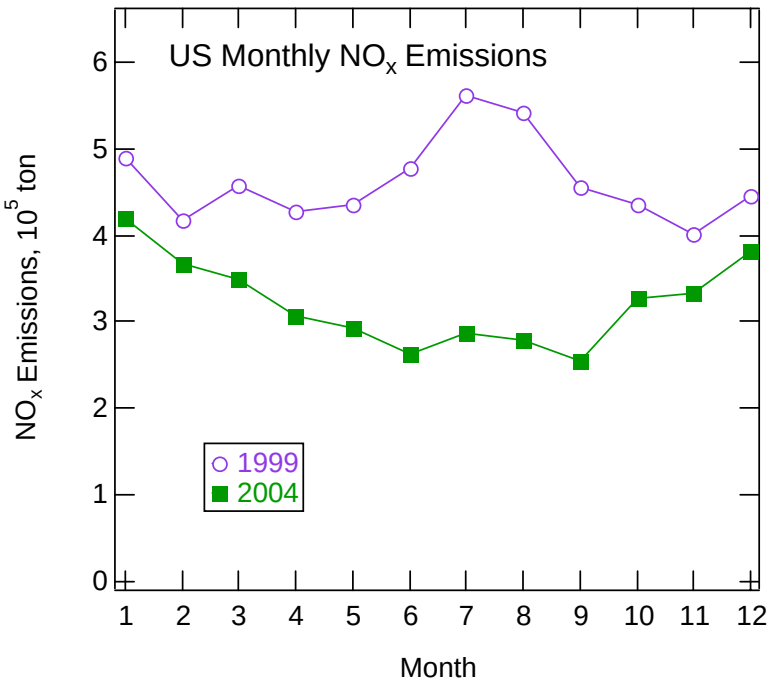


Seasonal NO_x CEMS Trends

O_3 season NO_x emissions

- May - September total
- Summer use of controls
- Larger decreases than annual
- Ohio River region got even greater benefit than nation as a whole





Monthly power plant NO_x emissions

- Before controls: maximum in summer
- After controls: minimum in summer

➢Changes in seasonal behavior of power plant NO_x emissions

Satellite Instruments

SCIAMACHY

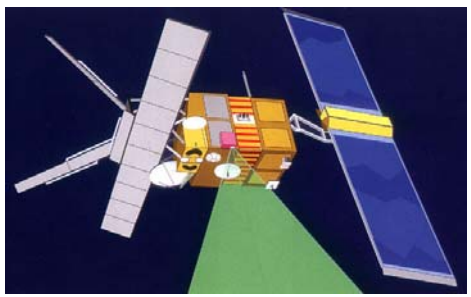
SCanning ***I***maging ***A***bsorption spectro***M***eter for ***A***tmospheric ***CH***artograph***Y***

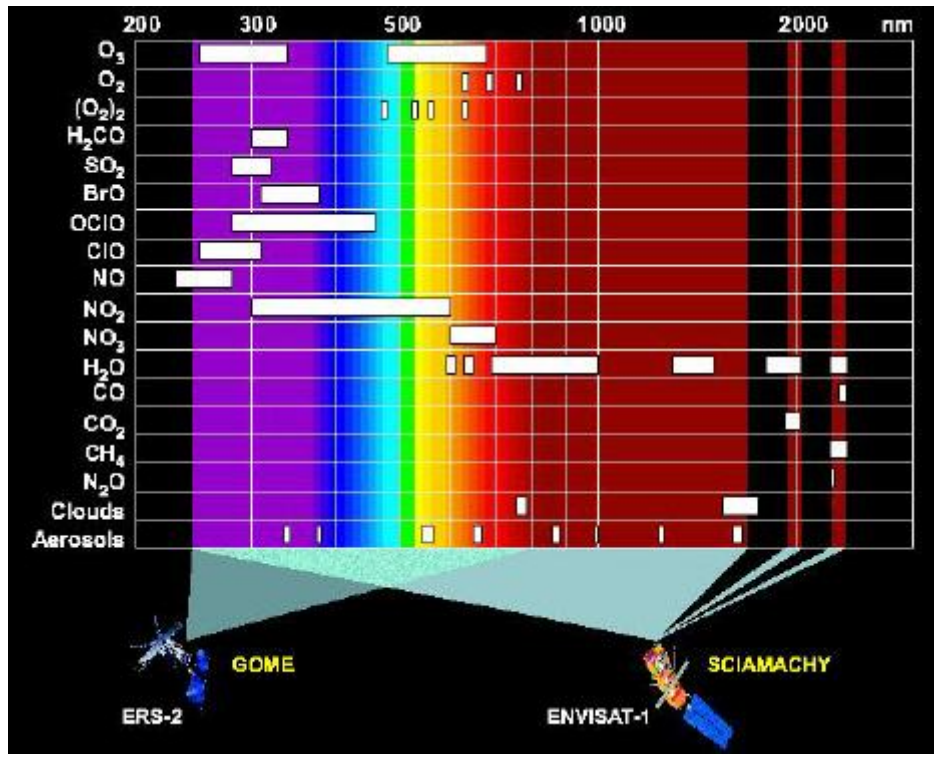
- launched in March 2002 on ENVISAT
- horizontal resolution: 60 × 30 km^2

GOME

Global ***O***zone ***M***onitoring ***E***xperiment

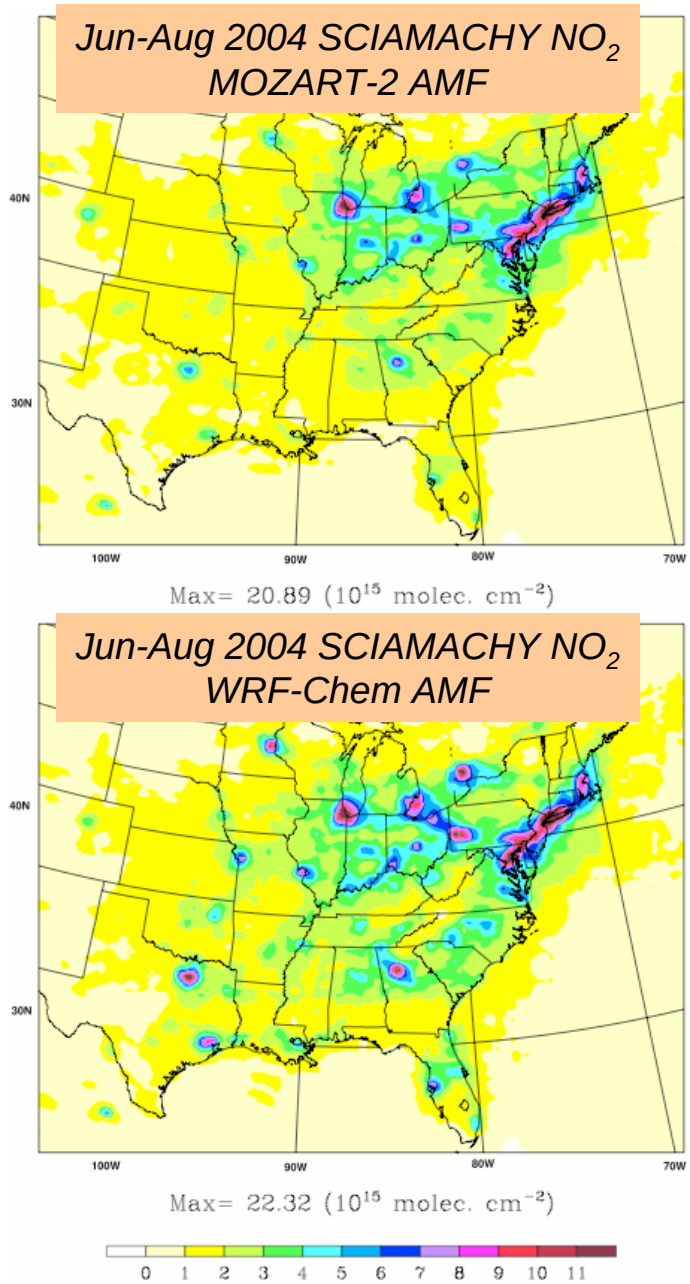
- launched in April 1995 on ESA ERS-2
- operated from August 1995 to June 2003
- horizontal resolution: 320 × 40 km^2





Extracting NO_2 Vertical Columns from Satellite Measurements

- Measure NO_2 absorption
  - Differential Optical Absorption method (425-450 nm)
- Remove stratospheric component
  - subtract clean reference sector data from same day
- Cloud filtering
  - remove data with cloud fraction > 0.15
- Convert tropospheric residual to vertical column
  - account for vertical sensitivity
    - $\Rightarrow$ radiative transfer model SCIATRAN
  - Air Mass Factor (AMF): *a priori* information on surface spectral reflectance, surface altitude, aerosol loading and shape of NO_2 vertical distribution
    - $\Rightarrow$ chemical transport model
    - Previously: MOZART-2 ($2^\circ \times 2^\circ$)
    - This study: WRF-Chem (27×27 km^2)

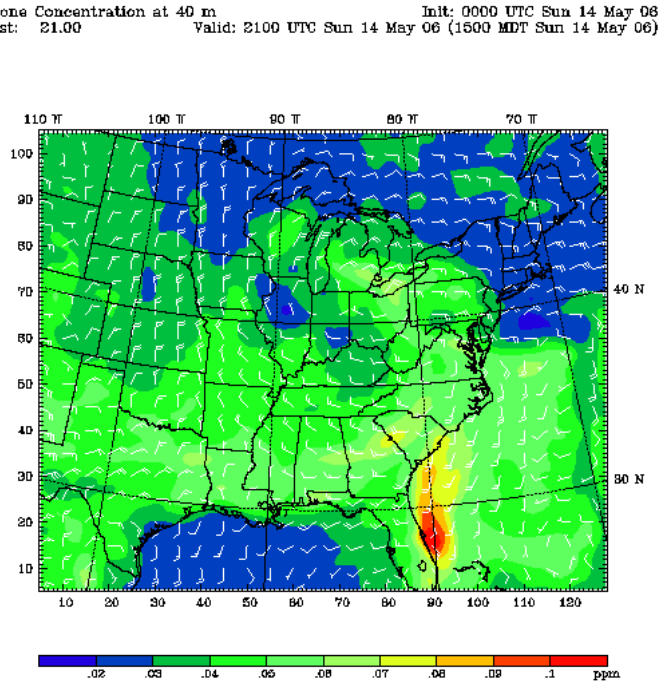


Air Quality Model Description

WRF-Chem

Weather **R**esearch & **F**orecasting Model with On-line **Chem**istry

- WRF version 2
- RADM II chemical mechanism
- MADE/SORGAM aerosol mechanism
- BEIS3.11 biogenic emissions
- YSU PBL scheme
- NOAH land-surface model
- Grell-Devenyi ensemble cumulus scheme
- WSM6 microphysics scheme
- Horizontal domain: 60.9°W-112.1°W, 23.2°N-51.5°N
- Vertical domain: 0 to ~18 km
- Horizontal resolution: 27 km
- Vertical resolution: 0.017 (surface) to 2.4 km (20 hPa)
- Retrospective 24-hour forecasts starting at 00Z every day from 1 April 2004 to 31 October 2004
- More WRF-Chem details:
  - ❖ *http://ruc.fsl.noaa.gov/wrf/WG11/*
  - ❖ G. Grell et al., *Atmospheric Environment*, 2005



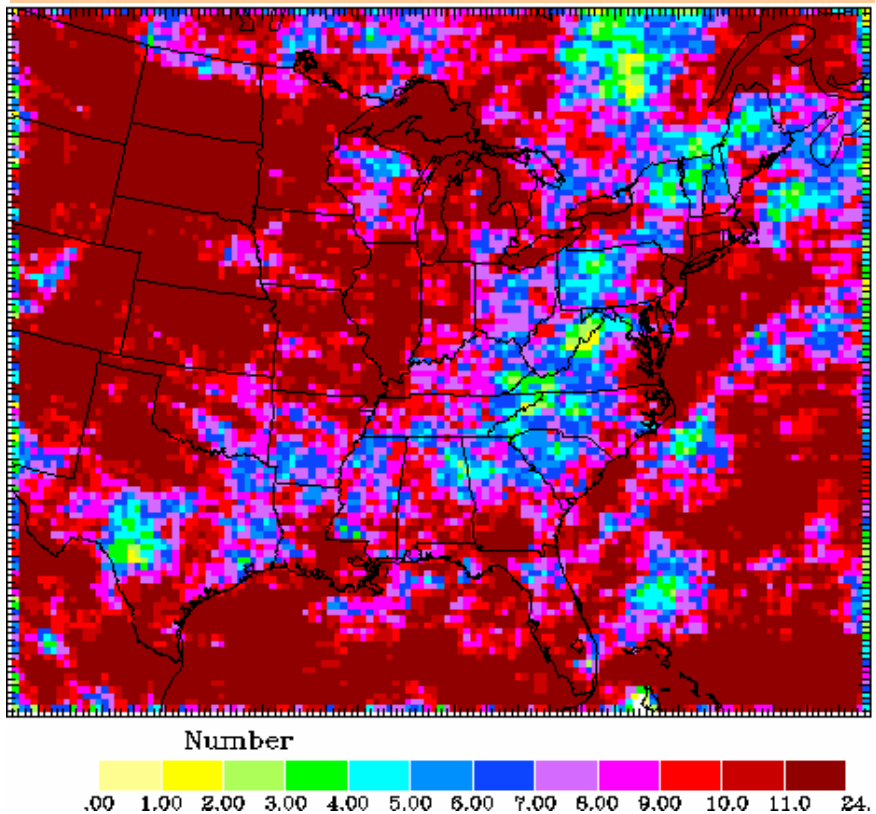
Real time air quality forecasts:
http://www-frd.fsl.noaa.gov/aq/wrf/

Data Sampling and Averaging

- SCIAMACHY data projected on to WRF-Chem grid
- Model sampled at ~10:30 LT during satellite overpass
- Cloudy grid cells filtered from both satellite and model data

➢ Same number of satellite and model data samples in each grid cell

Jun-Aug 2004 Number of Samples per Grid Cell



Reference Emission Inventory

Continuous Emission Monitoring System (CEMS)

- http://www.epa.gov/airmarkets/emissions
- compiled by electric power industry
- hourly measurements
- NO_x, SO_2, CO_2, heat input

National Emissions Inventory (NEI)

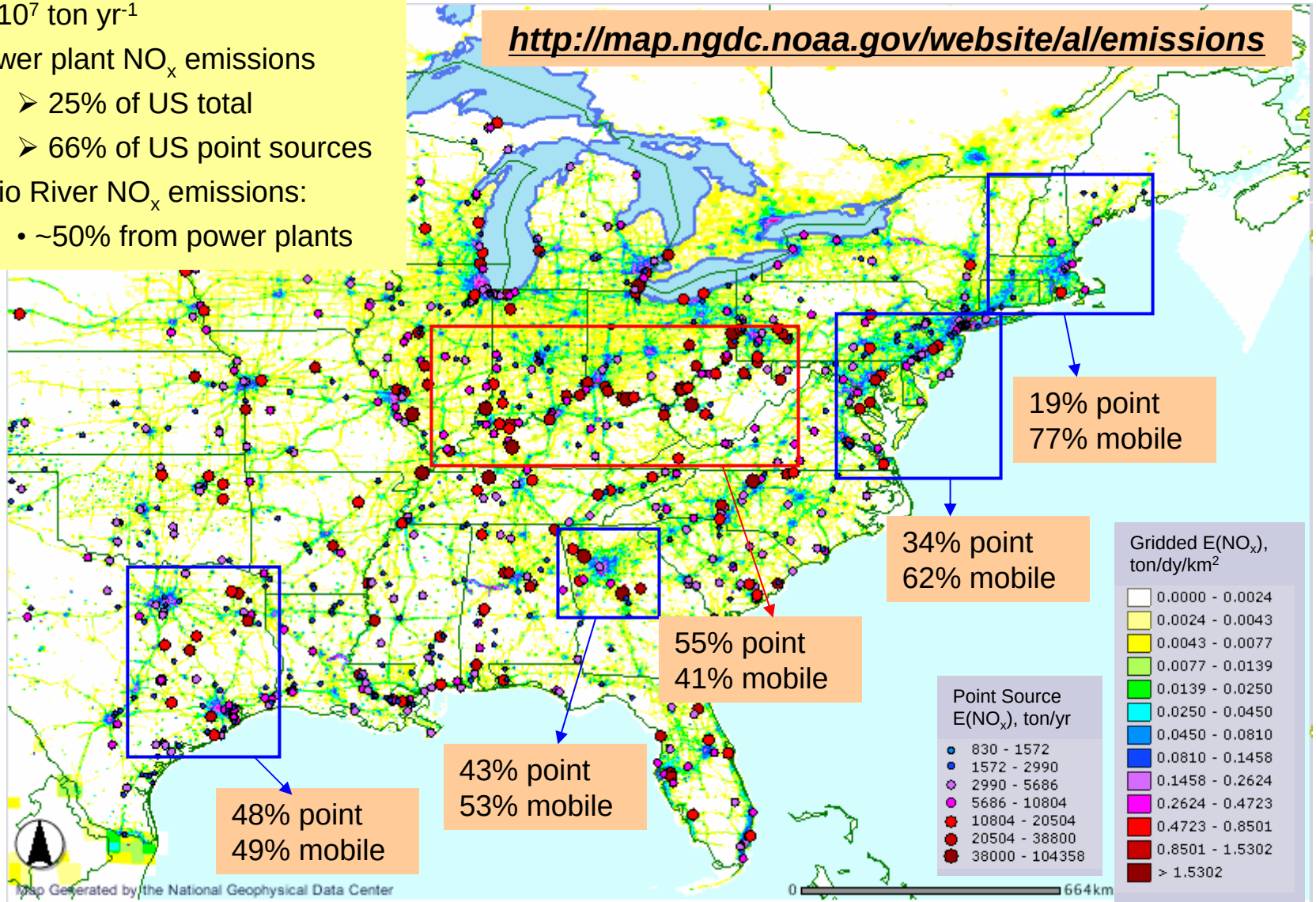
- http://www.epa.gov/ttn/chief/emch/index.html
- compiled every 3 years by EPA
- latest final dataset: 1999 version 3 (available March 2004!)
- county level
- annual and O_3 season day
- NO_x, CO, SO_2, VOCs, NH_3, PM2.5/10

1999 NOAA/AL Model EI

- http://ruc.fsl.noaa.gov/wrf/WG11/ /anthropogenic.htm
- 4 km grid
- O_3 season day
- RADM2, RACM, SAPRC-99, CB-IV, CBM-Z
- Emissions mapviewer:
http://map.ngdc.noaa.gov/website/al/emissions

NEI 1999 NO_x Emissions

- NEI 1999 US NO_x emissions = 2.4×10^7 ton yr^{-1}
- Power plant NO_x emissions
  - 25% of US total
  - 66% of US point sources
- Ohio River NO_x emissions:
  - ~50% from power plants



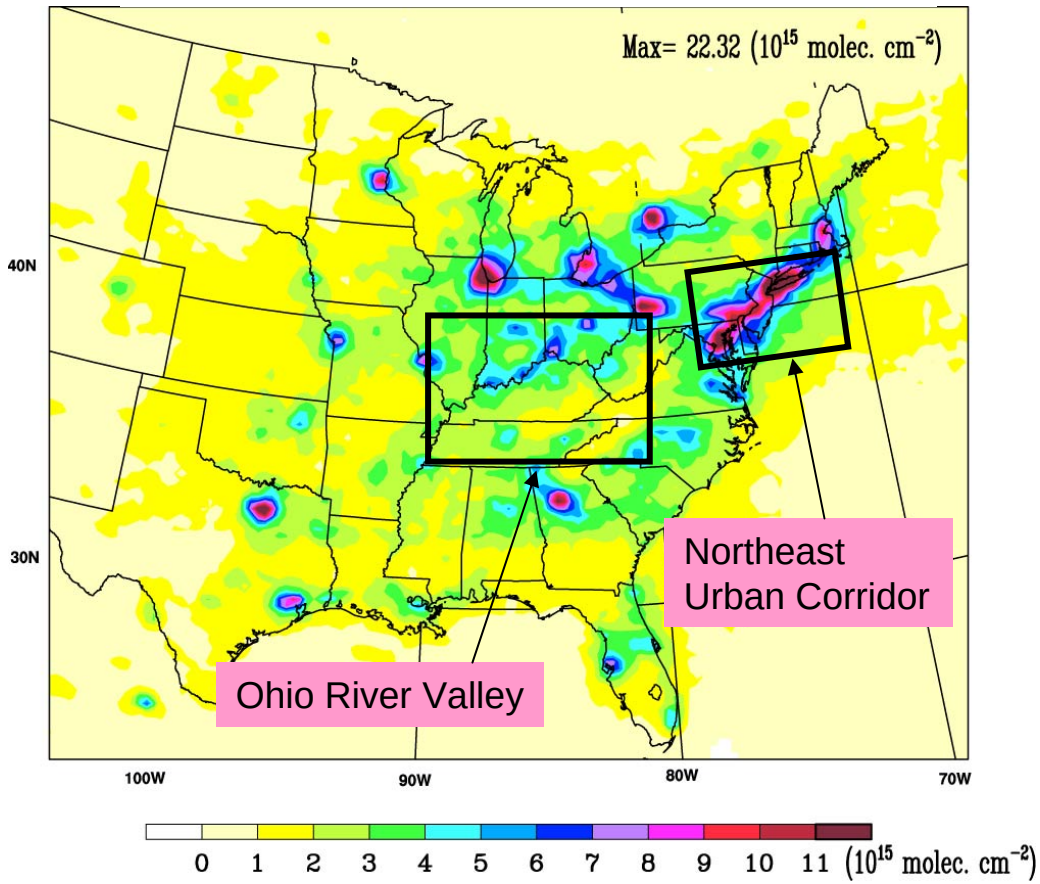
Updated Emission Inventory

- Processor updates NEI 1999 point source emissions with CEMS data reports generated by Clean Air Markets Query Wizard
- CEMS monthly NO_x and SO_2 emissions for April - October 2004
- Updated about 1000 facilities in NEI 1999
- NEI 1999 point source must have ORISPL code
  - ❑ 66% of NO_x and 82% of SO_2 total NEI 1999 point source emissions
  - ❑ updated 97% of NO_x and SO_2 emissions from these sources
  - ❑ assigned 95% of NO_x and 99% of SO_2 emissions in 2004 monthly CEMS datasets to these sources
- Emissions from facilities in NEI 1999 but not in CEMS dataset
  - ❑ keep at 1999 levels
- Emissions from facilities in CEMS dataset but not in NEI 1999
  - ❑ not included
- NEI 1999 area and mobile emissions
  - ❑ not modified

Spatial Distribution of NO_2 Columns

SCIAMACHY

Summer 2004 (June-August) Averages

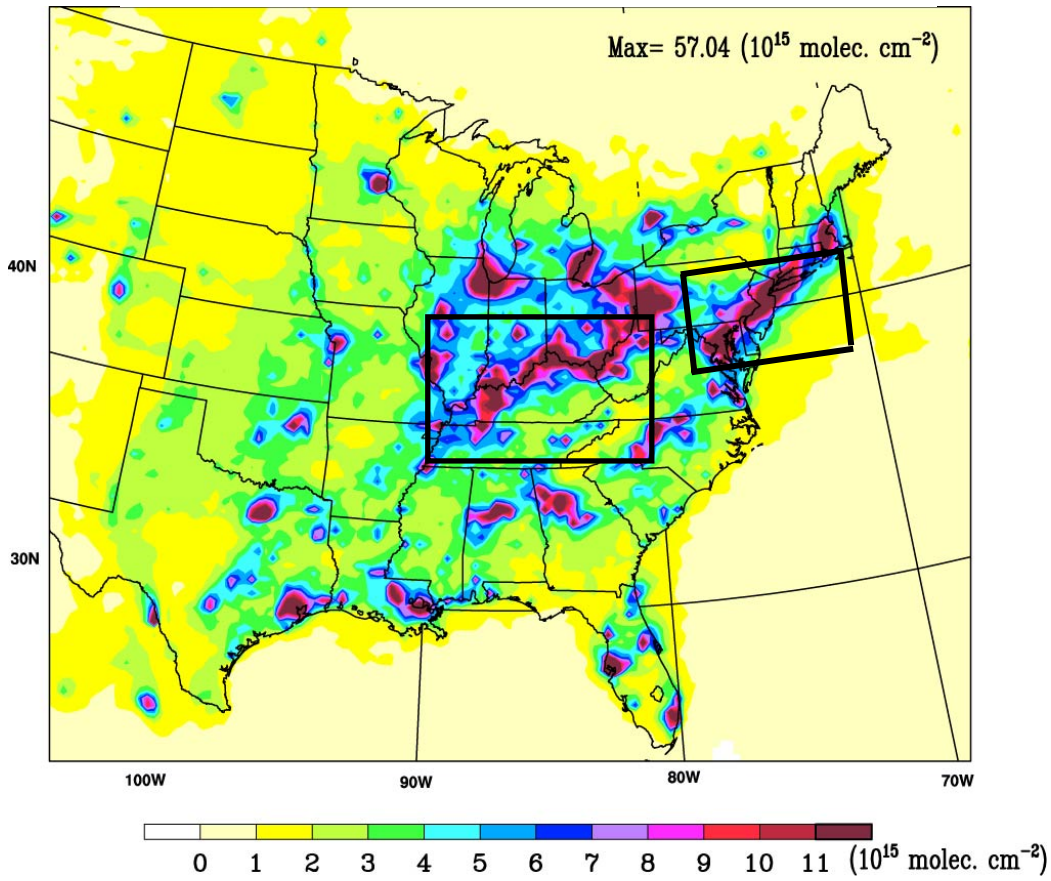


Spatial Distribution of NO_2 Columns

WRF-Chem with Reference Emissions

- NEI 1999

Summer 2004 (June-August) Averages



Model vs satellite linear fit

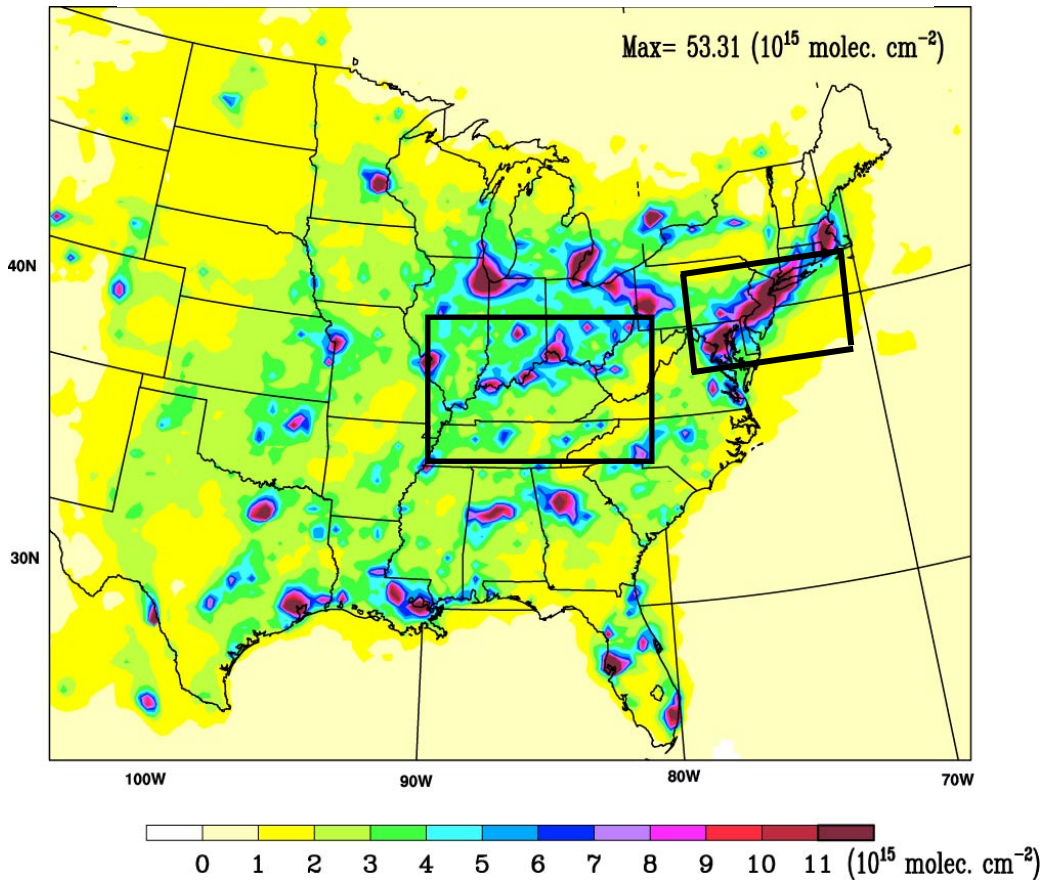
- slope = 1.48, r = 0.84

Spatial Distribution of NO_2 Columns

WRF-Chem with Updated Emissions

- ~1000 power plants updated with 2004 monthly CEMS data
- All other sources same as NEI 1999

Summer 2004 (June-August) Averages



Model vs satellite linear fit

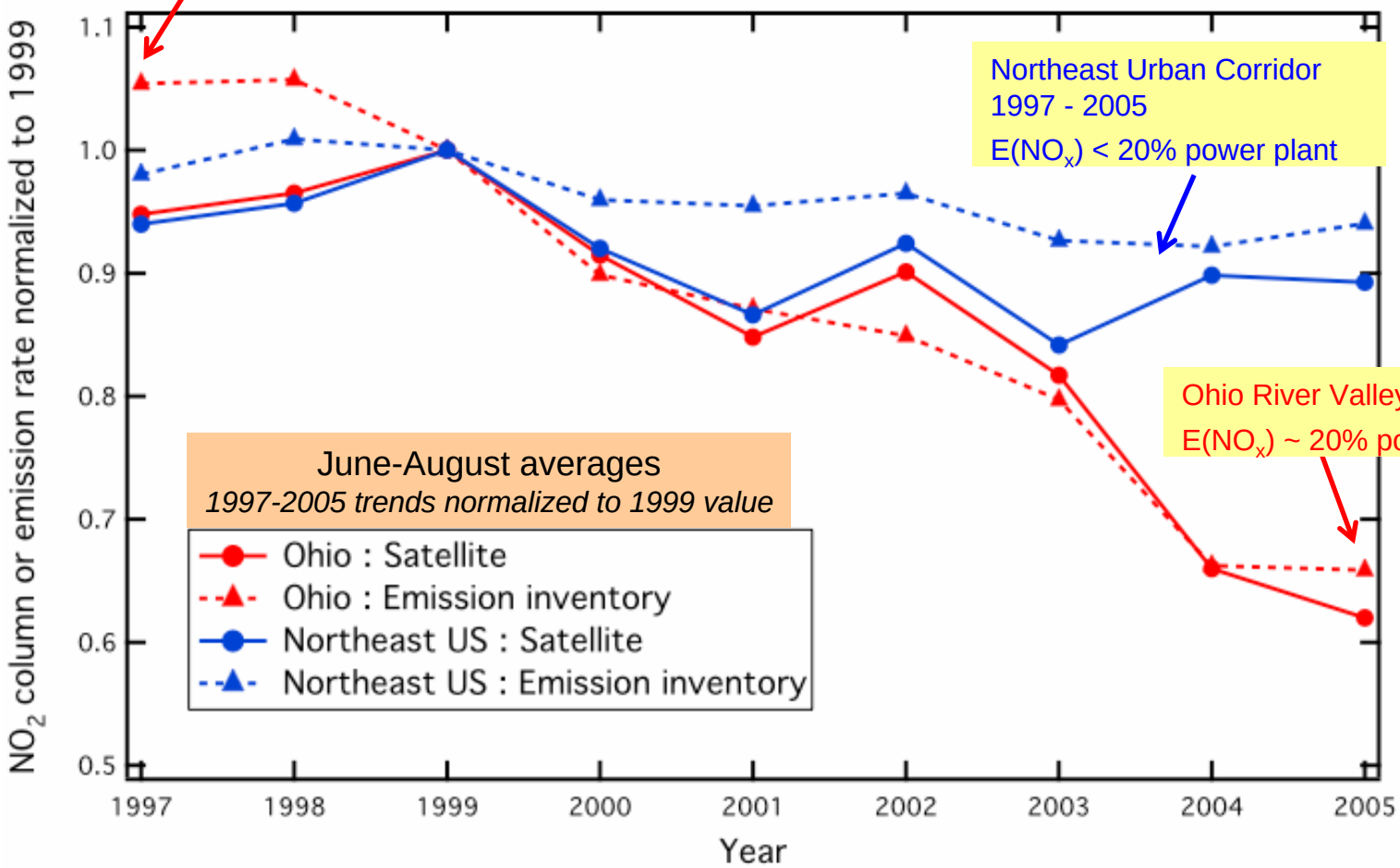
- slope = 1.15, r = 0.85

- *Satellite detects changes in Ohio River Valley from recent power plant NO_X emission controls*

Annual Changes in Satellite NO_2 Columns and Emissions

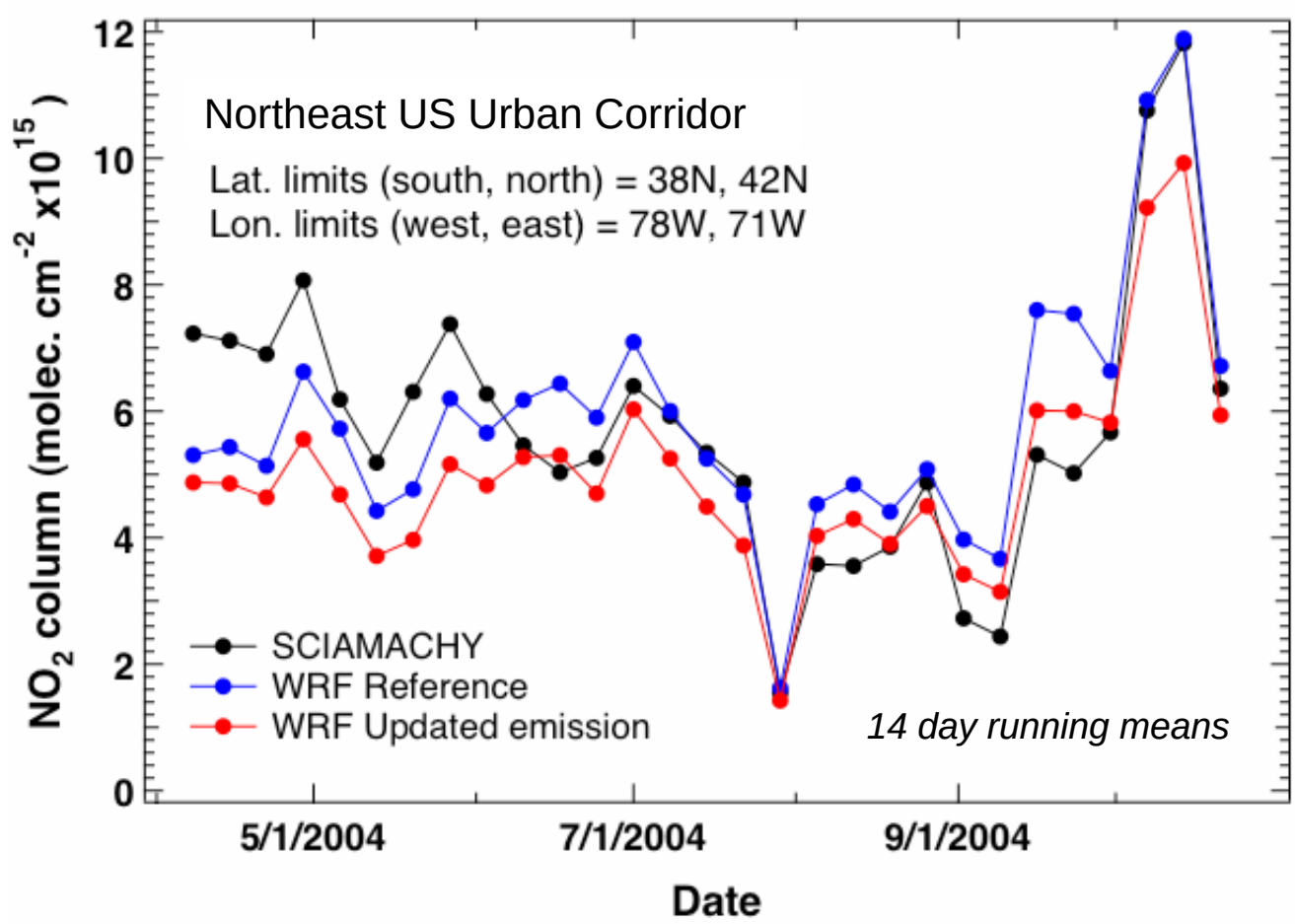
Ohio River Valley 1997
$E(NO_x)$ ~ 50% power plant

- Satellite NO_2 columns = GOME (1997-2002) & SCIAMACHY (2003-2005)
- Bottom-up NO_x emission trend derived from monthly CEMS reports assuming all other NO_x sources constant at summer 1999



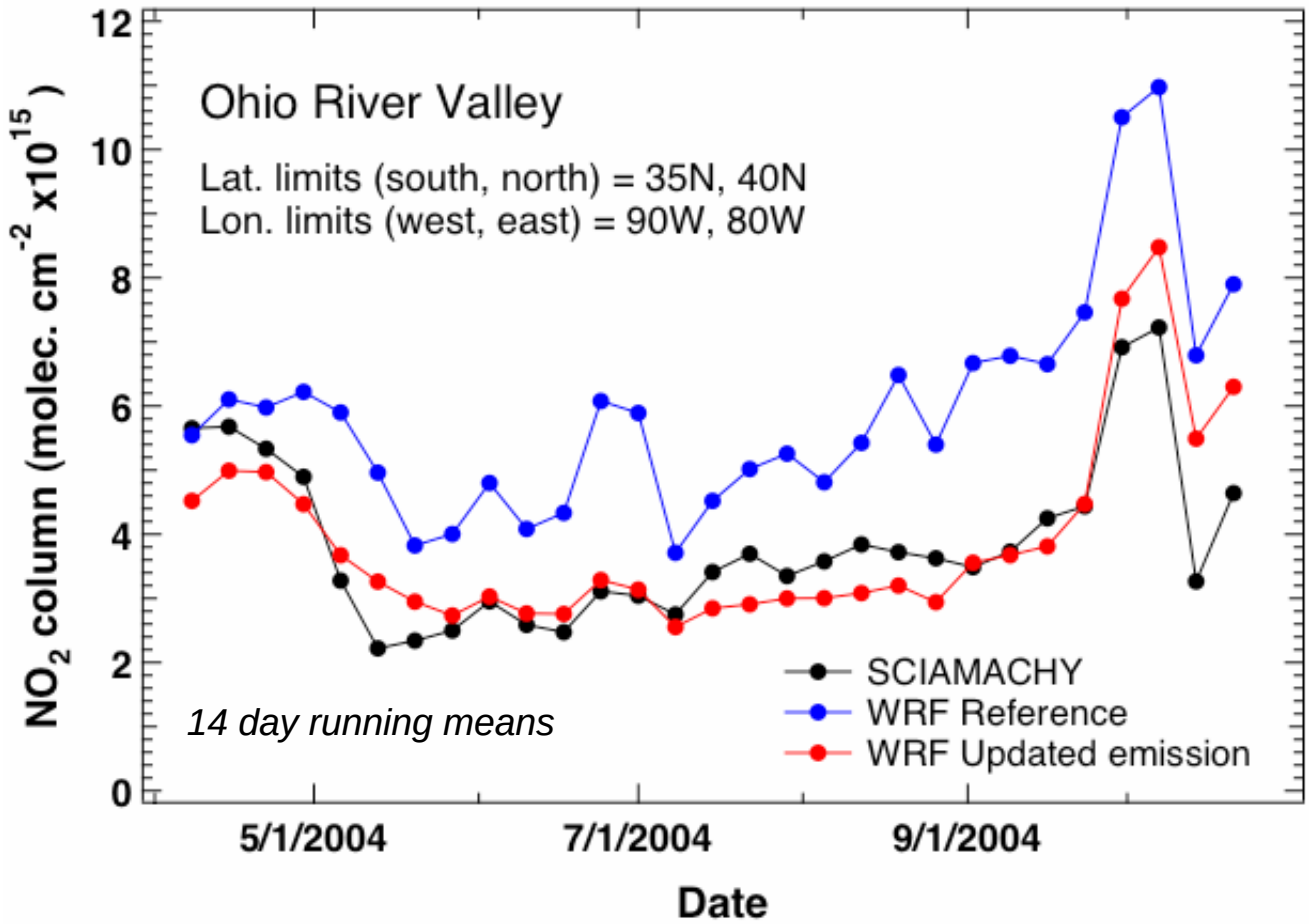
- Similar trends in satellite NO_2 columns and NO_x emissions
  - ➢ Power plant NO_x controls have affected NO_2 columns
  - ➢ Mobile NO_x emission changes smaller than those for power plants

Seasonal Changes in Satellite and Model NO_2 Columns



- Summer NO_2 columns < spring & fall NO_2 columns
  - Decreased NO_2 lifetime in response to higher solar actinic flux
    - ➢ Satellite detects seasonal changes due to natural photochemical cycle
- Model agrees well with satellite (r = 0.83 for either emission inventory)
    - ➢ Model captures variability caused by meteorology

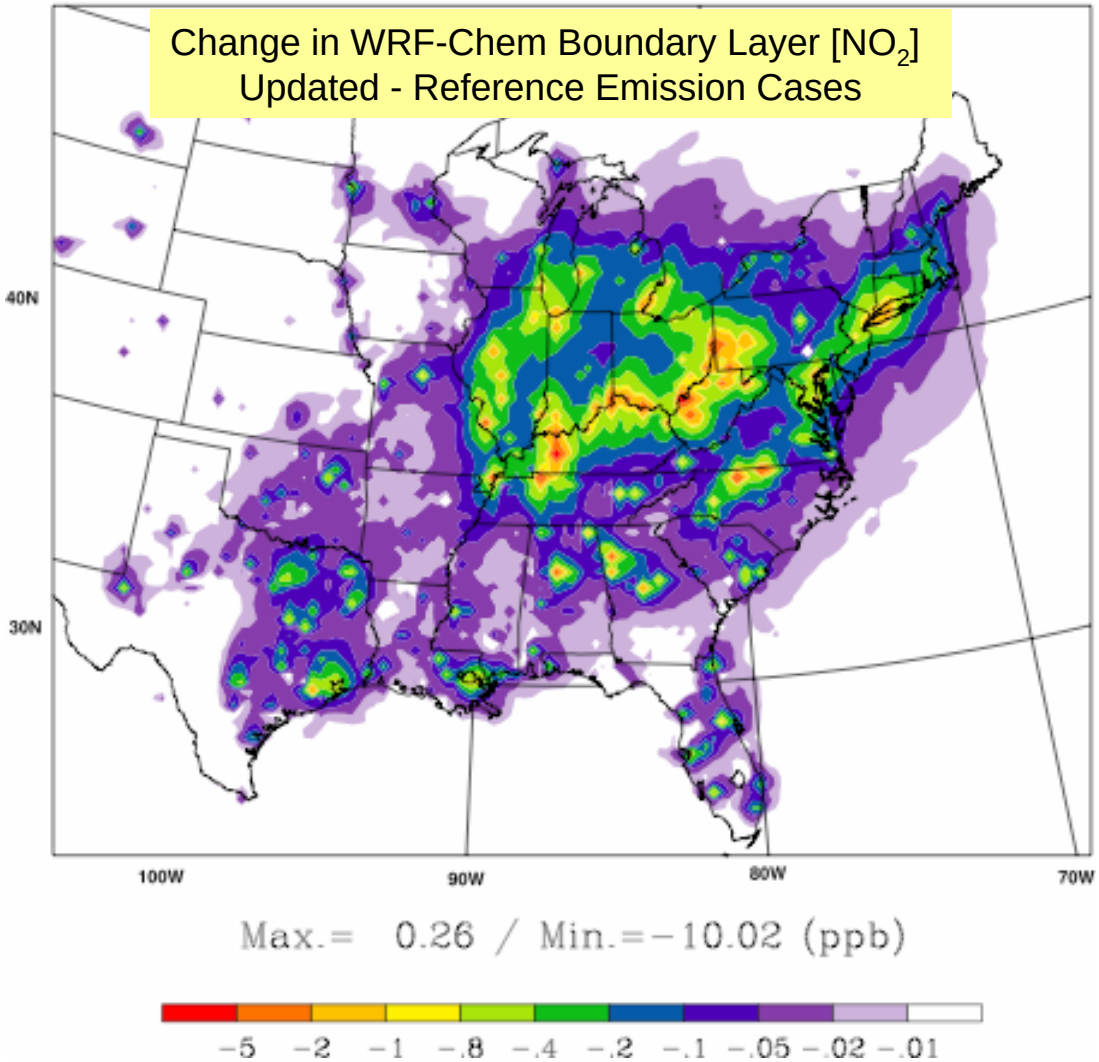
Seasonal Changes in Satellite and Model NO_2 Columns



- Summer NO_2 columns << spring & fall NO_2 columns
  - Point source NO_x controls target summer emissions
- Good model - satellite agreement requires monthly 2004 power plant emissions
  - r = 0.59 (reference emissions), r = 0.70 (updated emissions)

➢ Satellite detects seasonal changes due to summer use of power plant pollution controls

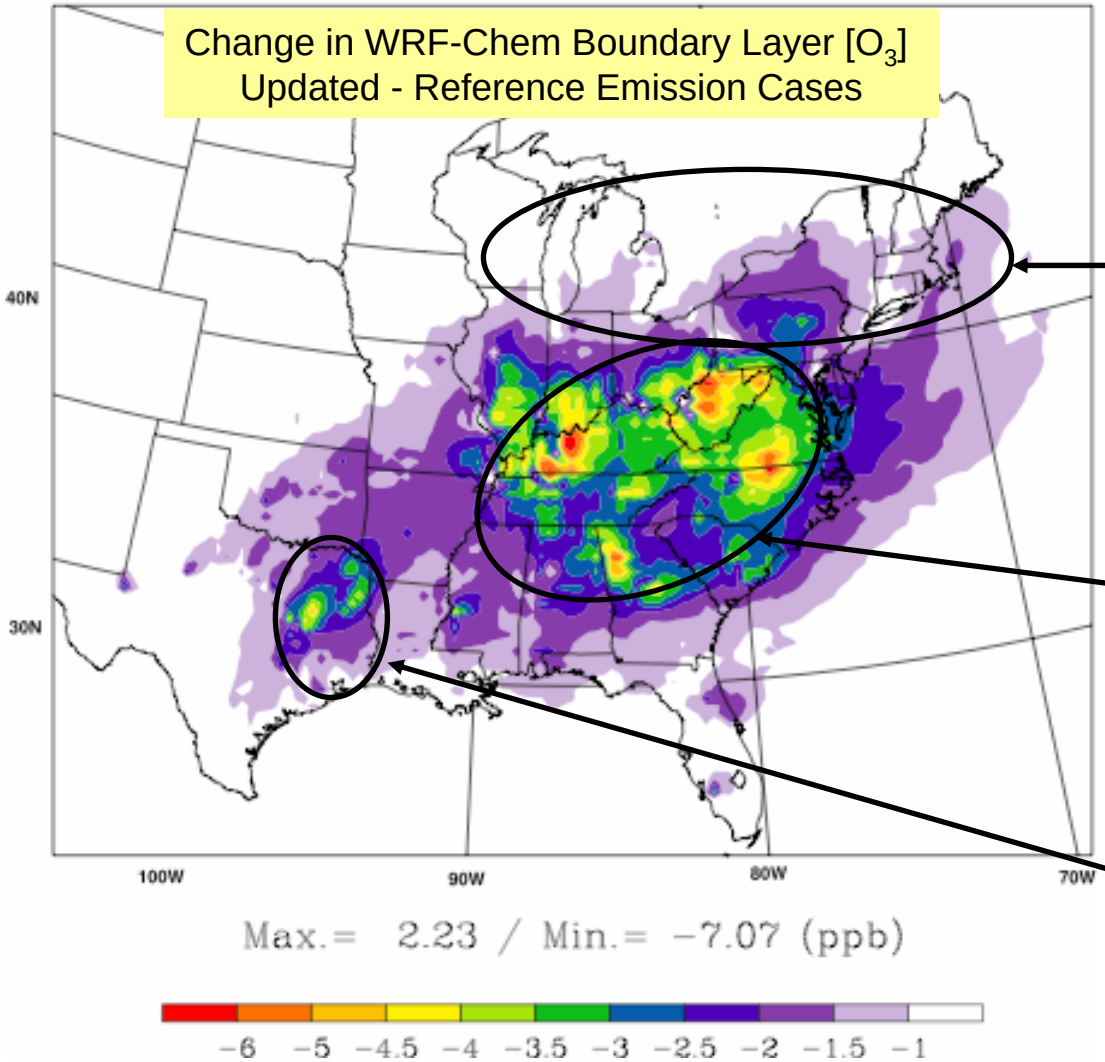
Boundary Layer NO_2 Response to NO_x Emission Reductions



- Largest reductions near power plants that installed controls between 1999 and 2004
- Maximum $\Delta[NO_2]$ = - 10 ppbv for reference case $[NO_2]$ = 12 ppbv

Average of all model output between 0 & 1 km at 20 UTC (1500 EST) for all days June-August 2004

Boundary Layer O_3 Response to NO_x Emission Reductions



- O_3 generally decreases in response to power plant NO_x emission reductions
- Small $\Delta[O_3]$ in northern US states
  - $\Rightarrow$ persistent cold fronts and unusually cold conditions in summer 2004
- Large decreases in Ohio River Valley, VA, NC, and GA
- Maximum $\Delta[O_3]$ = - 7 ppbv for reference case $[O_3]$ = 72 ppbv
- Differences in $\Delta[O_3]$ for comparable $\Delta E(NO_x)$
  - $\Rightarrow$ influence of biogenic E(VOC)

Average of all model output between 0 & 1 km at 20 UTC (1500 EST) for all days June-August 2004

Conclusions

- Power plant NO_x emission controls $\Rightarrow$ measurable impact on eastern US air quality
- Space-based spectrometers detect NO_2 column changes in Ohio River Valley
  - Year-to-year
  - Summer vs spring/fall
- Satellite observations validate bottom-up inventories
- Model needs month- and year-specific CEMS data to simulate spatial and temporal behavior of NO_x
  - Frequent NEI point source updates
- In response to power plant NO_x emission reductions, model predicts:
  - ΔO_3 = -4 to -10% in Ohio River Valley, Virginia and North Carolina
  - Small ΔO_3 in northeast US during cold summer of 2004
- EPA analysis of 1990 - 2004 surface O_3 monitor data sees some similar trends
  - *http://www.epa.gov/airtrends/ozone.html*
  - *Evaluating Ozone Control Programs in the Eastern United States: Focus on the NO_x Budget Trading Program, 2004*
- O_3 monitor trends complicated by differences in…
  - Meteorological conditions
  - Changes in NO_x from sources besides power plants
  - Changes in VOC emissions
  - ➢ Model simulations needed to understand trends in surface O_3 observations
- Satellite observations suggest further reductions in eastern US NO_x levels will require controls on both mobile source *and* power plant emissions