Modeling the Atmospheric Transport and Deposition of Mercury to the Great Lakes

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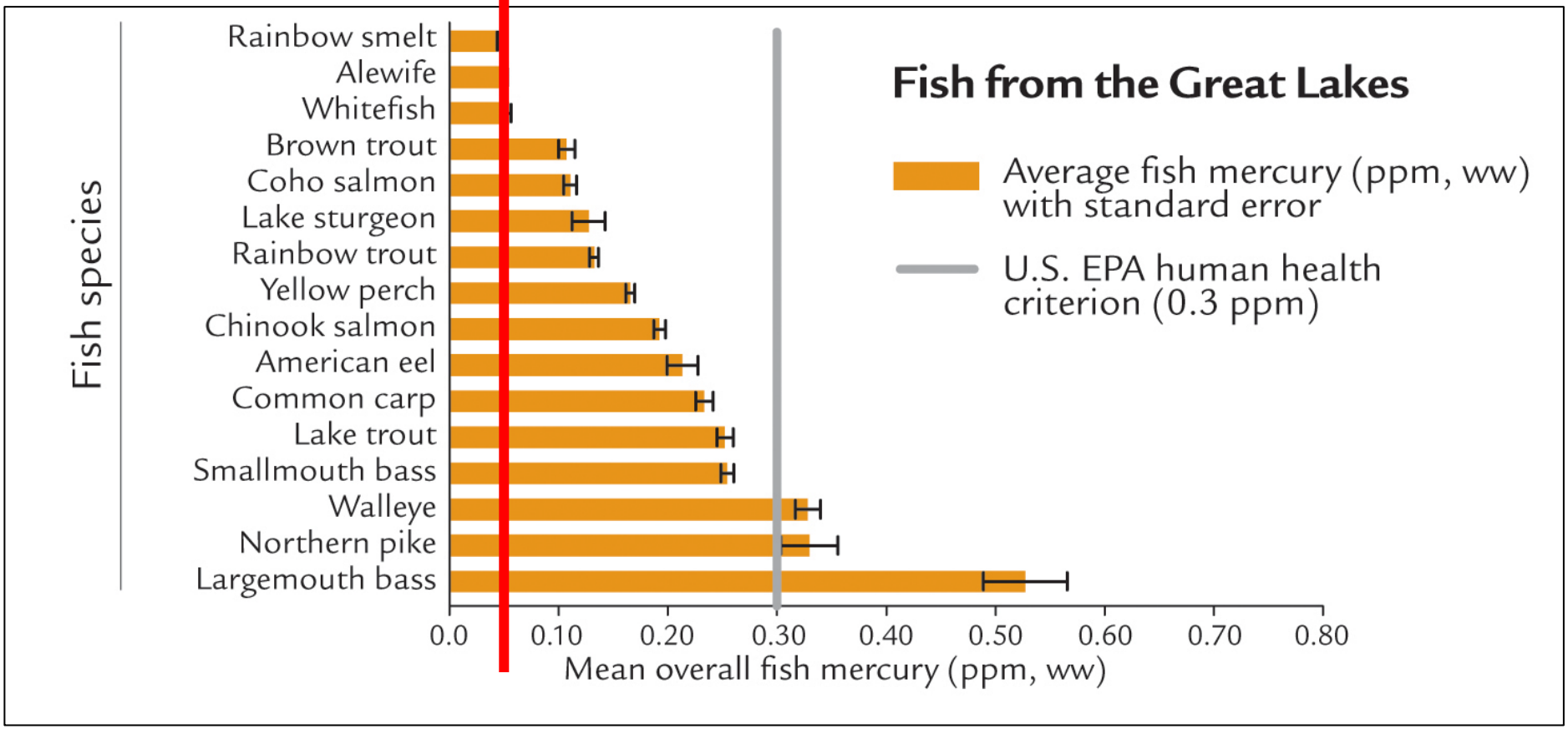
International Conference on Mercury as a Global Pollutant
July 28 – Aug 2, 2013, Edinburgh, Scotland

Mercury in Great Lakes Fish

0.05 ppm level recommended by the Great Lakes Fish Advisory Workgroup (2007)



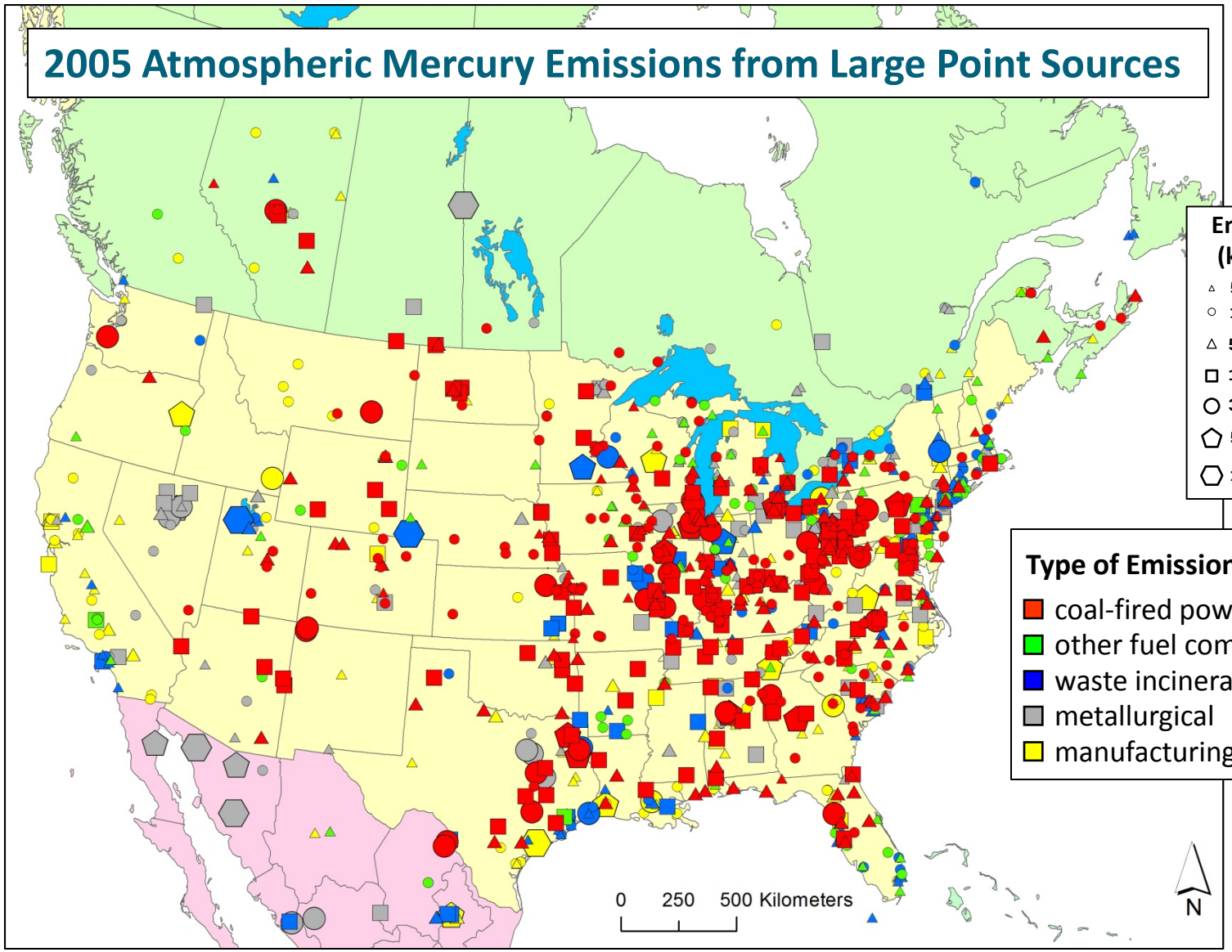
Evers, D.C., et al. (2011). *Great Lakes Mercury Connections: The Extent and Effects of Mercury Pollution in the Great Lakes Region*. Biodiversity Research Institute. Gorham, Maine. Report BRI 2011-18. 44 pages.

Atmospheric deposition is believed to be the largest current mercury loading pathway to the Great Lakes…

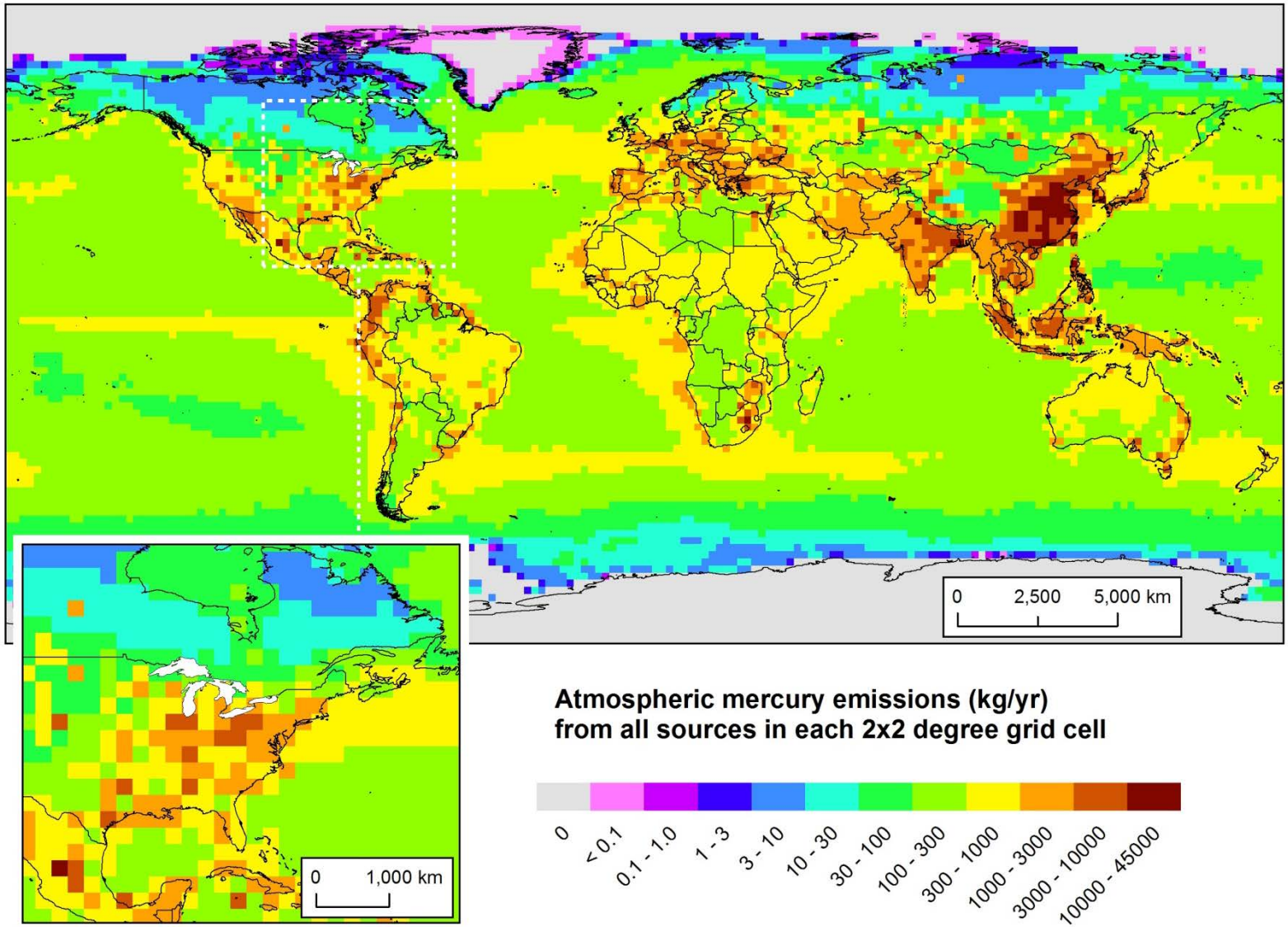
- **How much is deposited and where does it come from?**

(…this information can *only* be obtained via modeling...)

Starting point: where is mercury emitted to the air?



2005 Atmospheric Mercury Emissions (Direct Anthropogenic + Re-emit + Natural)



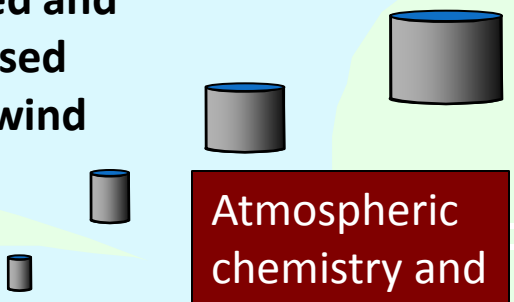
When puffs grow to sizes large relative to the meteorological data grid, they split, horizontally and/or vertically

To simulate the global transport of mercury, puffs are transferred Eulerian grid after a specified time downw (~3 weeks), and the mercury is simulated that grid from then on

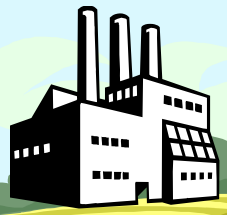
This is how we model the local & *regional* impacts.

But for *global* modeling, puff splitting overwhelms computational resources

Puffs of pollutant are emitted and dispersed downwind



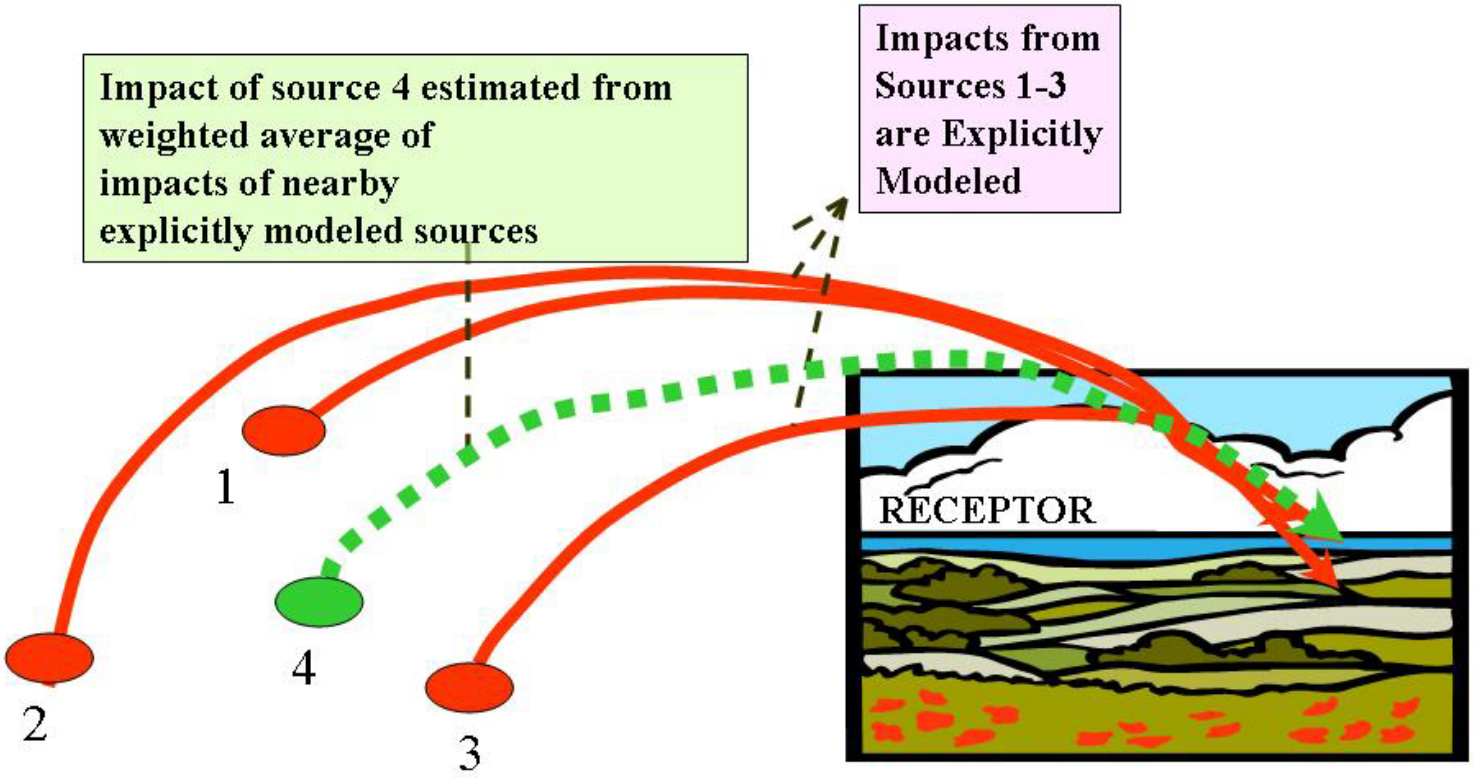
Atmospheric chemistry and deposition simulated for each puff



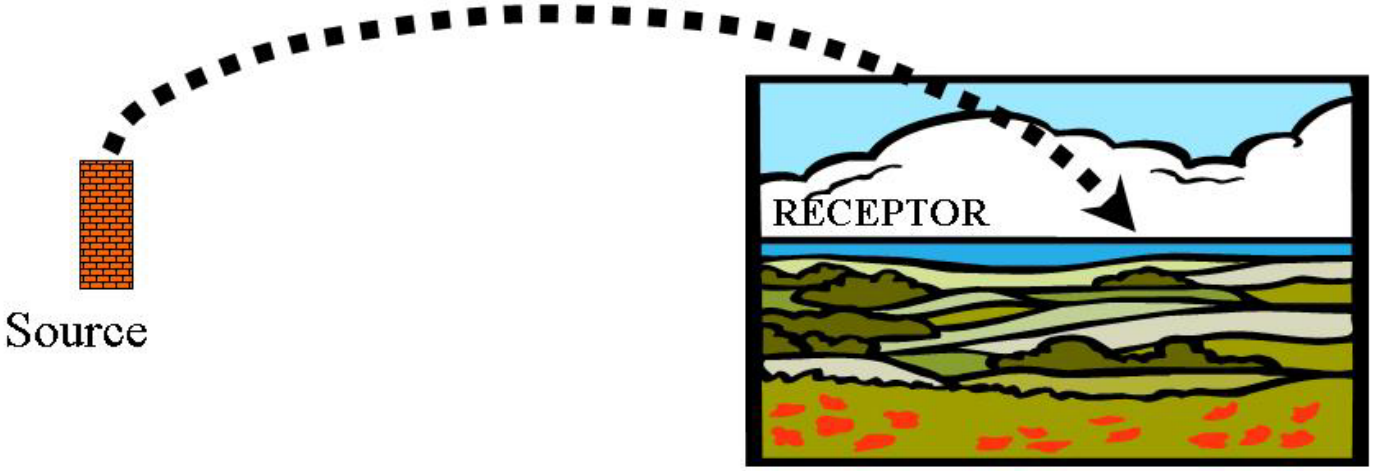
Computational Challenge

- **350,000 "sources" in global emissions inventory**
- **Would like to keep track of each source individually**
- **typical one-year simulation takes ~96 processor hours**
- **~3800 processor years, if ran explicit simulation for each source**
- **~240 years on 16-processor workstation**

Spatial Interpolation



Chemical Interpolation



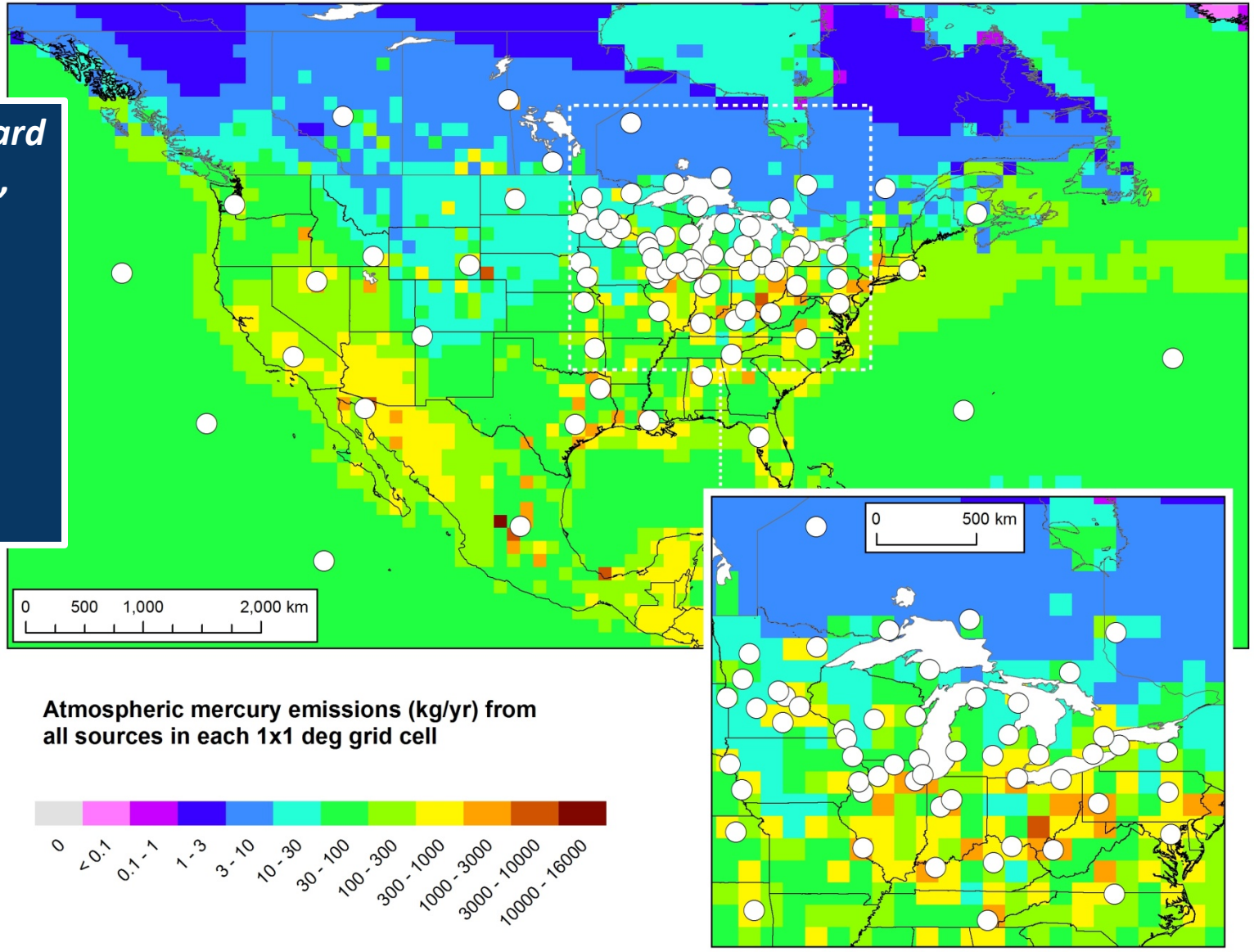
Impact of Source Emitting
30% Hg(0)
50% Hg(II)
20% Hg(p)

$$= 0.3 \times \text{Impact of Source Emitting Pure Hg(0)} + 0.5 \times \text{Impact of Source Emitting Pure Hg(II)} + 0.2 \times \text{Impact of Source Emitting Pure Hg(p)}$$

Standard Points in North America

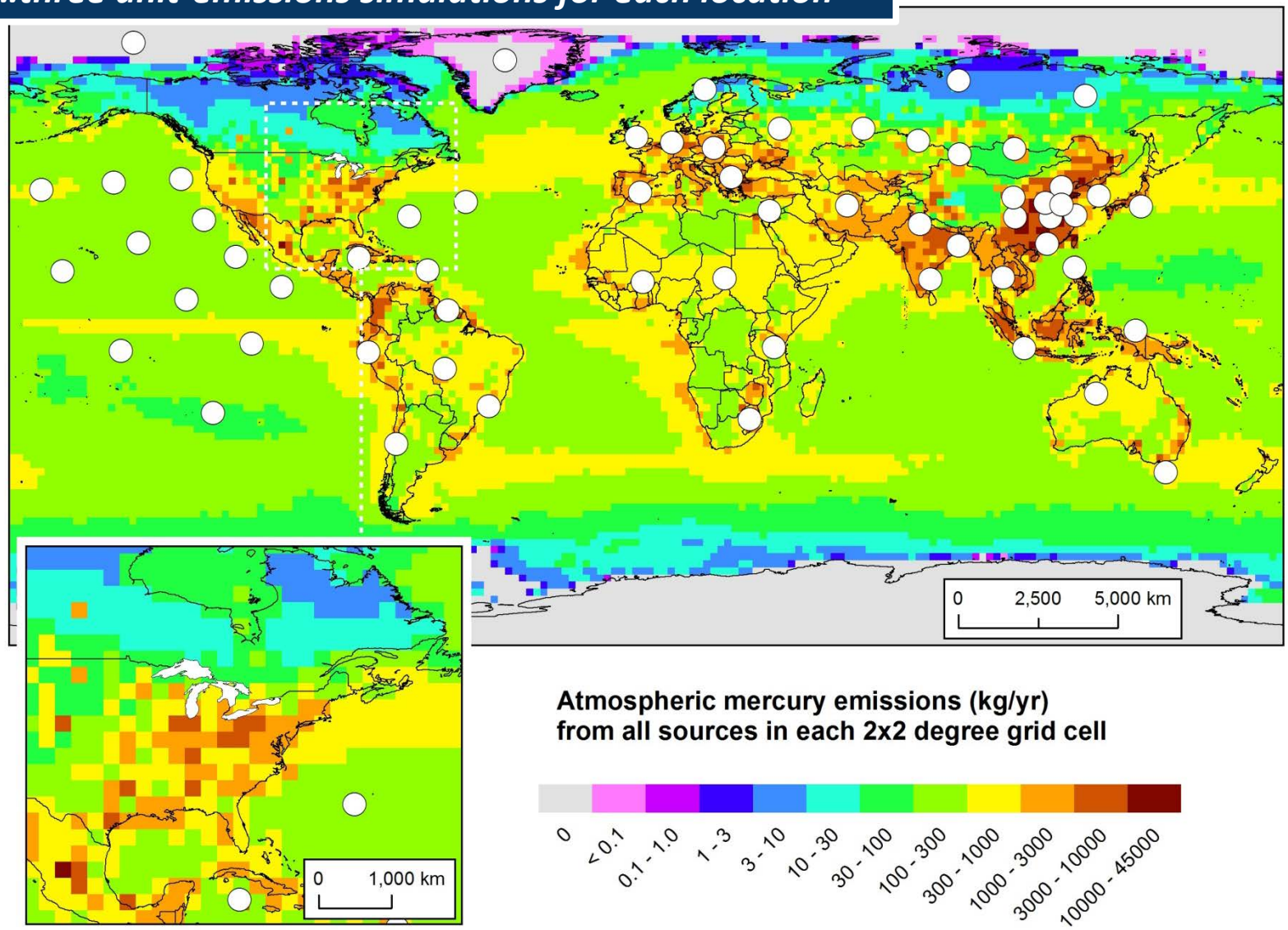
For each standard source location, we do three unit-emissions simulations:

- *pure Hg(0),*
- *pure HgII (RGM)*
- *pure Hg(p)*



Standard Points Outside of North America

…three unit-emissions simulations for each location



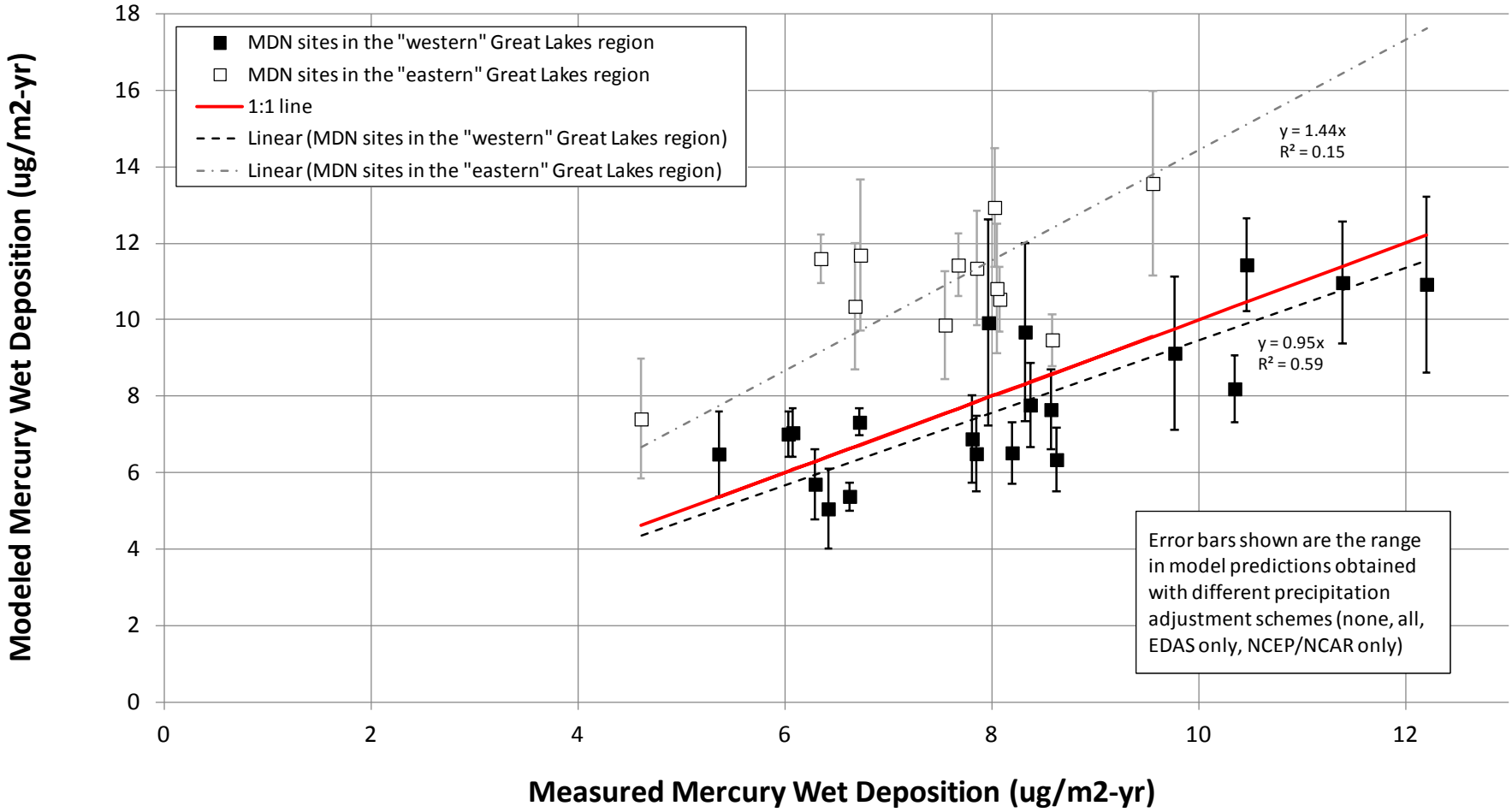
Computational Solution

- **This analysis done with 136 standard source locations**
  - **3 unit emissions simulations from each location (Hg(0), RGM, and Hg(p)**
    - **~4.5 processor years**
      - **~3.5 months on 16-processor workstation**

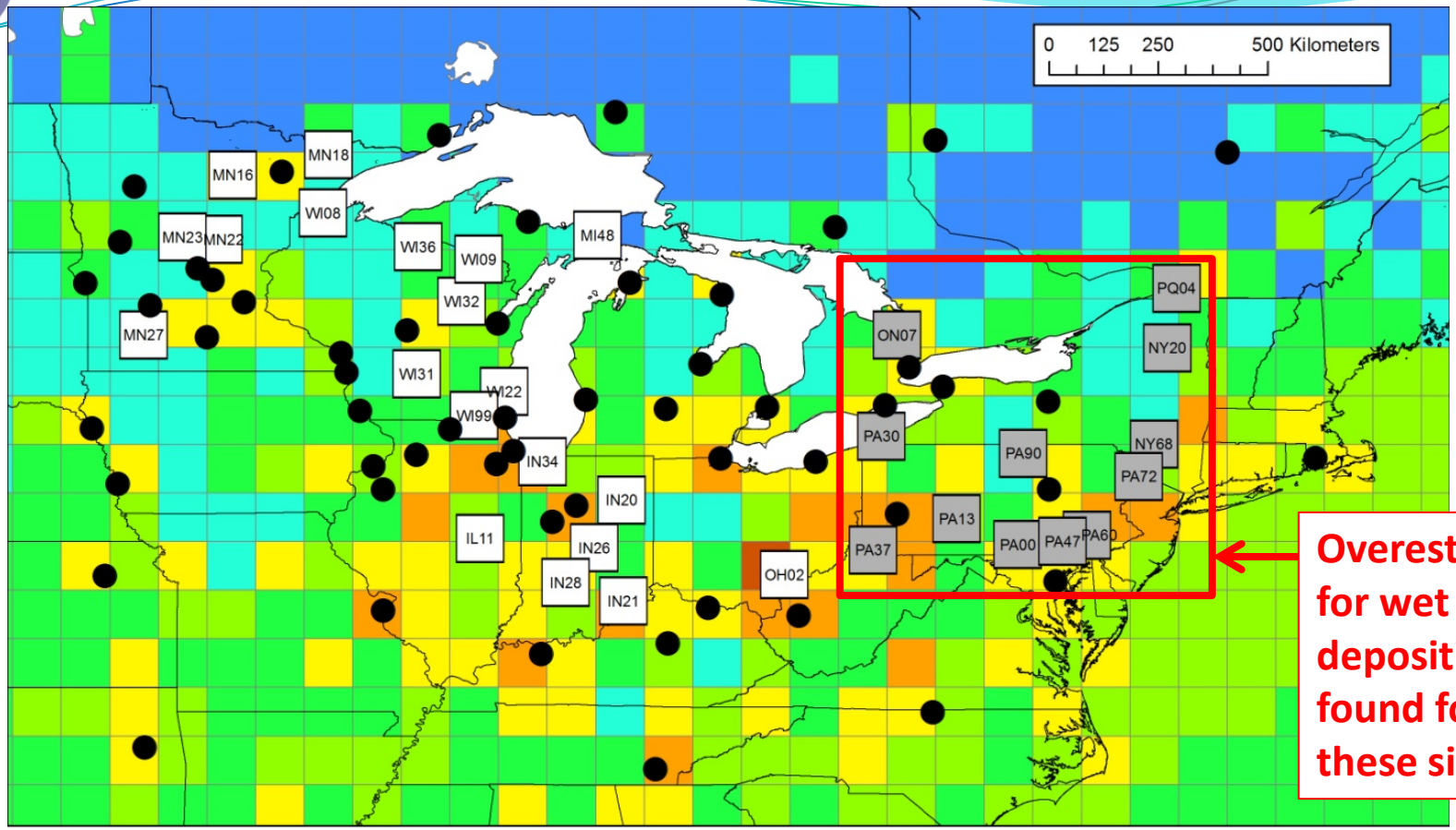
instead of 240 years … almost 1000x less!

After all the standard source simulations have been run, and the impacts of each of the ~350,000 sources worldwide are estimated using spatial and chemical interpolation, is the model giving reasonable results?

Modeled vs. Measured Wet Deposition of Mercury at Sites in the Great Lakes Region



Standard source locations, MDN sites, and mercury emissions in the Great Lakes region



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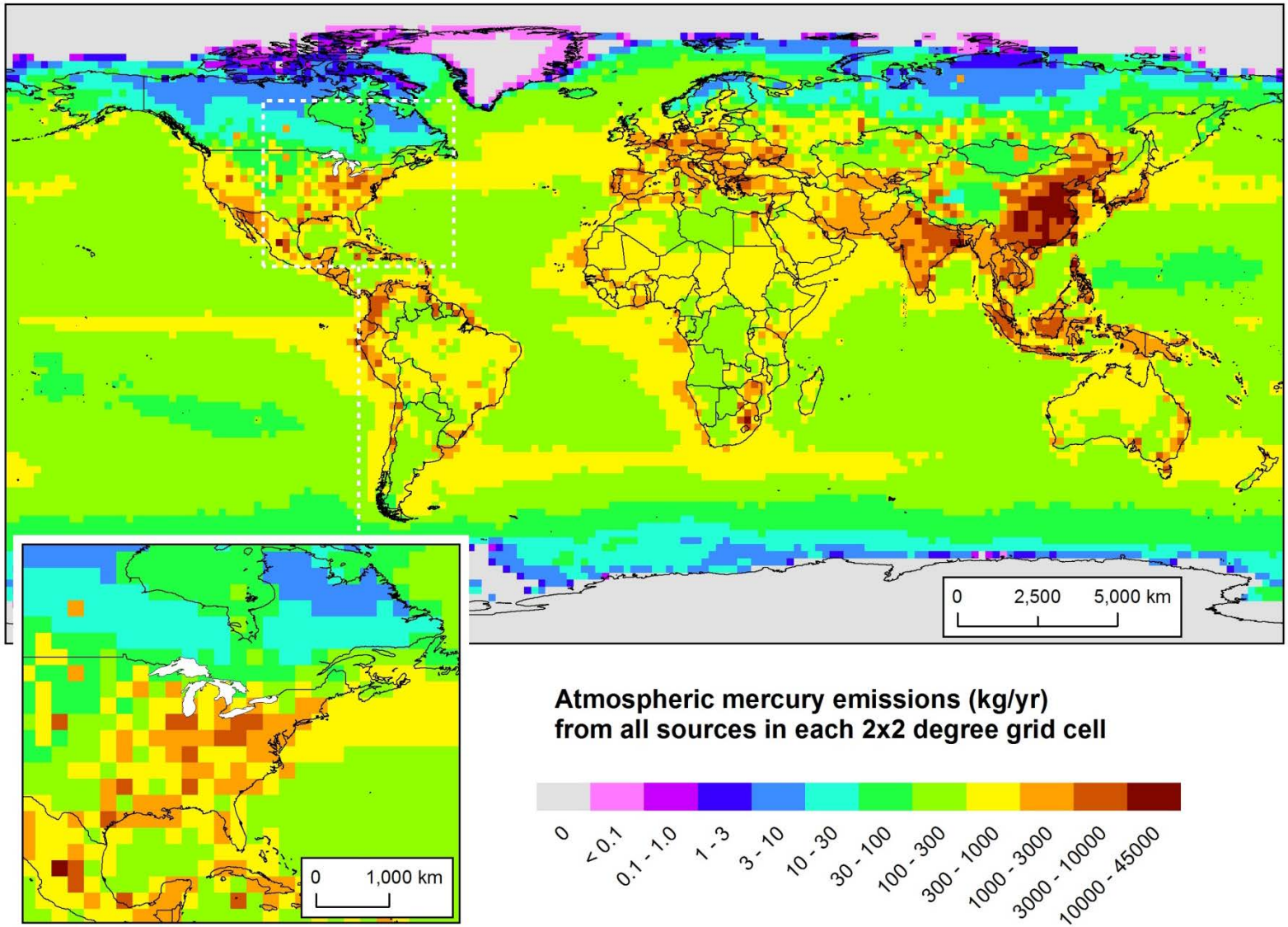
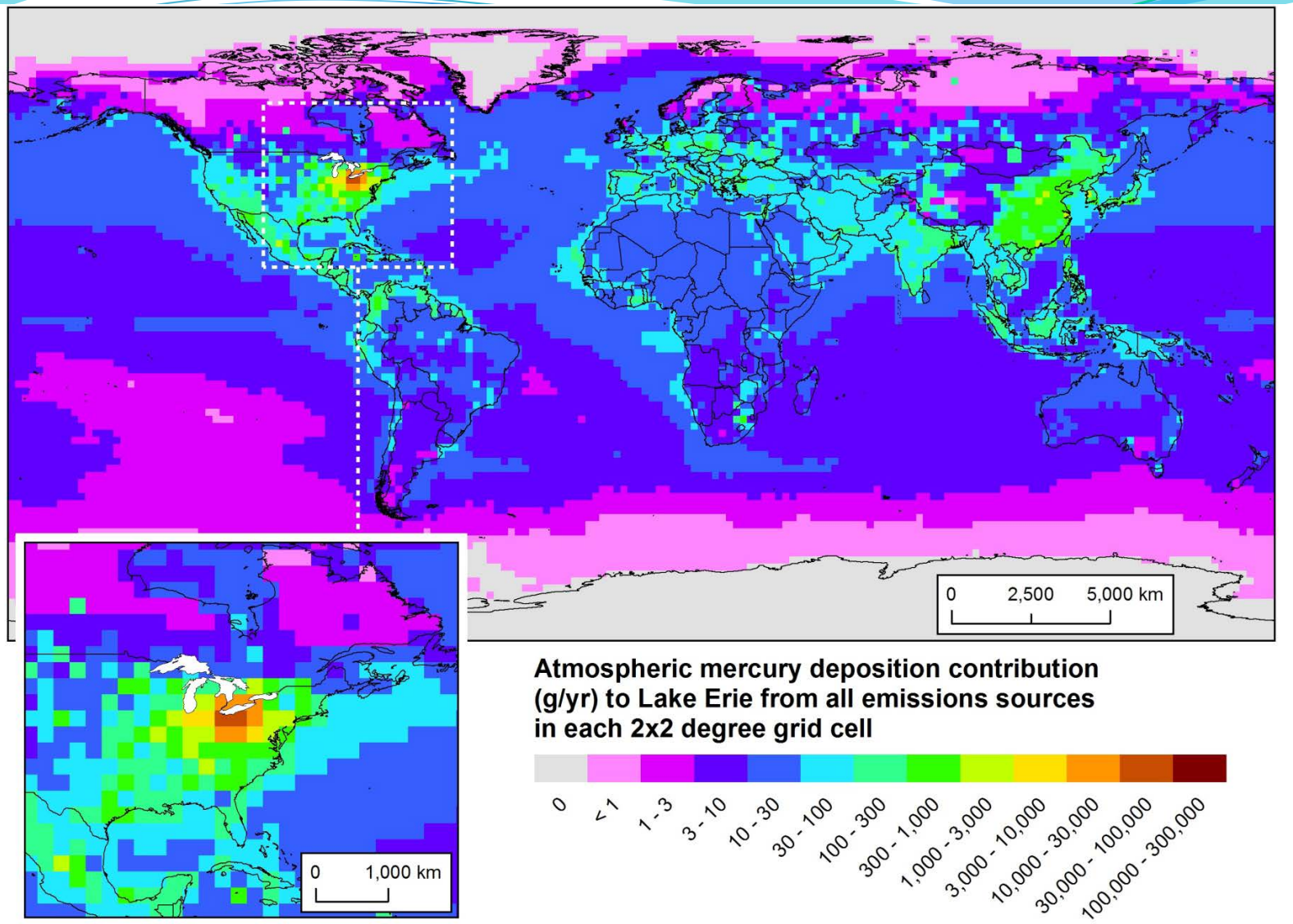


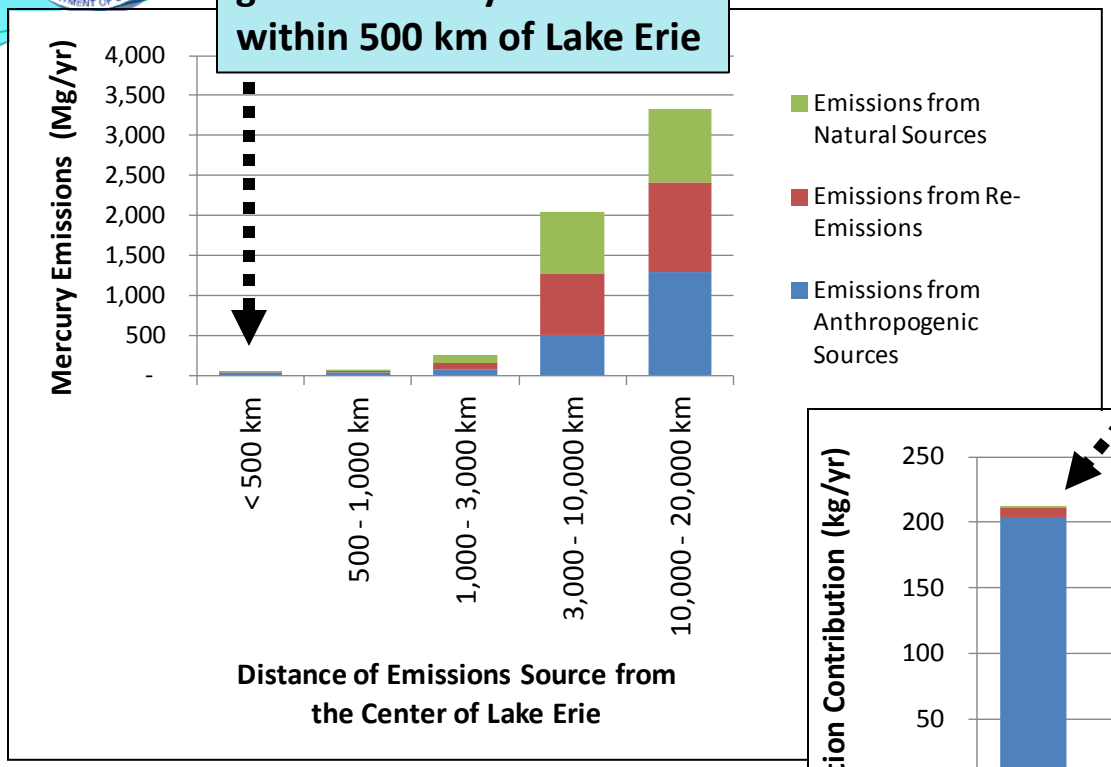
Keep track of the contributions from each source, and add them up



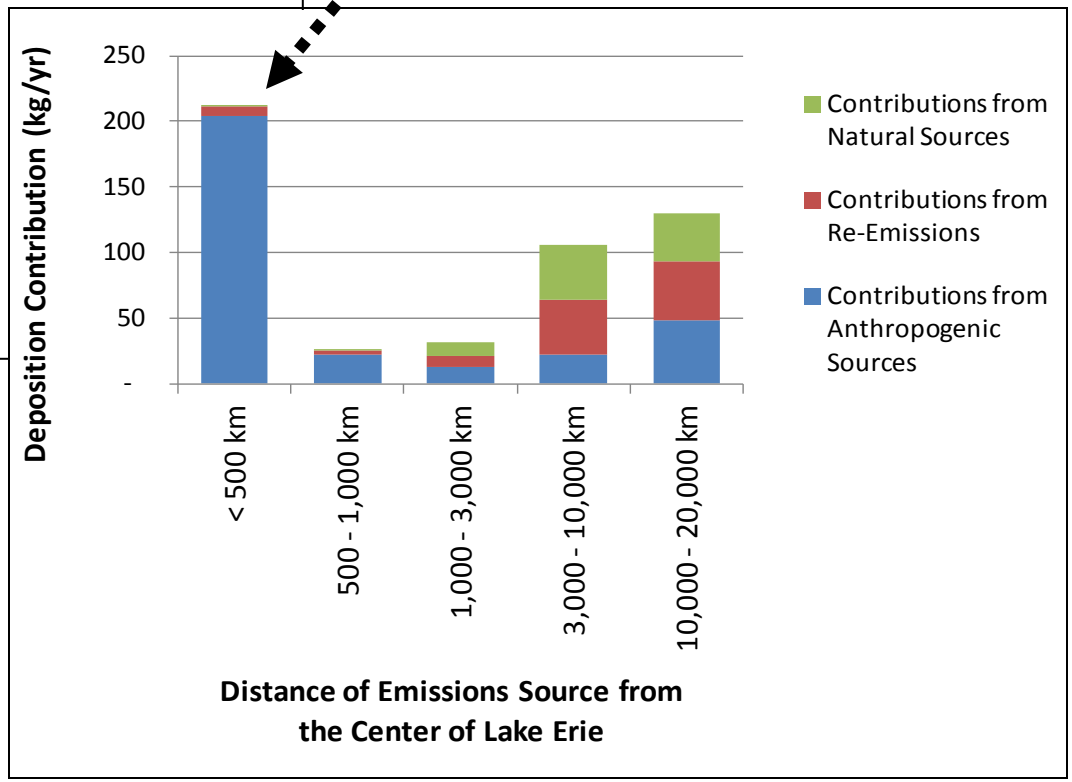
Geographical Distribution of 2005 Atmospheric Mercury Deposition Contributions to Lake Erie

Results can be shown in many ways…

A tiny fraction of 2005 global mercury emissions within 500 km of Lake Erie

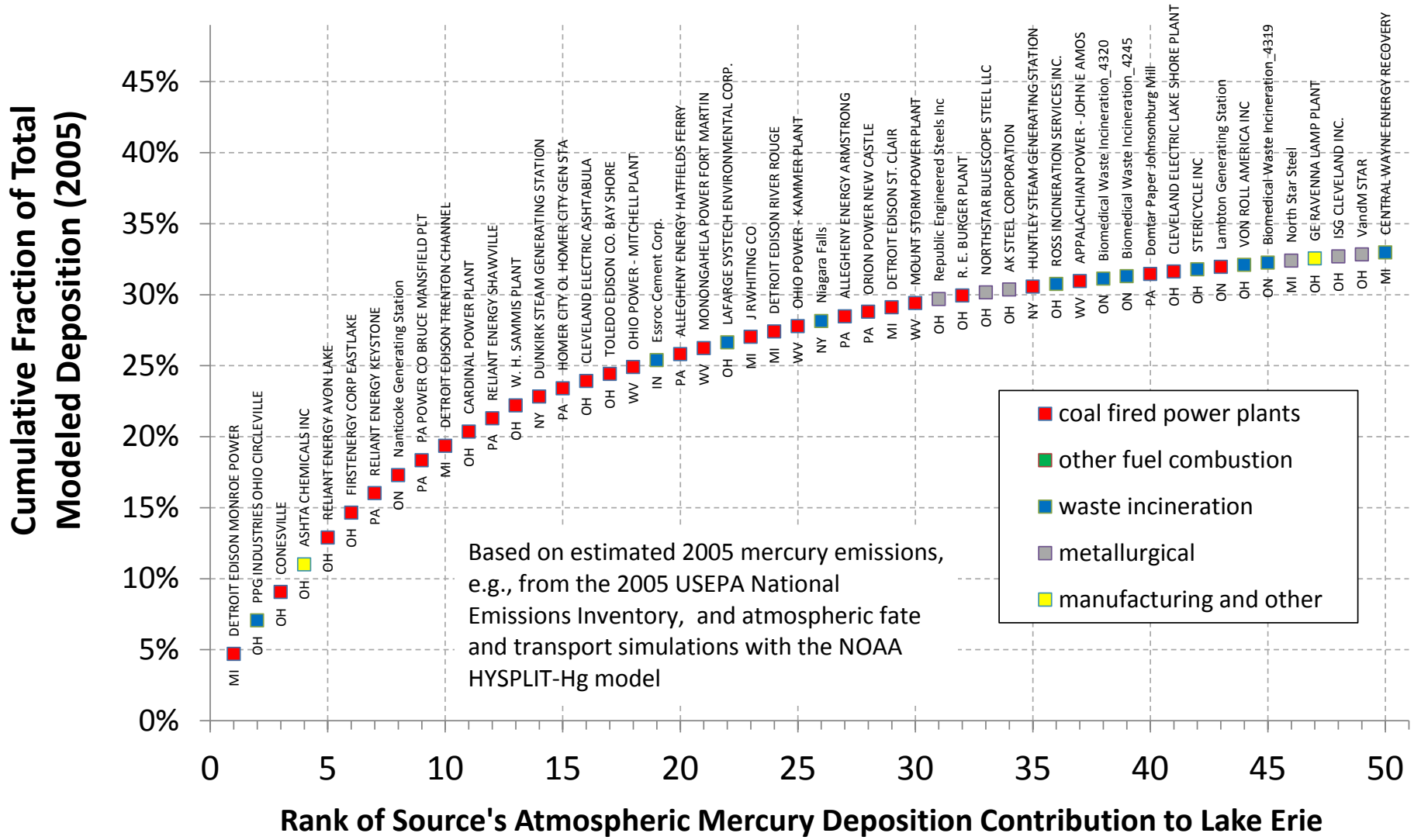


Modeling results show that these "regional" emissions are responsible for a large fraction of the modeled 2005 atmospheric deposition

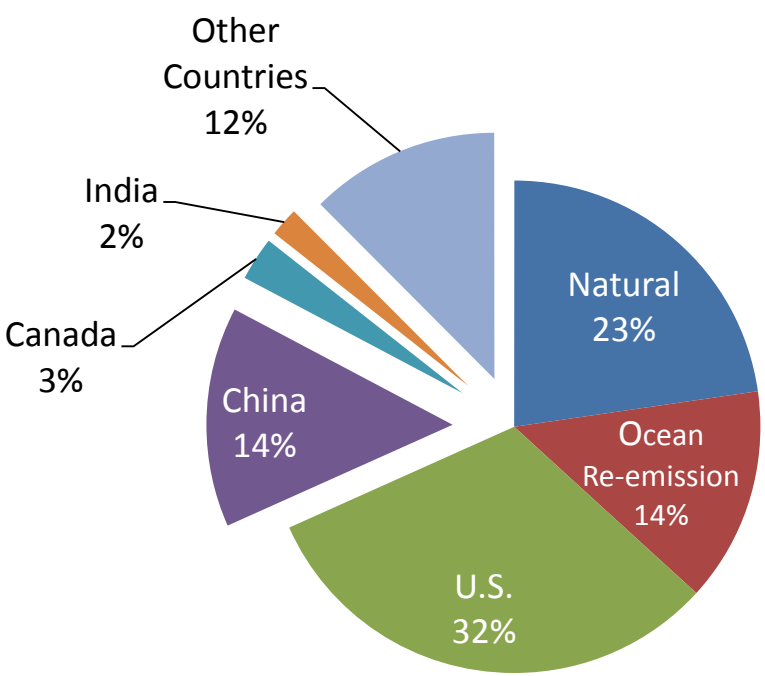


Important policy implications!

Top 50 Atmospheric Deposition Contributors to Lake Erie

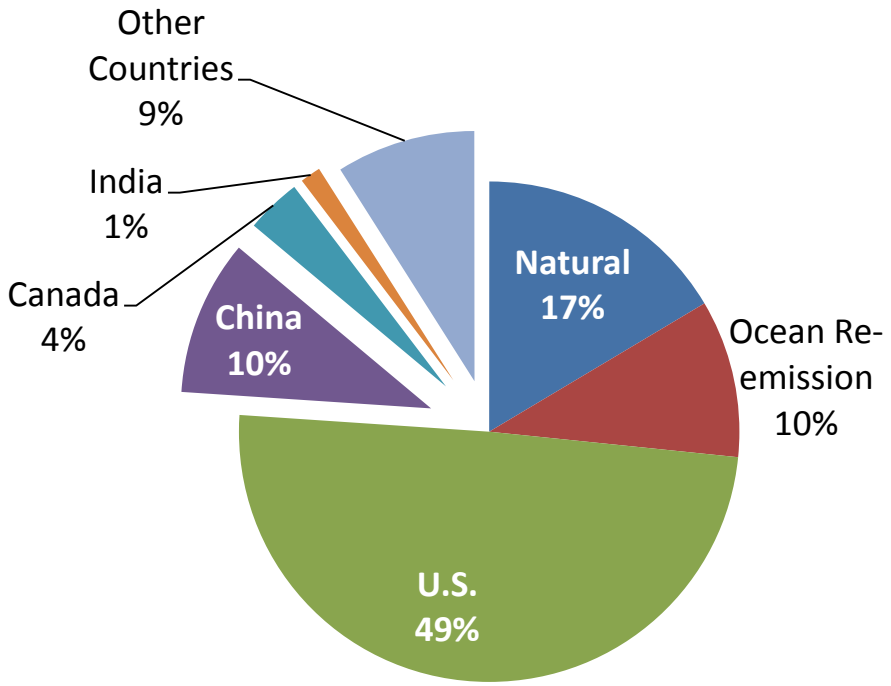


Sources of Mercury Deposition to the Great Lakes Basin 2005 Baseline Analysis



Total = 11,300 kg/yr

Sources of Mercury Deposition to the Lake Erie Basin 2005 Baseline Analysis

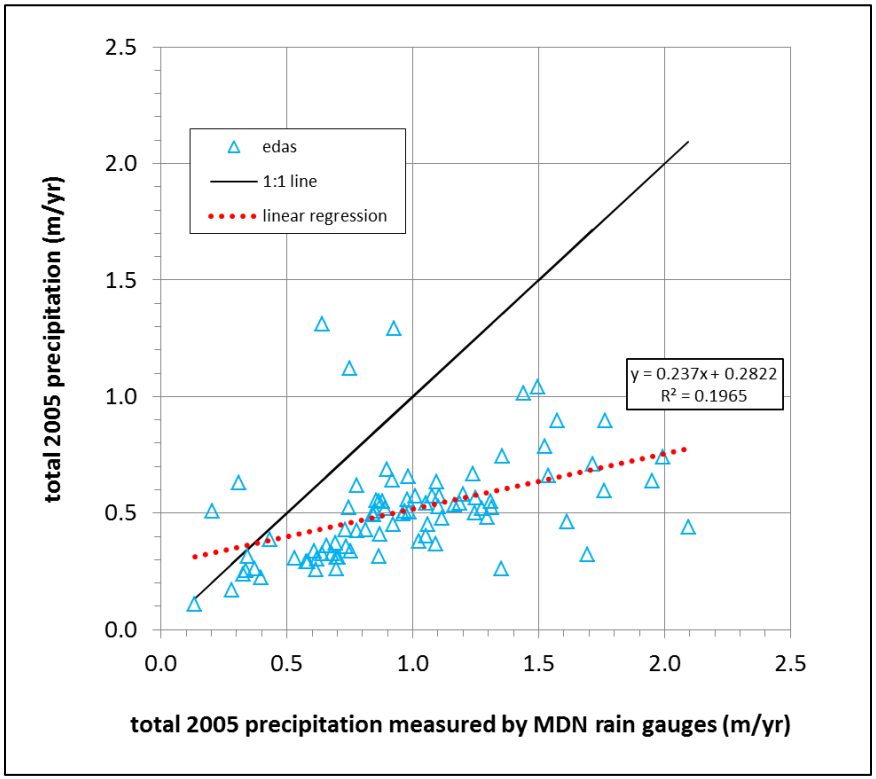


Total = 2,300 kg/yr

Comparison of precipitation measured by rain gauges at Mercury Deposition Network sites with that in the EDAS and NARR meteorological datasets used to drive the HYSPLIT-Hg model

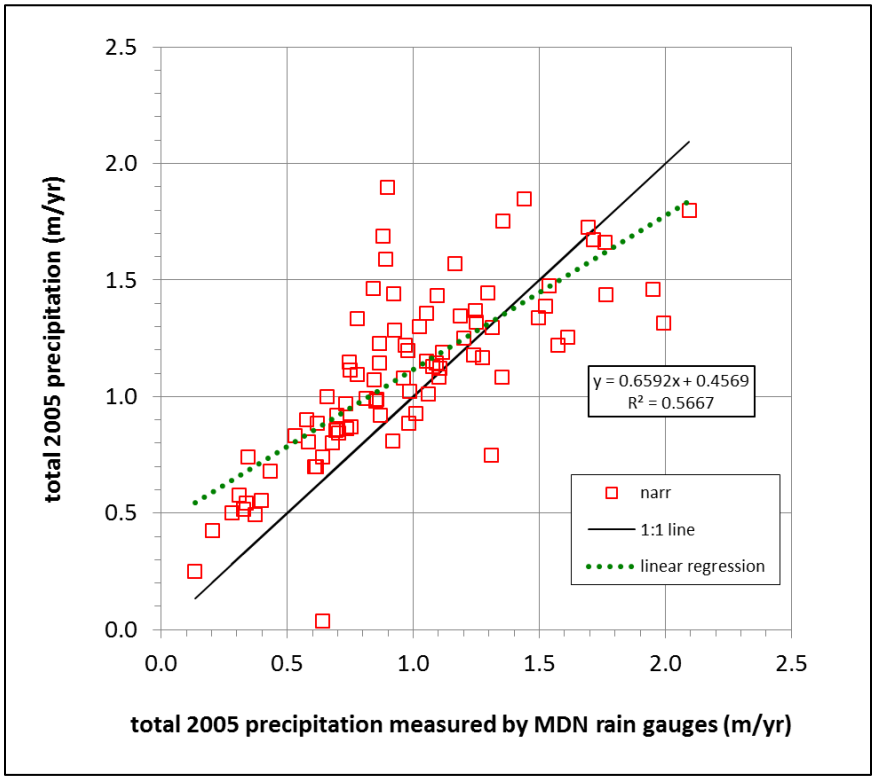
EDAS

used in Phase 1 baseline analysis

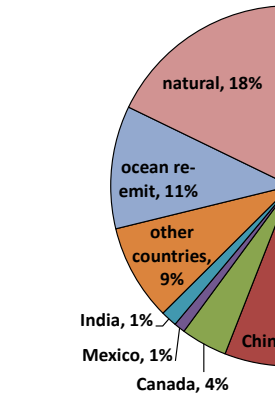


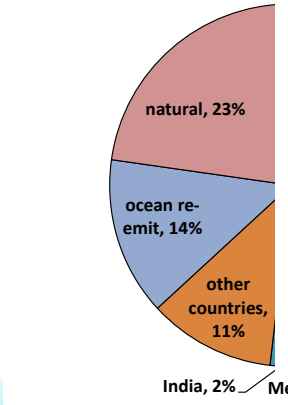
NARR

used in Phase 2 sensitivity analysis

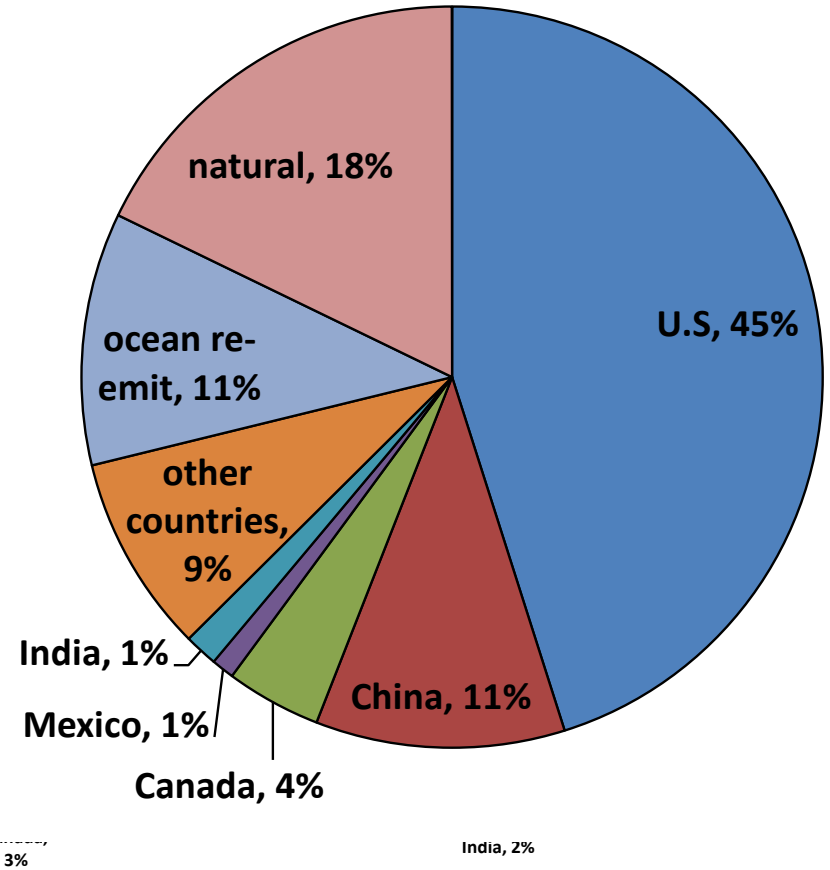


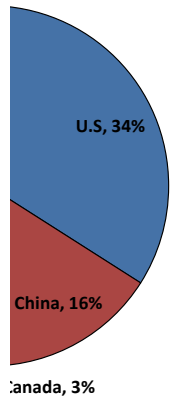
Overall source attribution results not changed dramatically for Lake Erie (top) or the Great Lakes Basin (bottom) for largest variations in modeling methodology; 2005 baseline (left); variations (center & right)

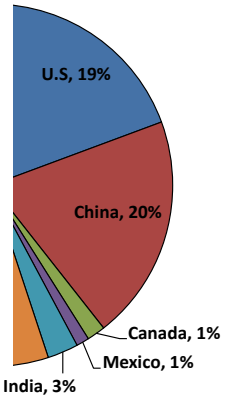




Contributions to 2005 Atmospheric Mercury Deposition to Lake Erie (EDAS met data)







Thanks!

This work was partially funded through the Great Lakes Restoration Initiative

Great Lakes RESTORATION

EXTRA SLIDES

Atmospheric Mercury Deposition to the Great Lakes
A Multi-Year Study Supported by the Great Lakes Restoration Initiative

- Phase 1: Baseline analysis for 2005
  - Used "EDAS" meteorological data
  - One set of model parameters and emissions data
  - Summary: *http://www.arl.noaa.gov/documents/reports/GLRI_Atmos_Mercury_Summary.pdf*
  - Final Report: *http://www.arl.noaa.gov/documents/reports/GLRI_FY2010_Atmospheric_Mercury_Final_Report_2011_Dec_16.pdf*
  - Recent Presentation: *http://www.arl.noaa.gov/documents/reports/Cohen_ARL_Seminar_Feb_7_2013.pptx*
- Phase 2: Sensitivity analysis
  - Used "NARR" meteorological data
  - Numerous variations of model parameters and emissions data
  - Overall results – even for largest variations found – not changed dramatically (see pie charts below)
  - Conclusion: results are robust
  - Final Report being prepared
- Phase 3: Analysis of alternative future emissions scenarios
  - Work is beginning on this policy-relevant analysis
- Phase 4: Updates to more recent years
  - To start when FY13 GLRI funding received

Acknowledgements

Other members of HYSPLIT Model Development Team at ARL:
Glenn Rolph
Barbara Stunder
Ariel Stein
Fantine Ngan

Other members of Mercury Research Team at ARL:
Winston Luke
Paul Kelley
Steve Brooks
Xinrong Ren

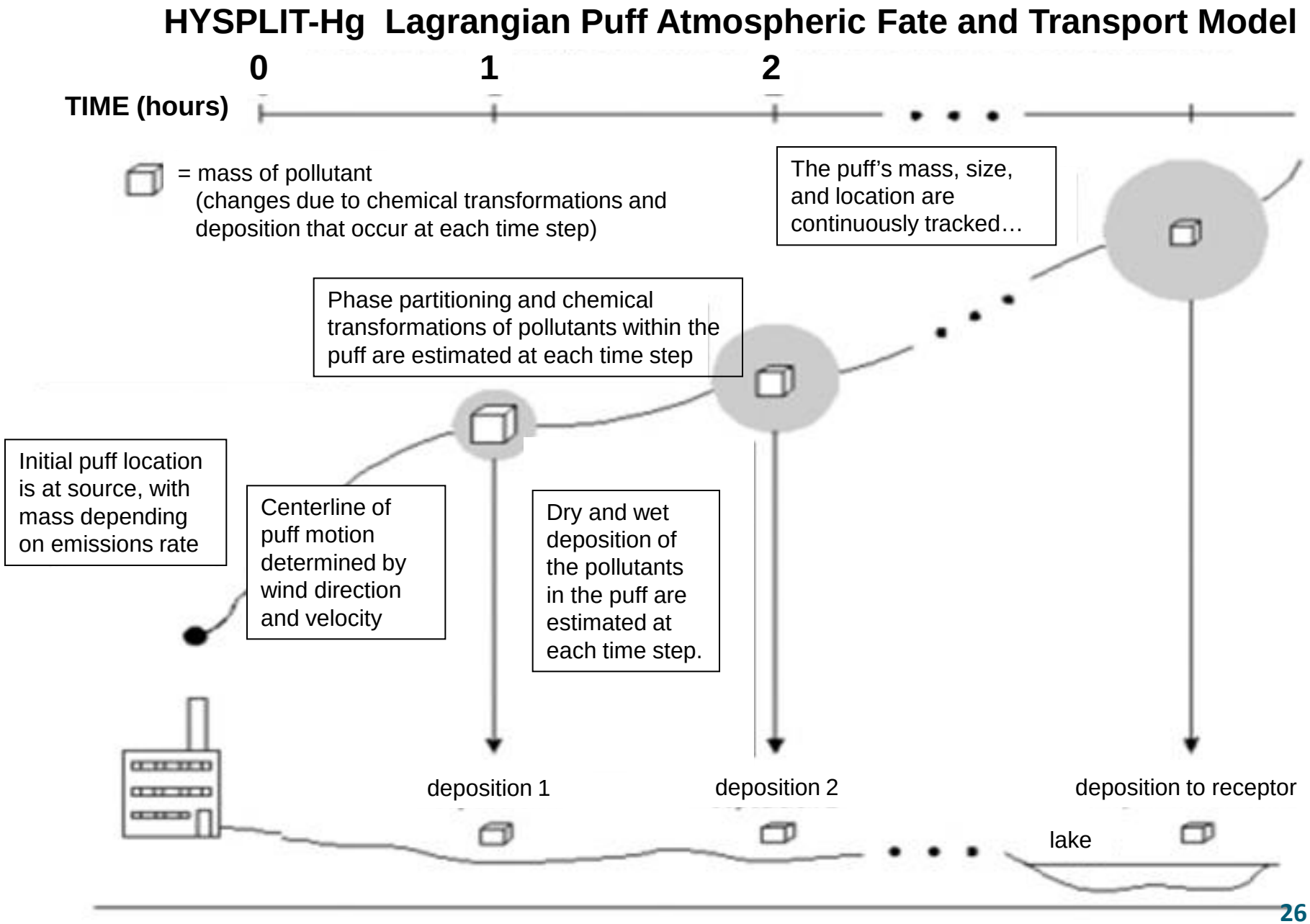
IT Team at ARL:
Rick Jiang
Yan Huang

Funding:
Great Lakes Restoration Initiative, via Interagency Agreement with USEPA

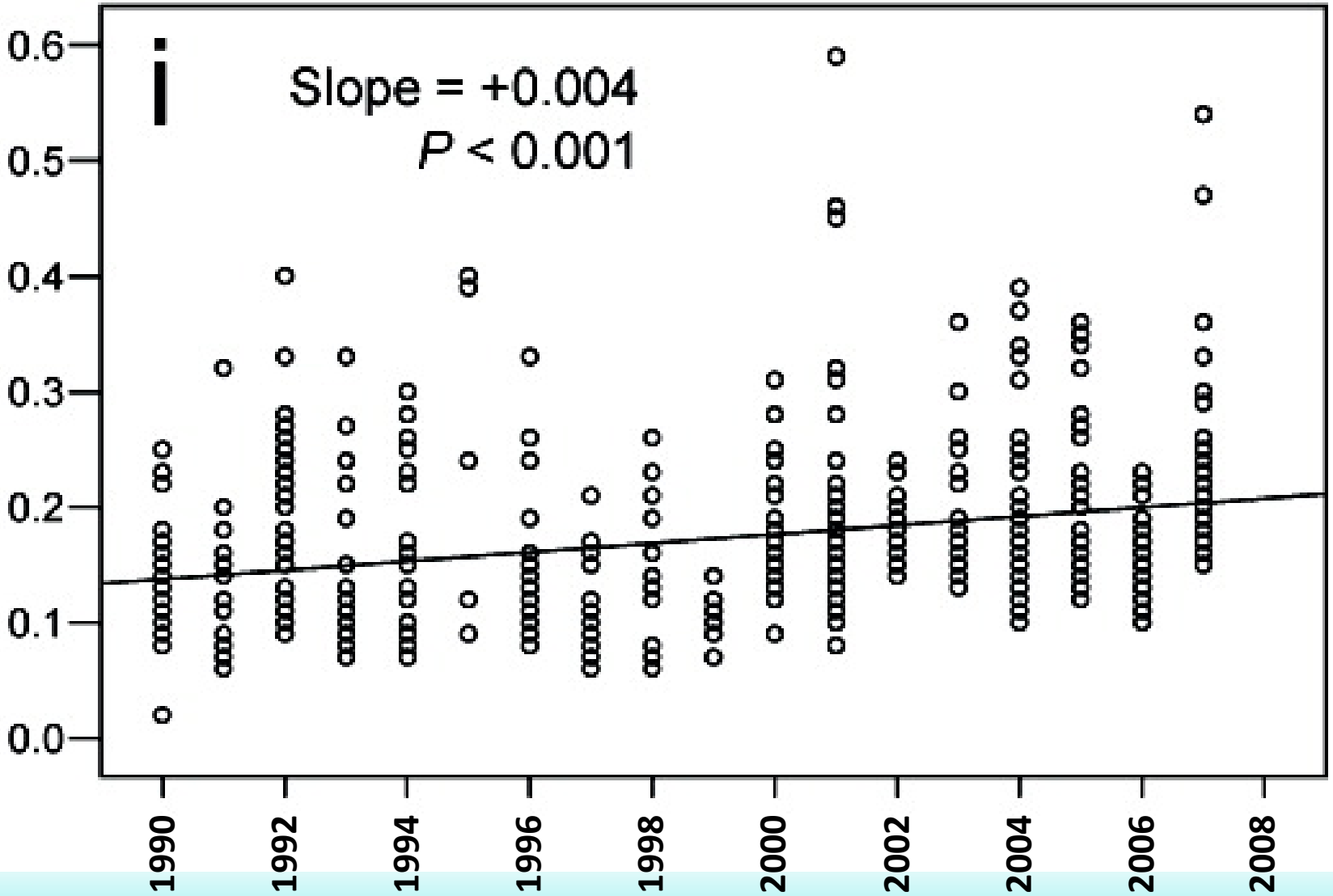
+ numerous collaborations with external partners involving:

- emissions inventory data for model input, and
- atmospheric measurement data for model evaluation

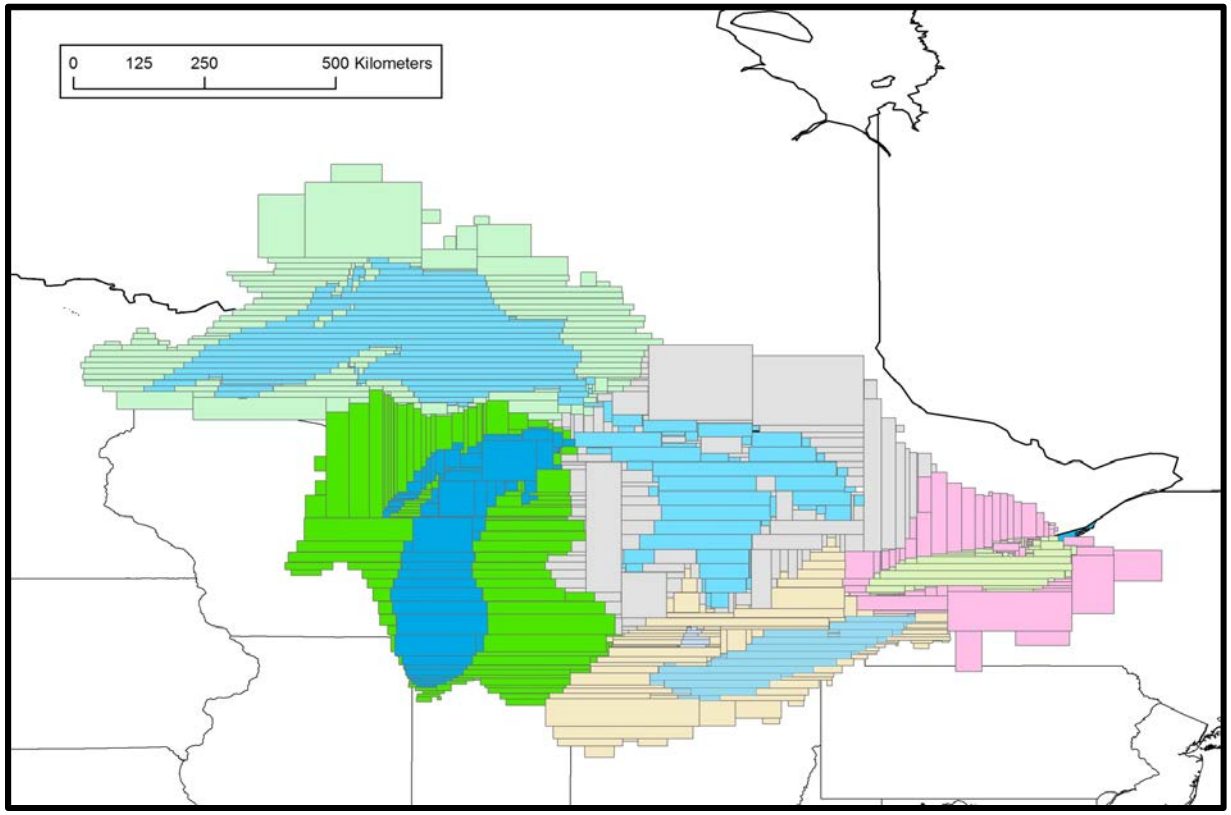
Next step: What happens to the mercury after it is emitted?



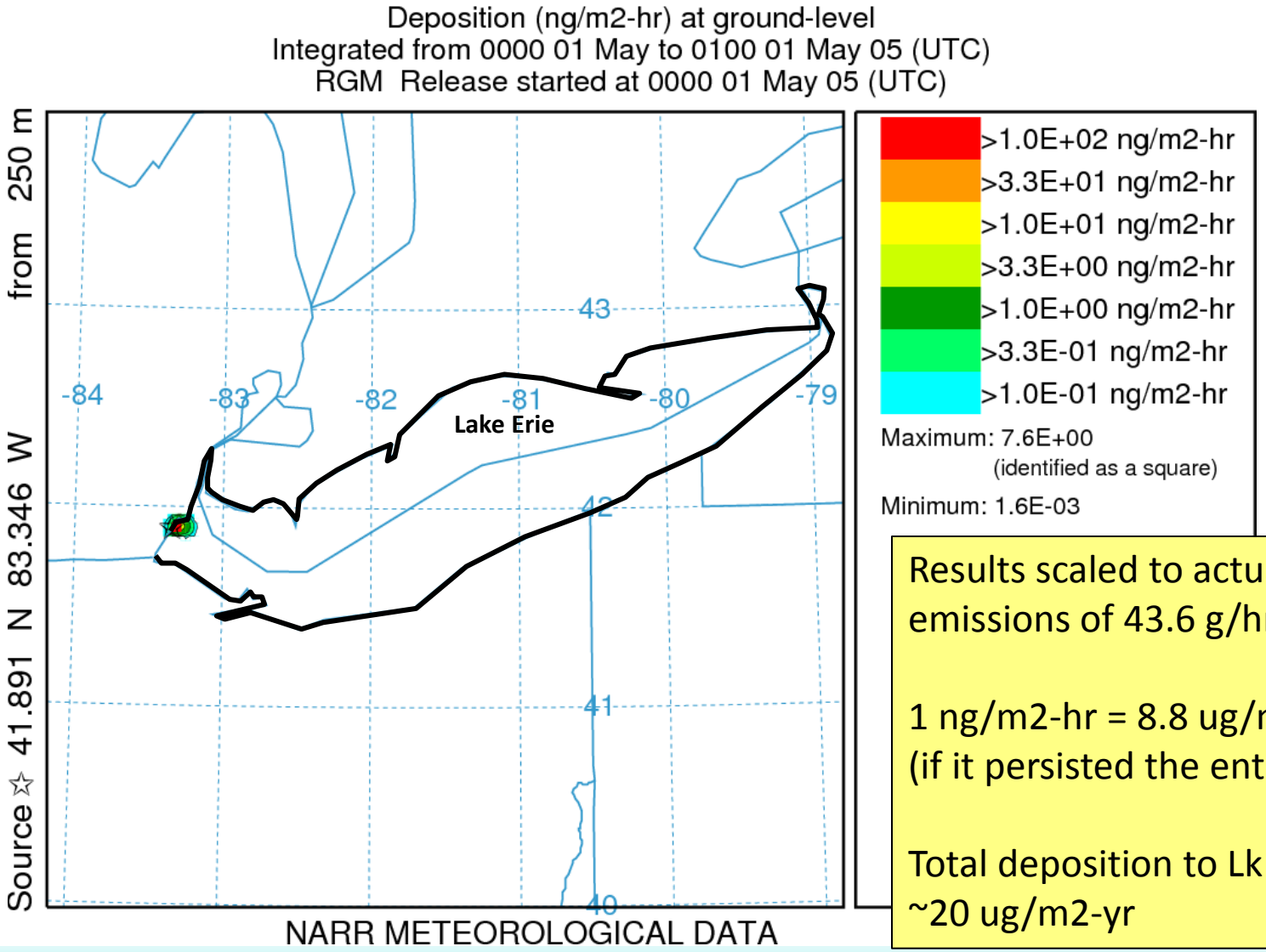
Temporal trends of mercury in Lake Erie
45–55 cm walleye collected between 1990–2007
{Bhavsar et al. (2010), *Environ. Sci. Technol.* 44, 3273-3279}



- **Deposition explicitly modeled to actual lake/watershed areas**
  - As opposed to the usual practice of ascribing portions of gridded deposition to these areas in a post-processing step



Illustrative simulation of reactive gaseous mercury (RGM) emissions from one power plant on the shore of Lake Erie: hourly deposition estimates for the first two weeks in May 2005

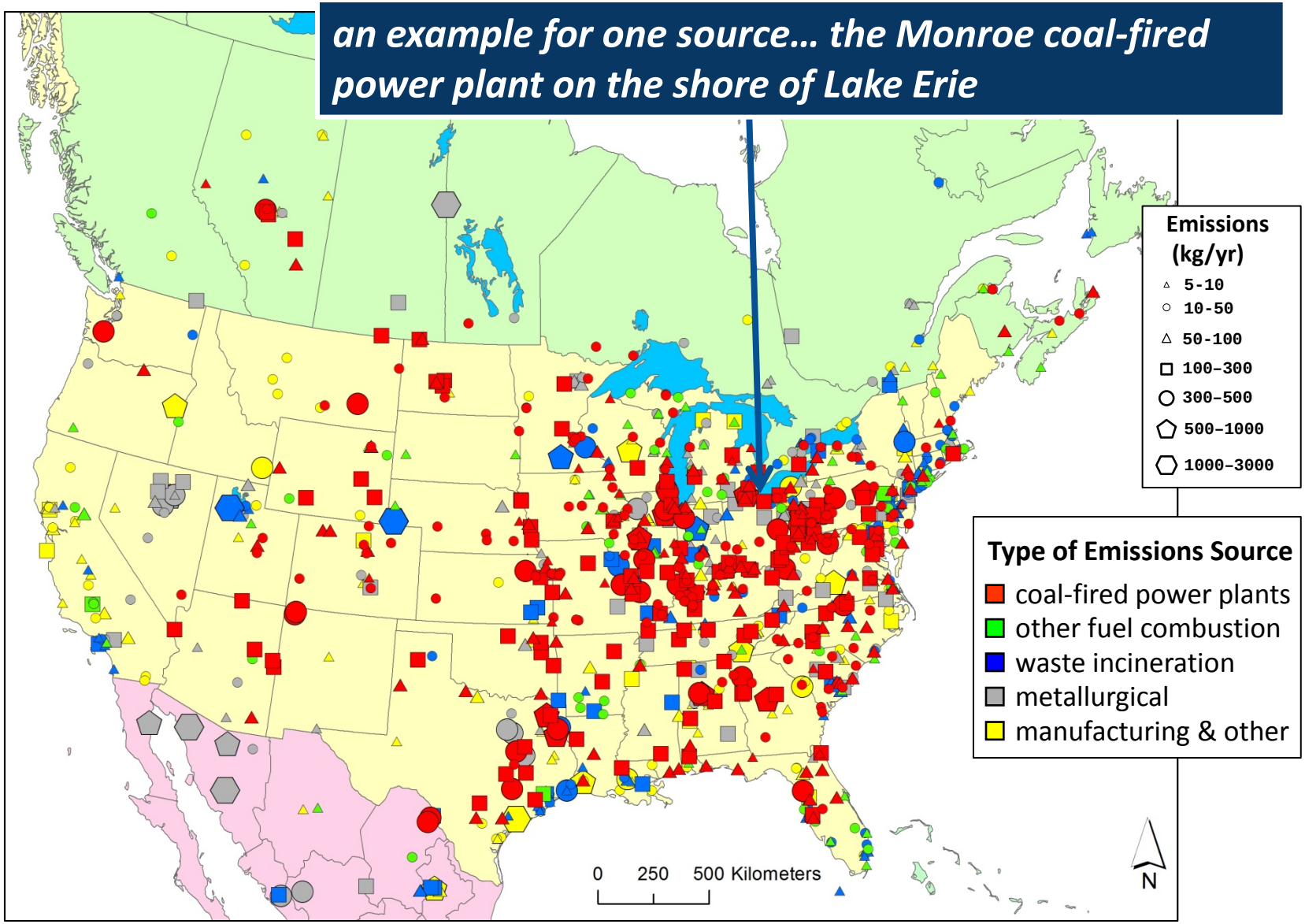


Results scaled to actual RGM emissions of 43.6 g/hr

1 ng/m2-hr = 8.8 ug/m2-yr
(if it persisted the entire year)

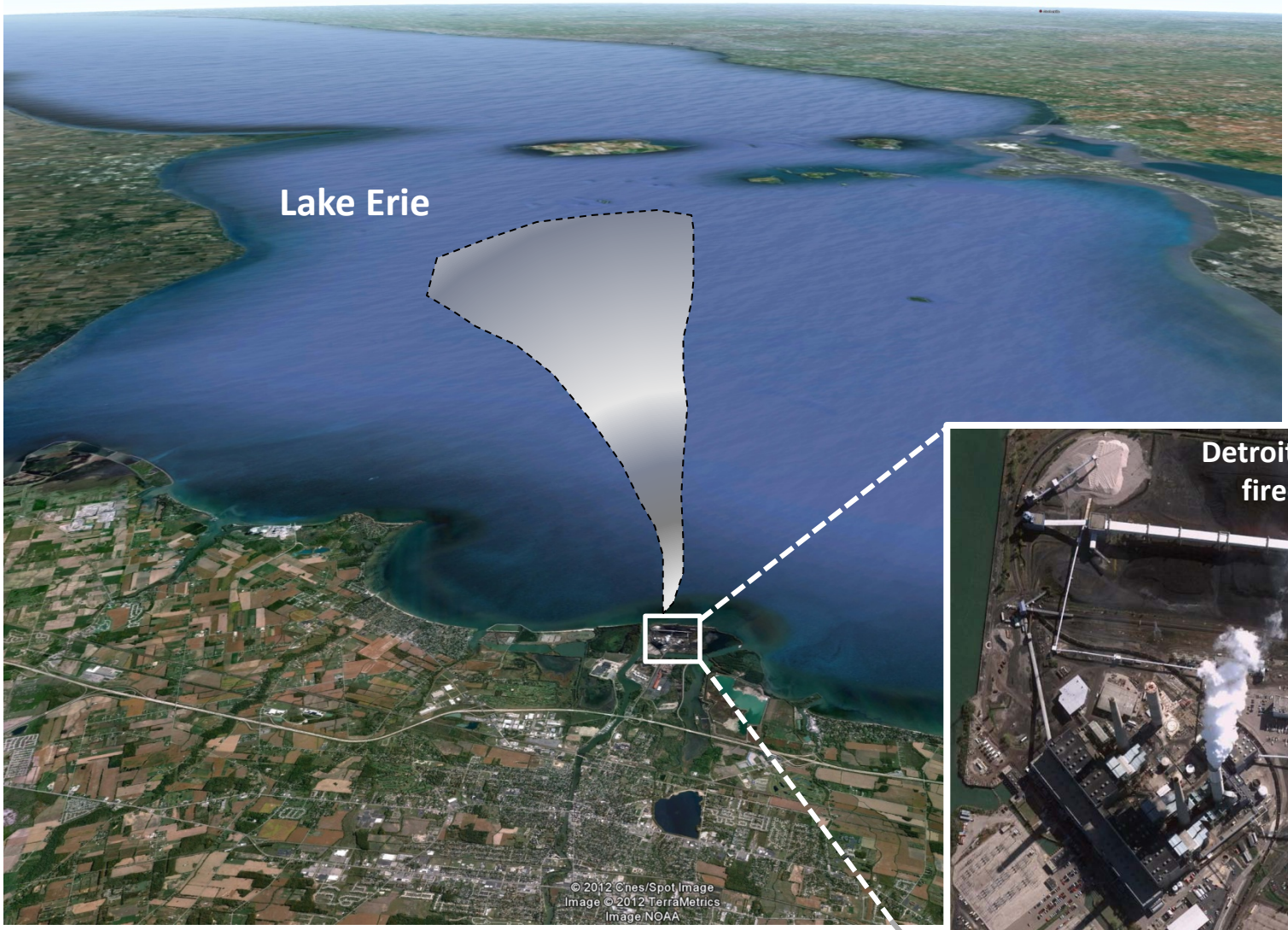
Total deposition to Lk Erie is ~20 ug/m2-yr

an example for one source… the Monroe coal-fired power plant on the shore of Lake Erie

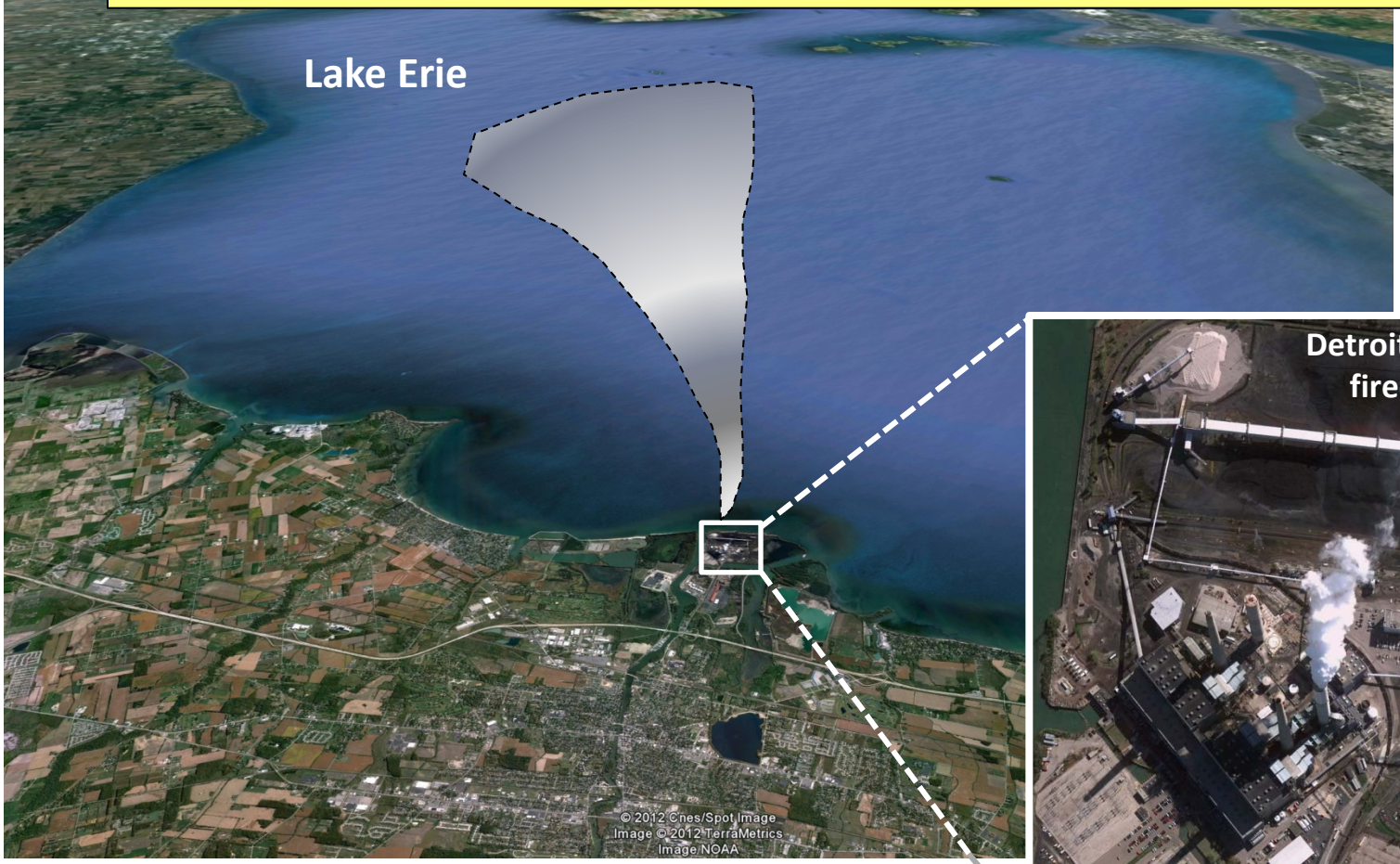


2005 Atmospheric Mercury Emissions from Large Point Sources

- Monroe emitted 561 kg of mercury in 2005 (EPA's National Emissions Inventory)
- How much of this mercury was deposited into Lake Erie and its watershed?



- Monroe emitted 561 kg of mercury in 2005 (EPA's National Emissions Inventory)
- Modeling results for this specific source:
  - 24 kg (~4%) of this emitted mercury was deposited directly into Lake Erie
  - 107 kg (~19%) of this emitted mercury was deposited in the Lake Erie Watershed
- We make this same type of estimate for *every source* in the national and global emissions inventories used as model input… *using spatial and chemical interpolation*



Outline of Modeling Analysis

- **HYSPLIT**
- **HYSPLIT-Hg** (with mercury-specific chemistry, …)
- **Unit Emissions Simulations** of Hg(0), Hg(II) and Hg(p) from an array of standard source locations
- **Emissions Inventory** – emissions of Hg(0), Hg(II), and Hg(p) from sources at specified latitudes and longitudes
- **"Multiplication"** of emissions inventory by array of unit emissions simulations using spatial and chemical interpolation

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- **Evaluate** overall model results: compare against ambient measurements
- **Source-attribution** results for deposition to selected receptors

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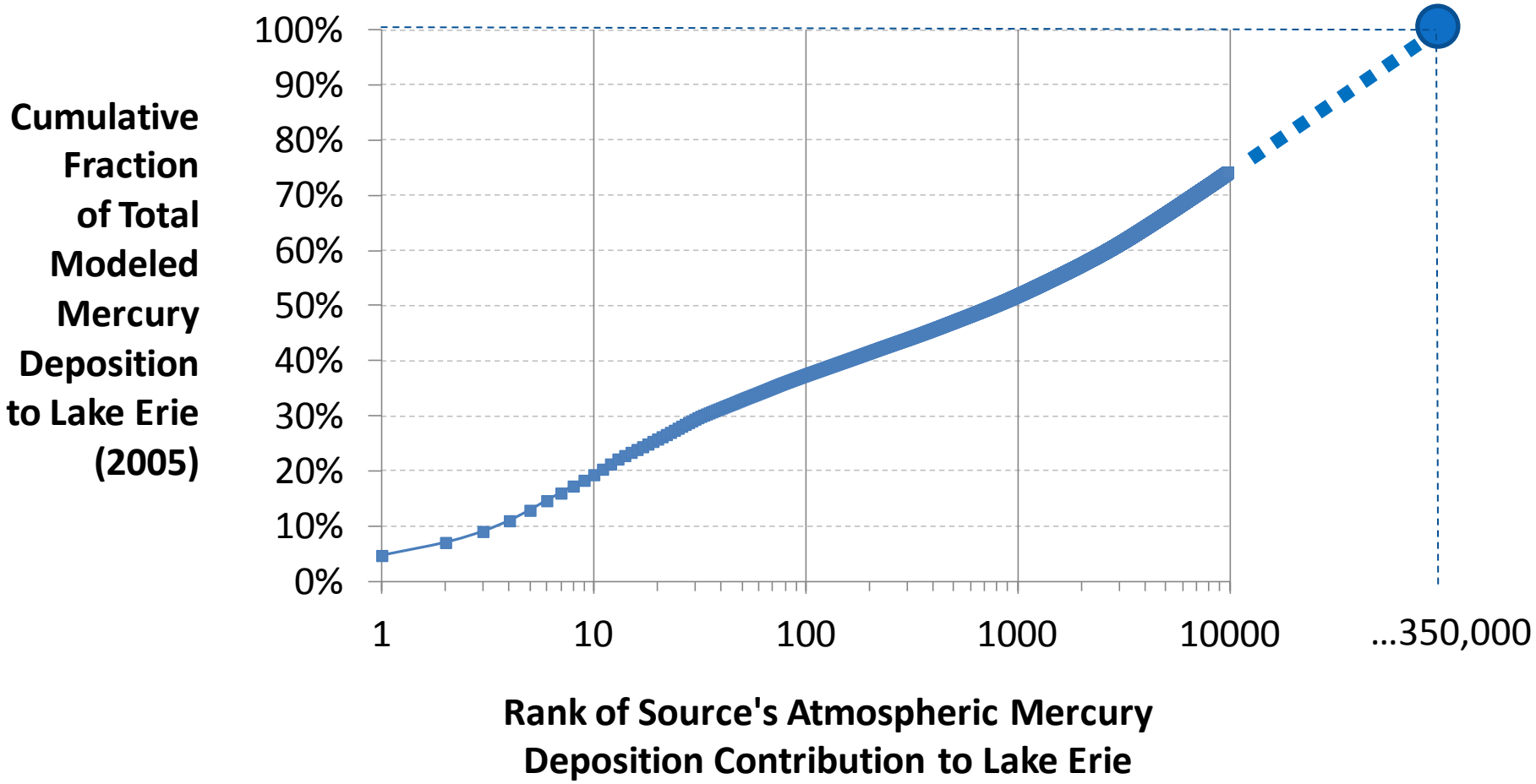
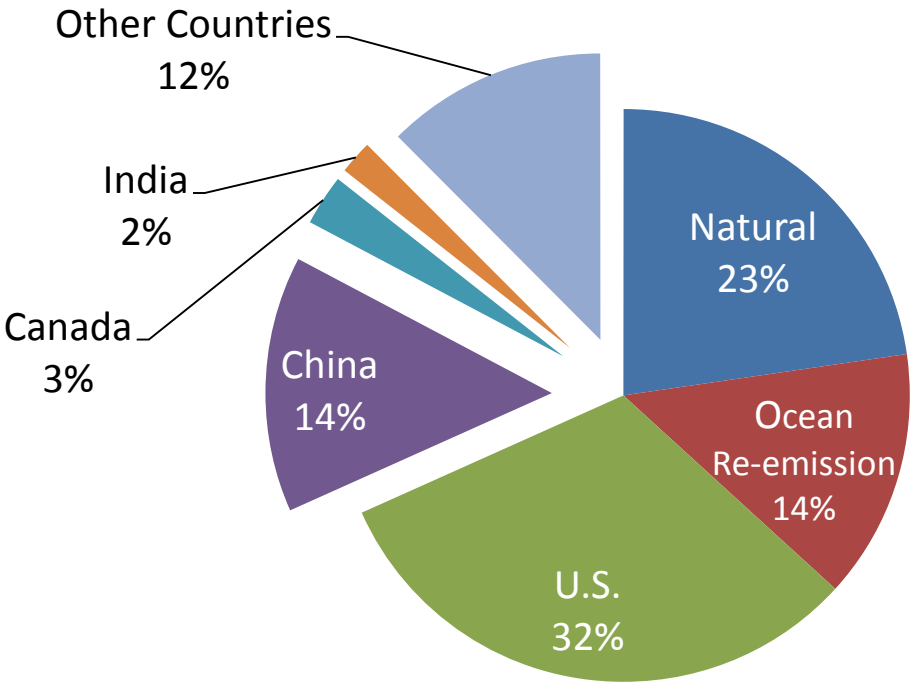

Cumulative Fraction of Total Modeled Mercury Deposition to Lake Erie (2005)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1
10
100
1000
10000
…350,000
Rank of Source's Atmospheric Mercury Deposition Contribution to Lake Erie

Sources of Mercury Deposition to the Great Lakes Basin 2005 Baseline Analysis



Total = 11,300 kg/yr

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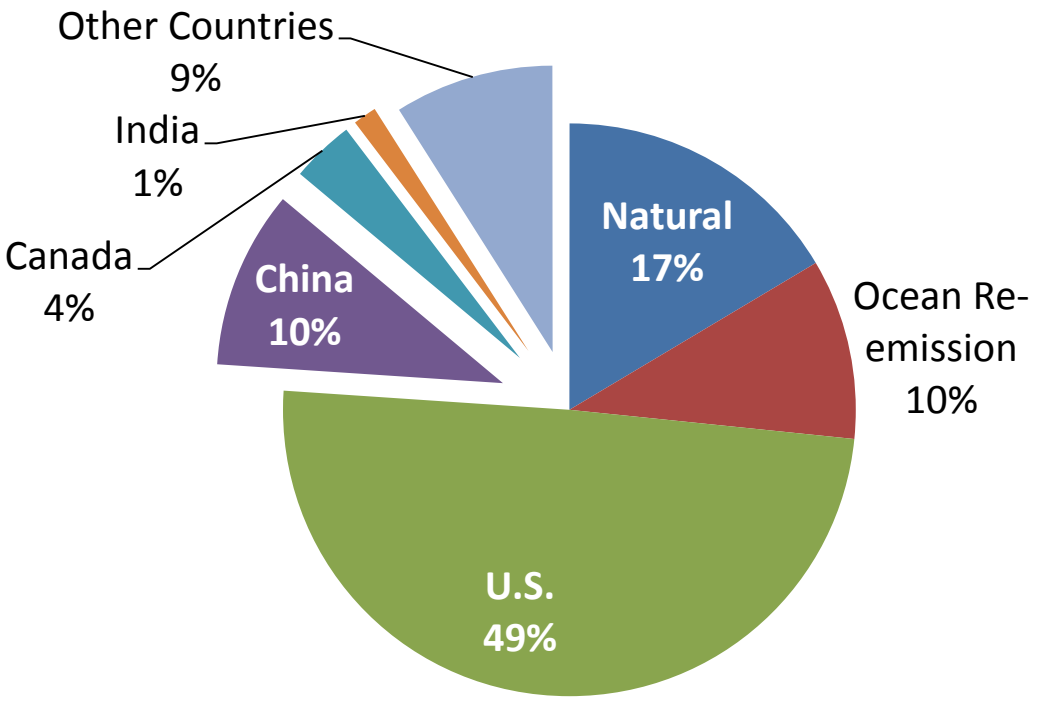
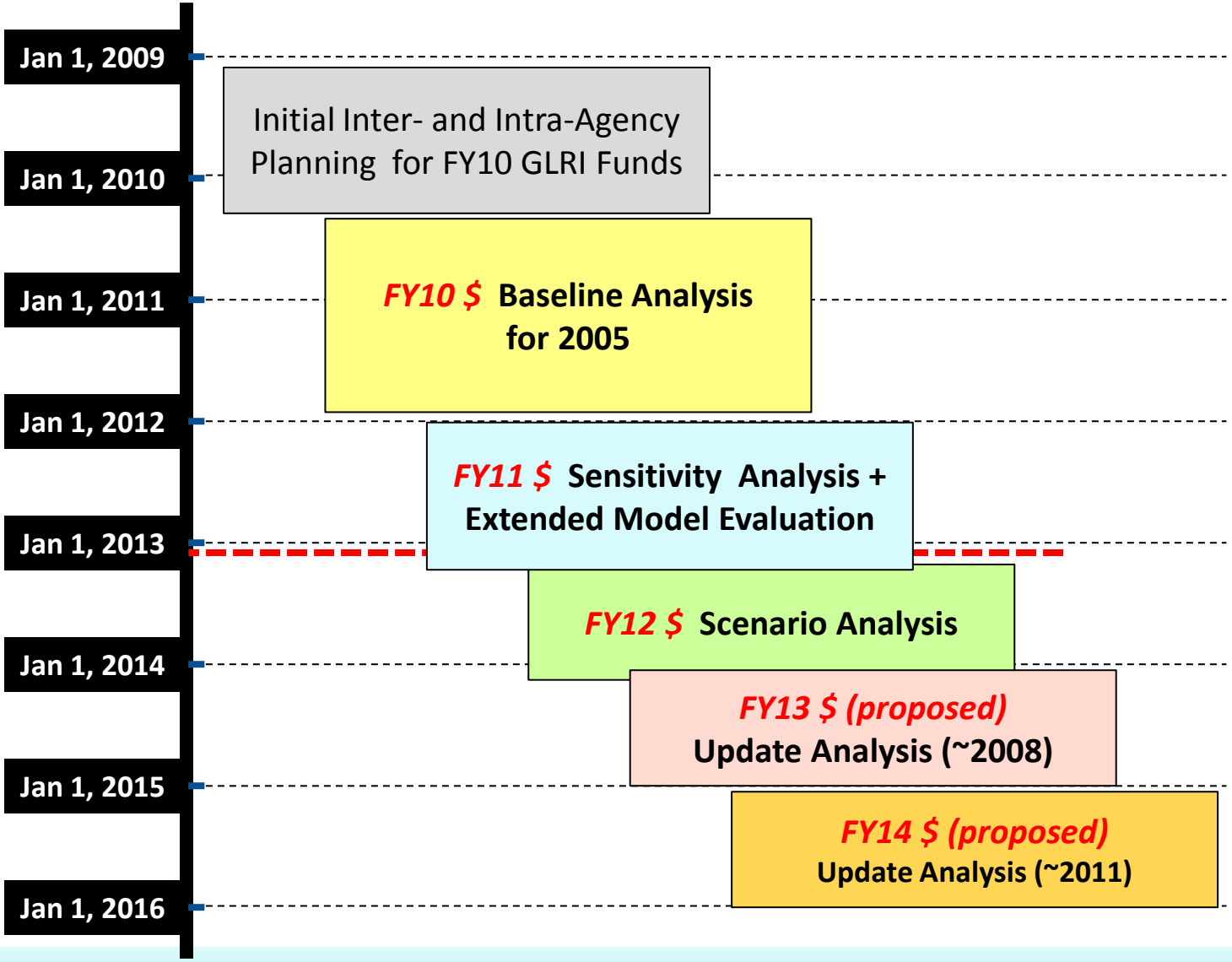


Total = 2,300 kg/yr

A multi-phase project

ARL's GLRI Atmospheric Mercury Modeling Project



Phase 1: Baseline Analysis for 2005

(Final Report Completed December 2011)

- 2005 was chosen as the analysis year, because 2005 was the latest year for which comprehensive mercury emissions inventory data were available at the start of this project
- Using 2005 meteorological data and emissions, the deposition and source-attribution for this deposition to each Great Lake and its watershed was estimated
- The model results were ground-truthed against 2005 Mercury Deposition Network data from sites in the Great Lakes region

Modeling Atmospheric Mercury Deposition to the Great Lakes. Final Report for work conducted with FY2010 funding from the Great Lakes Restoration Initiative. December 16, 2011. Mark Cohen, Roland Draxler, Richard Artz. NOAA Air Resources Laboratory, Silver Spring, MD, USA. 160 pages.

http://www.arl.noaa.gov/documents/reports/GLRI_FY2010_Atmospheric_Mercury_Final_Report_2011_Dec_16.pdf

http://www.arl.noaa.gov/documents/reports/Figures_Tables_GLRI_NOAA_Atmos_Mercury_Report_Dec_16_2011.pptx

One-page summary:
http://www.arl.noaa.gov/documents/reports/GLRI_Atmos_Mercury_Summary.pdf

Some Key Features of this Analysis

- **Deposition explicitly modeled to actual lake/watershed areas**
  - As opposed to the usual practice of ascribing portions of gridded deposition to these areas in a post-processing step
- **Combination of Lagrangian & Eulerian modeling**
  - allows accurate and computationally efficient estimates of the fate and transport of atmospheric mercury over all relevant length scales – from "local" to global.
- **Uniquely detailed source-attribution information is created**
  - deposition contribution to each Great Lakes and watersheds from each source in the emissions inventories used is estimated individually
  - The level of source discrimination is only limited by the detail in the emissions inventories
  - Source-type breakdowns not possible in this 1st phase for global sources, because the global emissions inventory available did not have source-type breakdowns for each grid square

Some Key Findings of this Analysis

- **"Single Source" results illustrate source-receptor relationships**
  - For example, a "typical" coal-fired power plant near Lake Erie may contribute on the order of 1000x the mercury – for the same emissions – as a comparable facility in China.

- **Regional, national, & global mercury emissions are all important contributors to mercury deposition in the Great Lakes Basin**
  - For Lakes Erie and Ontario, the U.S. contribution is at its most significant
  - For Lakes Huron and Superior, the U.S. contribution is less significant.
  - Local & regional sources have a much greater atmospheric deposition contributions than their emissions, as a fraction of total global mercury emissions, would suggest.

Some Key Findings of this Analysis (…continued)

- **Reasonable agreement with measurements**
  - Despite numerous uncertainties in model input data and other modeling aspects
  - Comparison at sites where significant computational resources were expended – corresponding to regions that were the most important for estimating deposition to the Great Lakes and their watersheds – showed good consistency between model predictions and measured quantities.
  - For a smaller subset of sites generally downwind of the Great Lakes (in regions not expected to contribute most significantly to Great Lakes atmospheric deposition), less computational resources were expended, and the comparison showed moderate, but understandable, discrepancies.

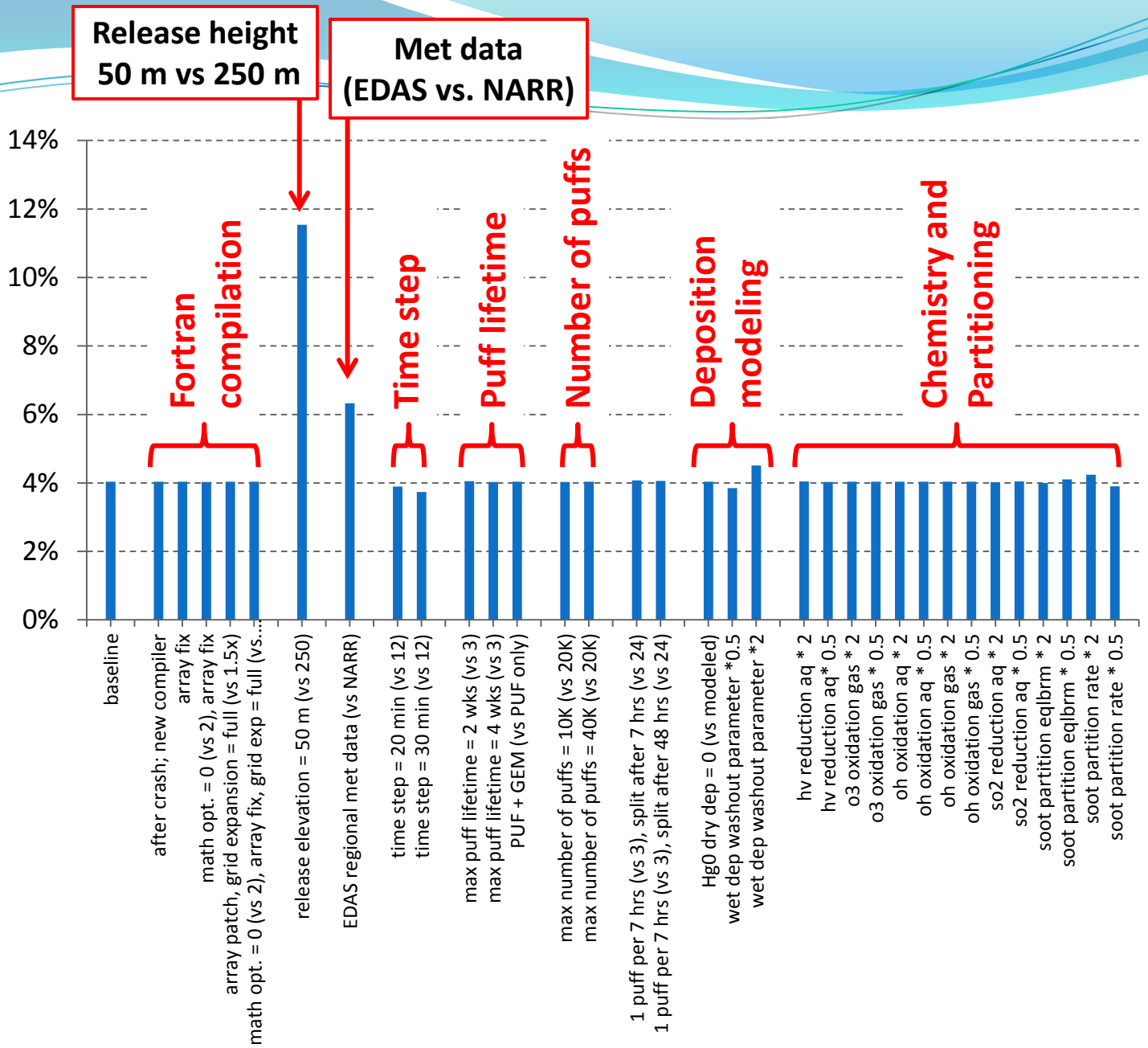
Phase 2: Sensitivity Analysis + Extended Model Evaluation

(current work, with GLRI FY11 funding)

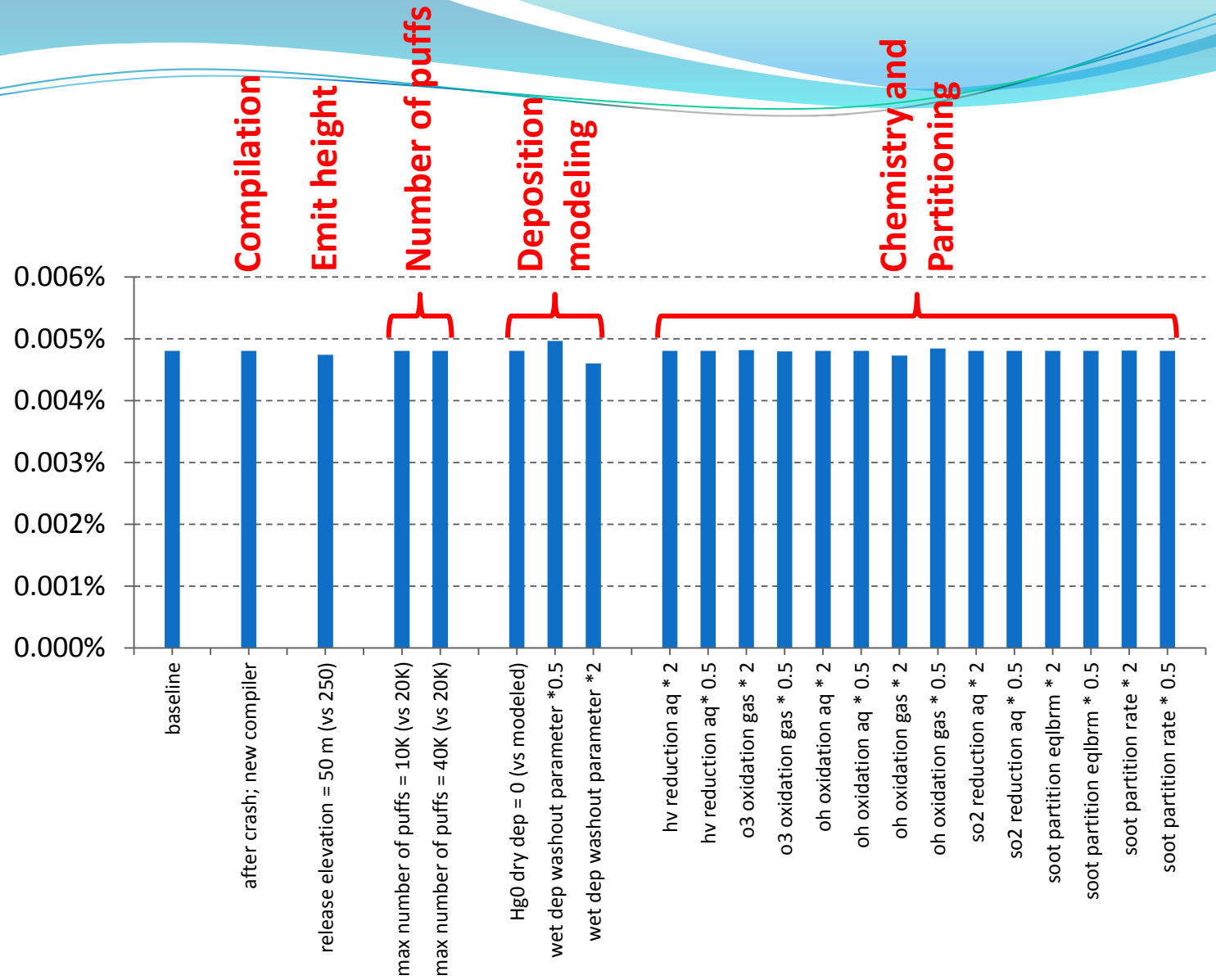
- Examining the influence of uncertainties on the modeling results, by varying critical model parameters, algorithms, and inputs, and analyzing the resulting differences in results

- Ground-truthing the model against additional ambient monitoring data, e.g., ambient mercury air concentration measurements and wet deposition data not included in the Mercury Deposition Network (MDN)

Fraction of RGM emissions deposited in Lake Erie from a hypothetical source in Detroit



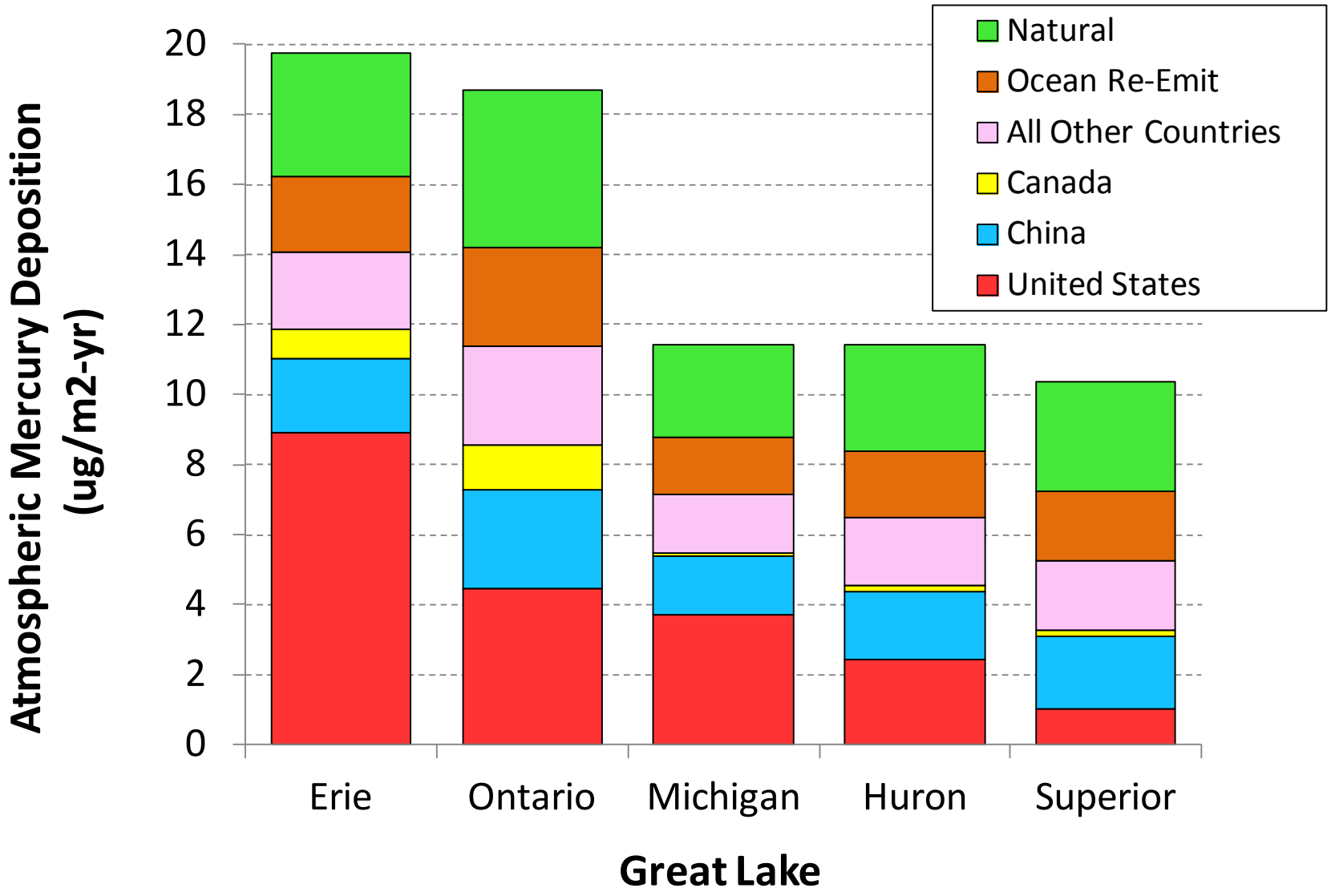
Fraction of Hg(0) emissions deposited in Lake Erie from a hypothetical source in China



Phase 3: Scenarios

(next year's work, with GLRI FY12 funding)

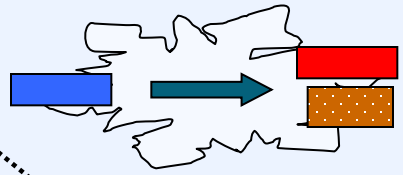
- A modeling analyses such as this is the *only* way to quantitatively examine the potential consequences of alternative future emissions scenarios
- We will work with EPA and other Great Lakes Stakeholders to identify and specify the most policy relevant scenarios to examine
- For each scenario, we will estimate the amount of atmospheric deposition to each of the Great Lakes and their watersheds, along with the detailed source-attribution for this deposition


Natural
Ocean Re-Emit
All Other Countries
Canada
China
United States
Atmospheric Mercury Deposition (ug/m2-yr)
0
2
4
6
8
10
12
14
16
18
20
Erie
Ontario
Michigan
Huron
Superior
Great Lake

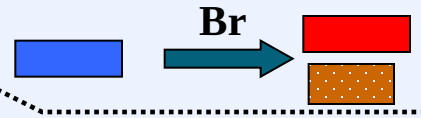
Atmospheric Mercury Fate Processes

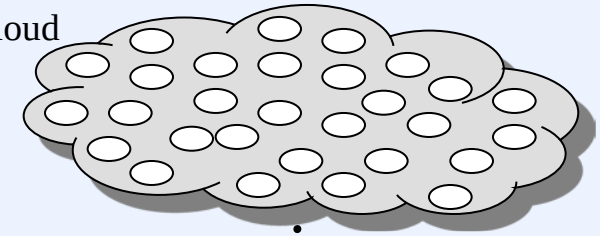
Elemental Mercury [Hg(0)]
Hg(II), ionic mercury, RGM
Particulate Mercury [Hg(p)]

Upper atmospheric halogen-mediated oxidation?



Polar sunrise "mercury depletion events"

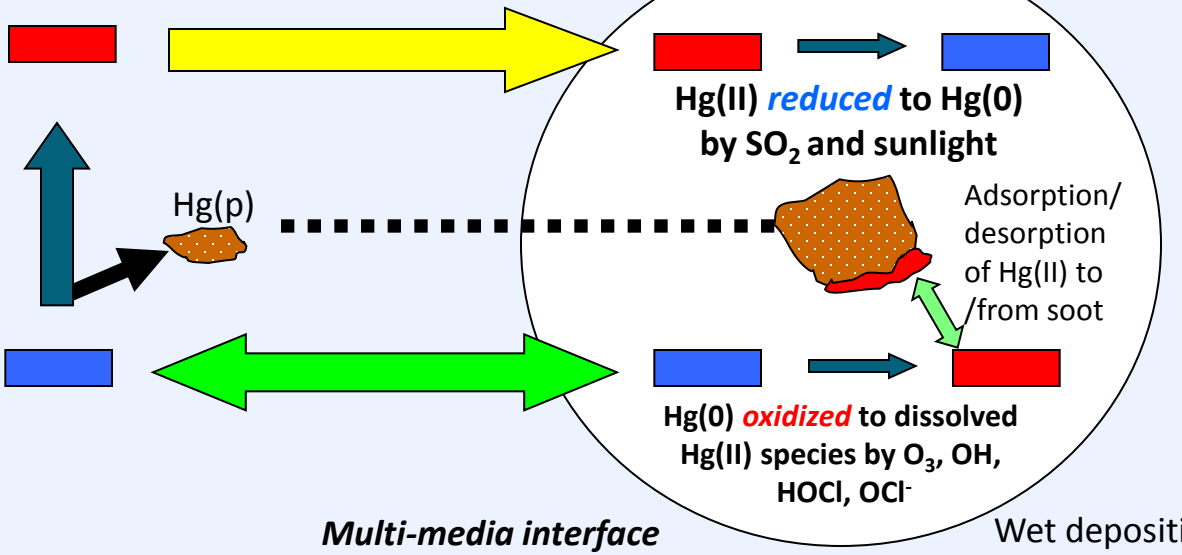




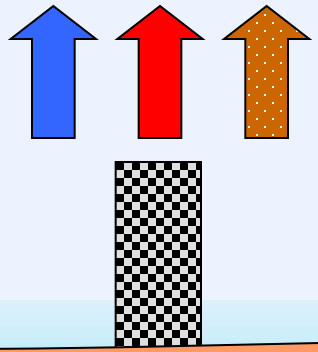
CLOUD DROPLET

Vapor phase:

Hg(0) oxidized to RGM and Hg(p) by O_3, H_2O_2, Cl_2, OH, HCl



Primary Anthropogenic Emissions



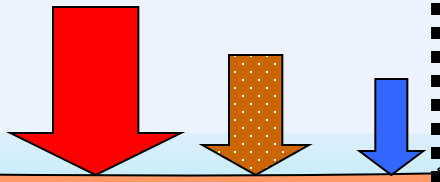
Multi-media interface

Natural emissions

Re-emission of previously deposited anthropogenic and natural mercury

Wet deposition

Dry deposition



(Evolving) Atmospheric Chemical Reaction Scheme for Mercury

	Reaction	Rate	Units	Reference
	GAS PHASE REACTIONS			
?	$Hg^0 + O_3 \rightarrow Hg(p)$	3.0E-20	cm^3/molec-sec	Hall (1995)
	$Hg^0 + HCl \rightarrow HgCl_2$	1.0E-19	cm^3/molec-sec	Hall and Bloom (1993)
	$Hg^0 + H_2O_2 \rightarrow Hg(p)$	8.5E-19	cm^3/molec-sec	Tokos et al. (1998) (upper limit based on experiments)
	$Hg^0 + Cl_2 \rightarrow HgCl_2$	4.0E-18	cm^3/molec-sec	Calhoun and Prestbo (2001)
?	$Hg^0 + OH \rightarrow Hg(p)$	8.7E-14	cm^3/molec-sec	Sommar et al. (2001)
new	$Hg^0 + Br \rightarrow HgBr_2$			
	AQUEOUS PHASE REACTIONS			
	$Hg^0 + O_3 \rightarrow Hg^{+2}$	4.7E+7	$(molar\text{-}sec)^{-1}$	Munthe (1992)
	$Hg^0 + OH \rightarrow Hg^{+2}$	2.0E+9	$(molar\text{-}sec)^{-1}$	Lin and Pehkonen(1997)
	$HgSO_3 \rightarrow Hg^0$	$T*e^{((31.971*T)-12595.0)/T)}$ sec^{-1} [T = temperature (K)]		Van Loon et al. (2002)
?	$Hg(II) + HO_2 \rightarrow Hg^0$	~ 0	$(molar\text{-}sec)^{-1}$	Gardfeldt & Jonnson (2003)
	$Hg^0 + HOCl \rightarrow Hg^{+2}$	2.1E+6	$(molar\text{-}sec)^{-1}$	Lin and Pehkonen(1998)
	$Hg^0 + OCl^{-1} \rightarrow Hg^{+2}$	2.0E+6	$(molar\text{-}sec)^{-1}$	Lin and Pehkonen(1998)
	$Hg(II) \leftrightarrow Hg(II)_{(soot)}$	9.0E+2	liters/gram; t = 1/hour	eqlbrm: Seigneur et al. (1998) rate: Bullock & Brehme (2002).
	$Hg^{+2} + hv \rightarrow Hg^0$	6.0E-7	$(sec)^{-1}$ (maximum)	Xiao et al. (1994); Bullock and Brehme (2002)

What year to model?

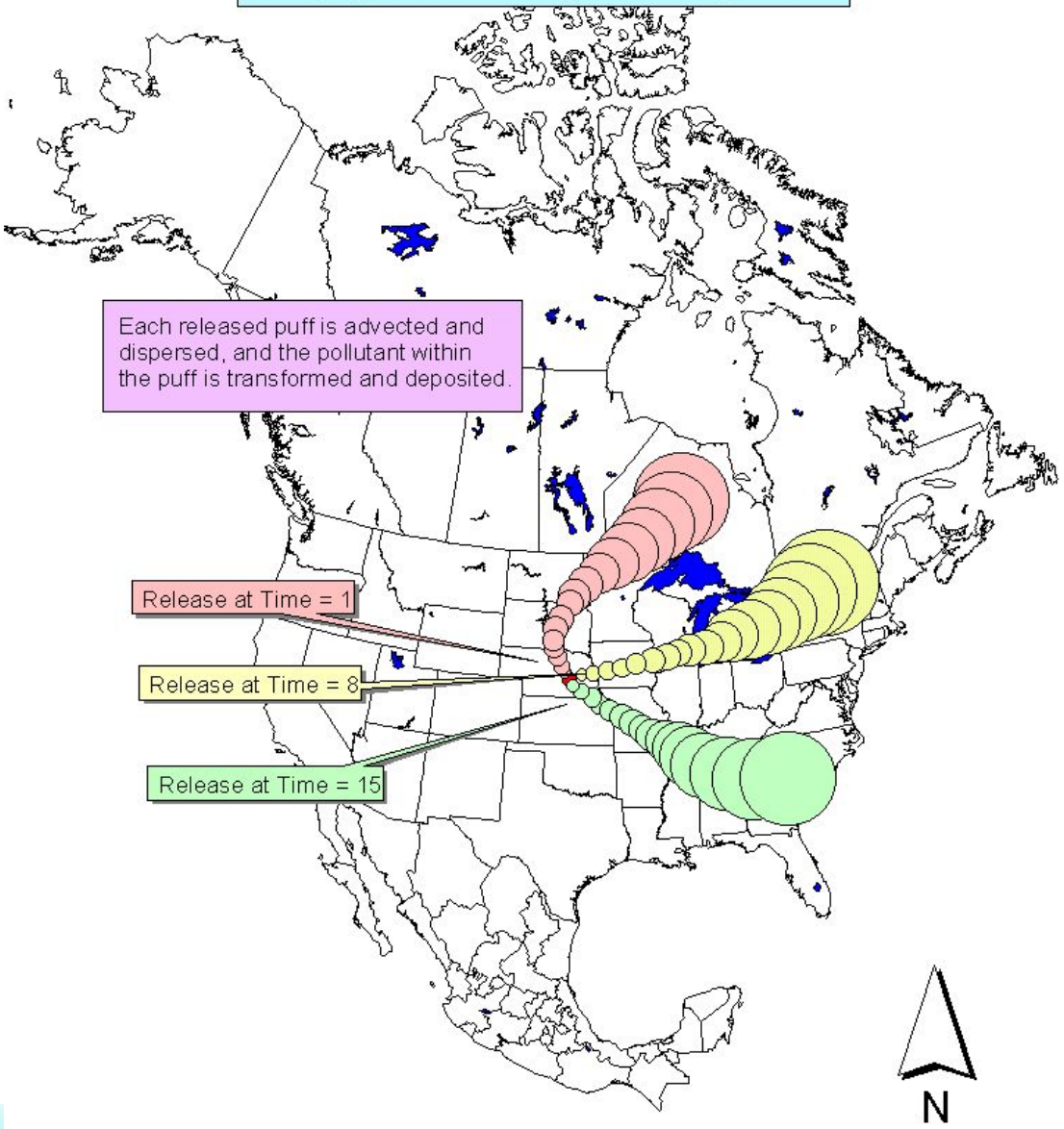
- **Mercury Emissions Inventory**
  - U.S. anthropogenic emissions inventory
  - Canadian anthropogenic emissions inventory
  - Mexican anthropogenic emissions inventory
  - Global anthropogenic emissions inventory
  - Natural emissions inventory
  - Re-emissions inventory
- **Ambient Data for Model Evaluation**
  - Wet deposition (Mercury Deposition Network)
  - "Speciated" Air Concentrations
- **Meteorological Data to drive model**
  - NCEP/NCAR Global Reanalysis (2.5 deg)
  - NCEP EDAS 40km North American Domain
  - North American Regional Reanalysis (NARR)

Dataset Available for 2005

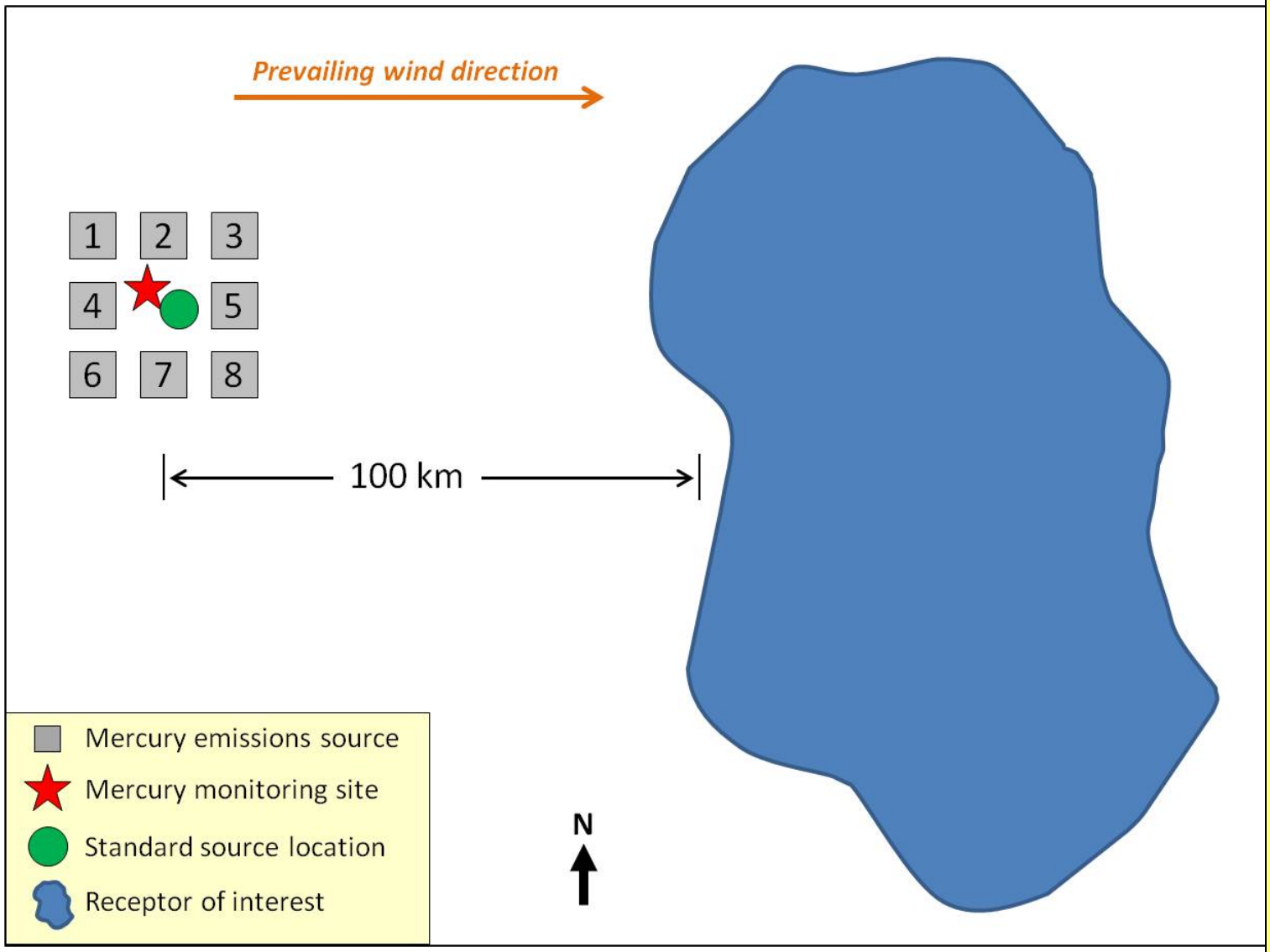
Need all of these datasets for the same year

2005 chosen for baseline analysis

Over the entire modeling period (e.g., one year), puffs are released at periodic intervals (e.g., once every 7 hours).



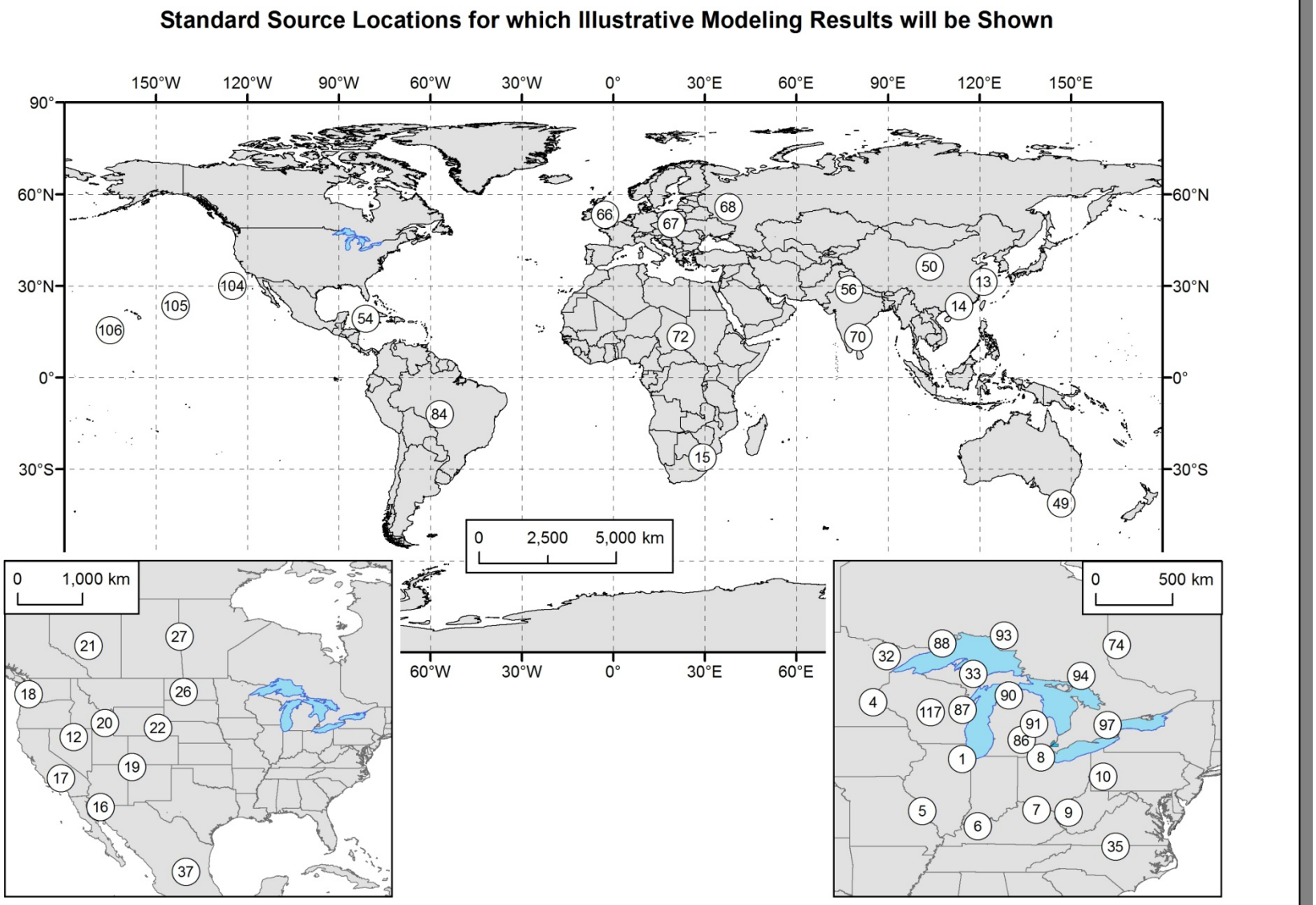
Getting good ground-truthing results harder than estimating deposition to the Great Lakes



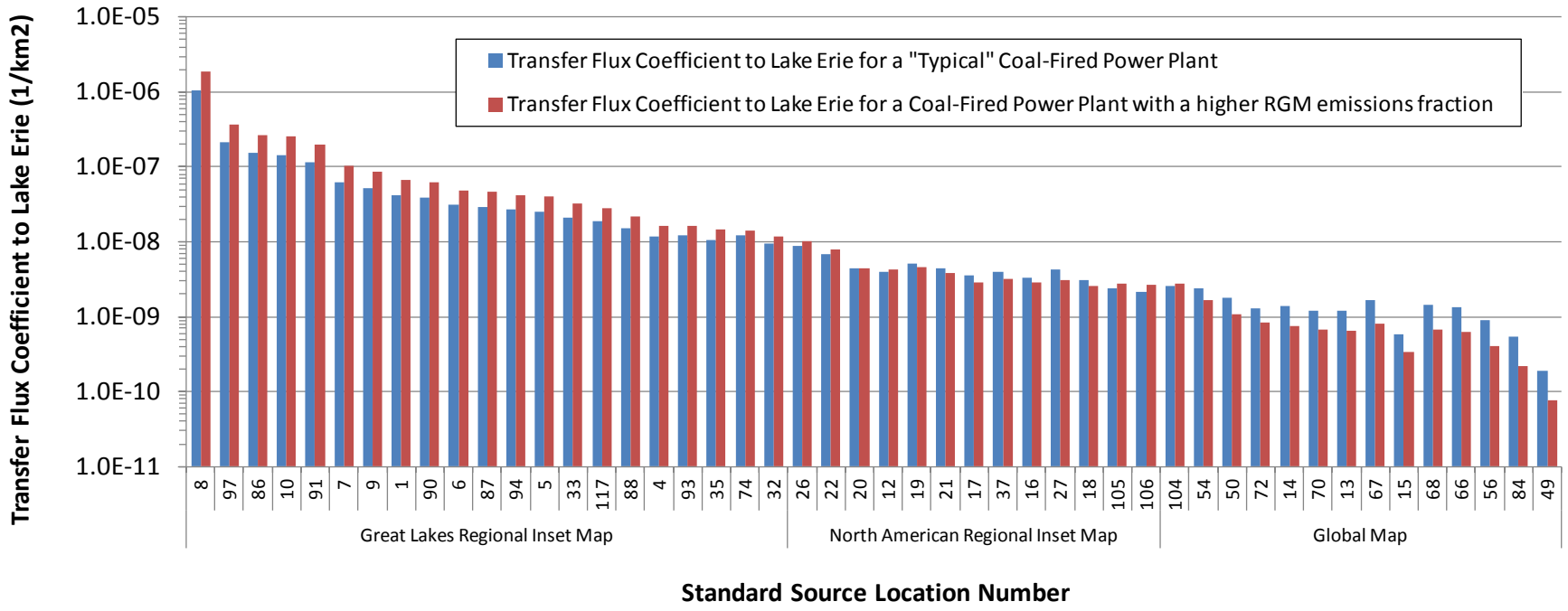
One Standard Source Location (green dot) would do a decent job of estimating deposition to the receptor, for all of the hypothetical, "actual" source locations shown (numbered boxes)

But the same Standard Source Location would be completely inadequate to estimate deposition and concentrations at the monitoring site (red star)

Standard Source Locations for Illustrative Modeling Results



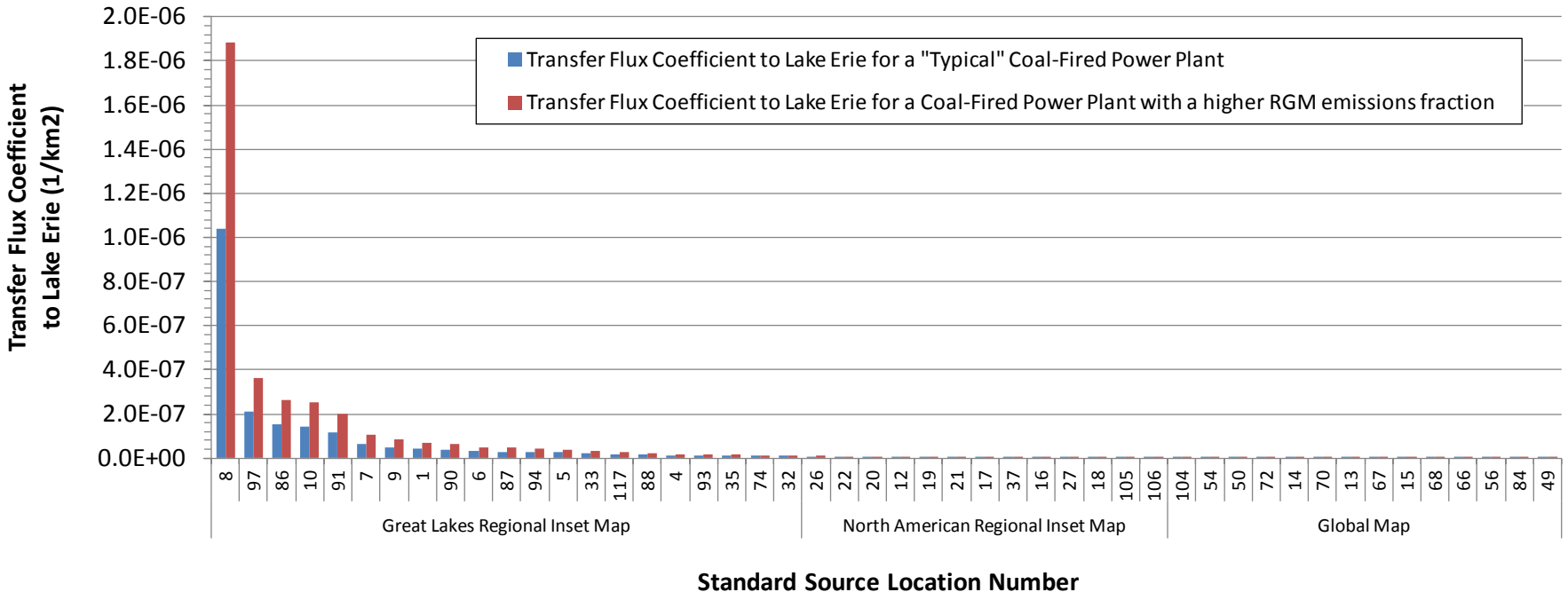
Lake Erie Transfer Flux Coefficients for two kinds of Generic Coal-Fired Power Plants (logarithmic scale)



The "Transfer Flux Coefficient" is calculated as the atmospheric deposition flux to a given receptor (in this case, Lake Erie) in units of g/km2-yr, divided by the total emissions from the source, in units of g/yr.

With this transfer flux coefficient, if one knows the emissions of the source in the given location, then the atmospheric deposition flux impact of the source on the receptor can be estimated, by simply multiplying the emissions by the transfer flux coefficient.

Lake Erie Transfer Flux Coefficients for two kinds of Generic Coal-FIred Power Plants (linear scale)



The "Transfer Flux Coefficient" is calculated as the atmospheric deposition flux to a given receptor (in this case, Lake Erie) in units of g/km2-yr, divided by the total emissions from the source, in units of g/yr.

With this transfer flux coefficient, if one knows the emissions of the source in the given location, then the atmospheric deposition flux impact of the source on the receptor can be estimated, by simply multiplying the emissions by the transfer flux coefficient.

In order to conveniently compare different model results,
a "transfer flux coefficient" X will be used,
defined as the following:

$$X = \frac{deposition\ flux\ rate}{emissions\ rate} = \frac{\frac{grams\ Hg\ deposited\ per\ year}{km^2\ of\ receptor\ area}}{grams\ Hg\ emitted\ per\ year\ from\ the\ source}\ [=]\ \frac{1}{km^2}$$

$$deposition\ flux\ rate = \frac{grams\ Hg\ deposited\ per\ year}{km^2\ of\ receptor\ area}\left(\frac{g}{km^2\,yr}\right)$$

$$= transfer\ flux\ coefficient\ \left(\frac{1}{km^2}\right) * source\ mercury\ emissions\ \left(\frac{g}{yr}\right)$$

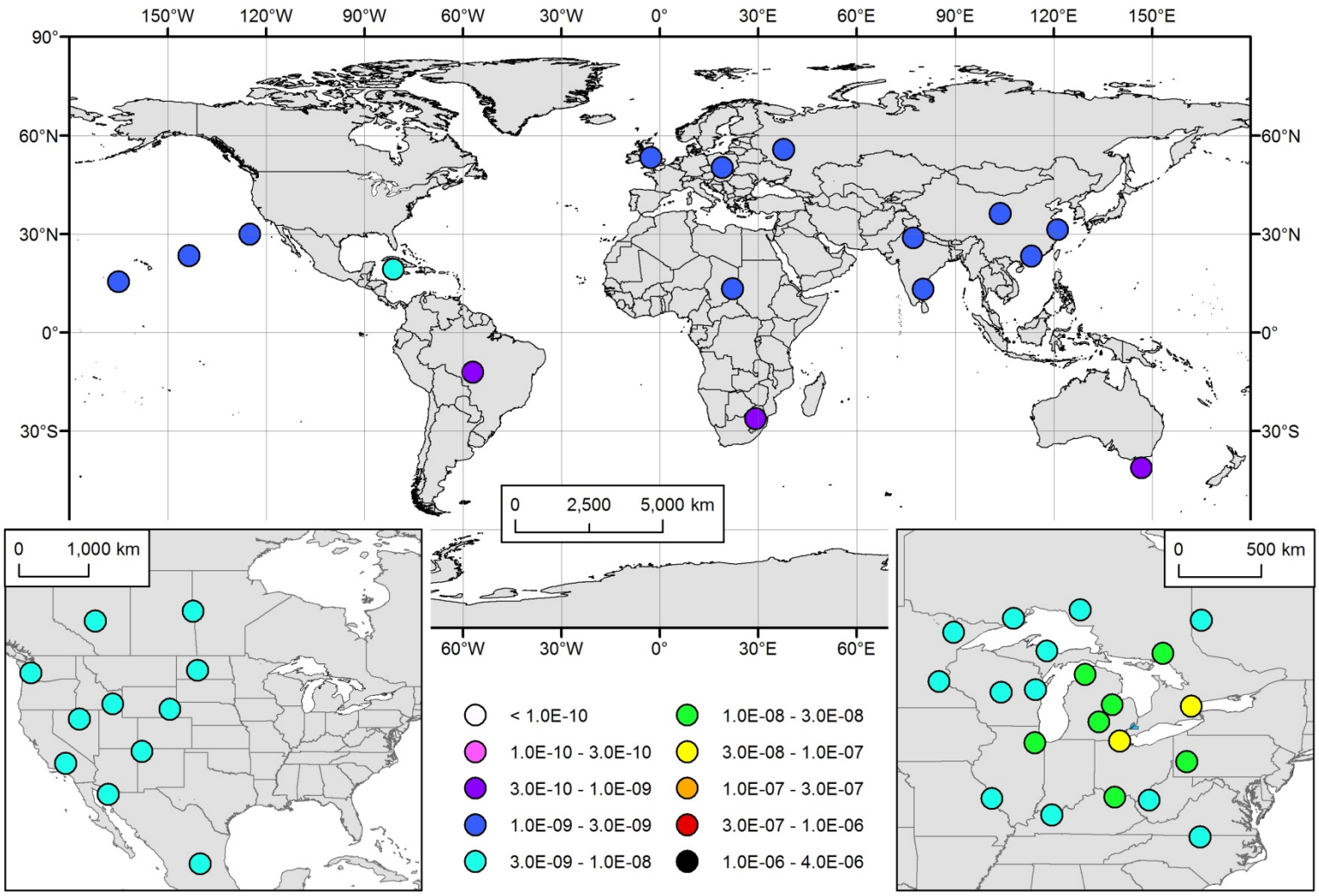
$$deposition\ flux\ rate = \frac{grams\ Hg\ deposited\ per\ year}{km^2\ of\ receptor\ area}\left(\frac{g}{km^2\,yr}\right)$$

$$= transfer\ flux\ coefficient\left(\frac{1}{km^2}\right) * source\ mercury\ emissions\ (\frac{g}{yr})$$

Transfer Flux Coefficients For Pure Elemental Mercury Emissions at an Illustrative Subset of Standard Source Locations, for Deposition Flux Contributions to Lake Erie

Transfer Flux Coefficient "X" for Elemental Mercury Emissions from Selected Locations to Lake Erie

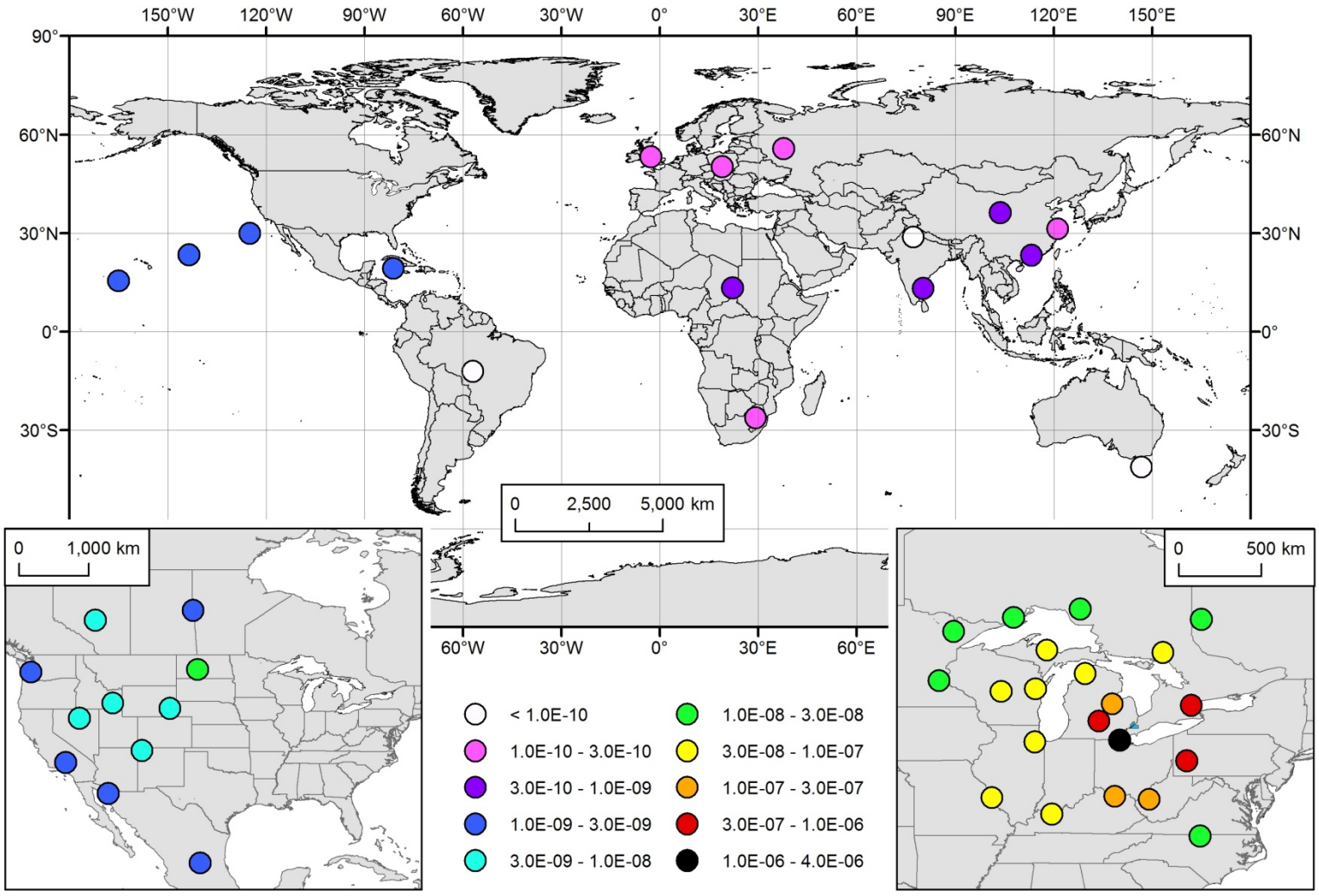
$$X = \frac{\text{(grams Hg deposited per year) / (km2)}}{\text{(grams Hg emitted per year from the source)}} \quad [=] \ 1/km2$$



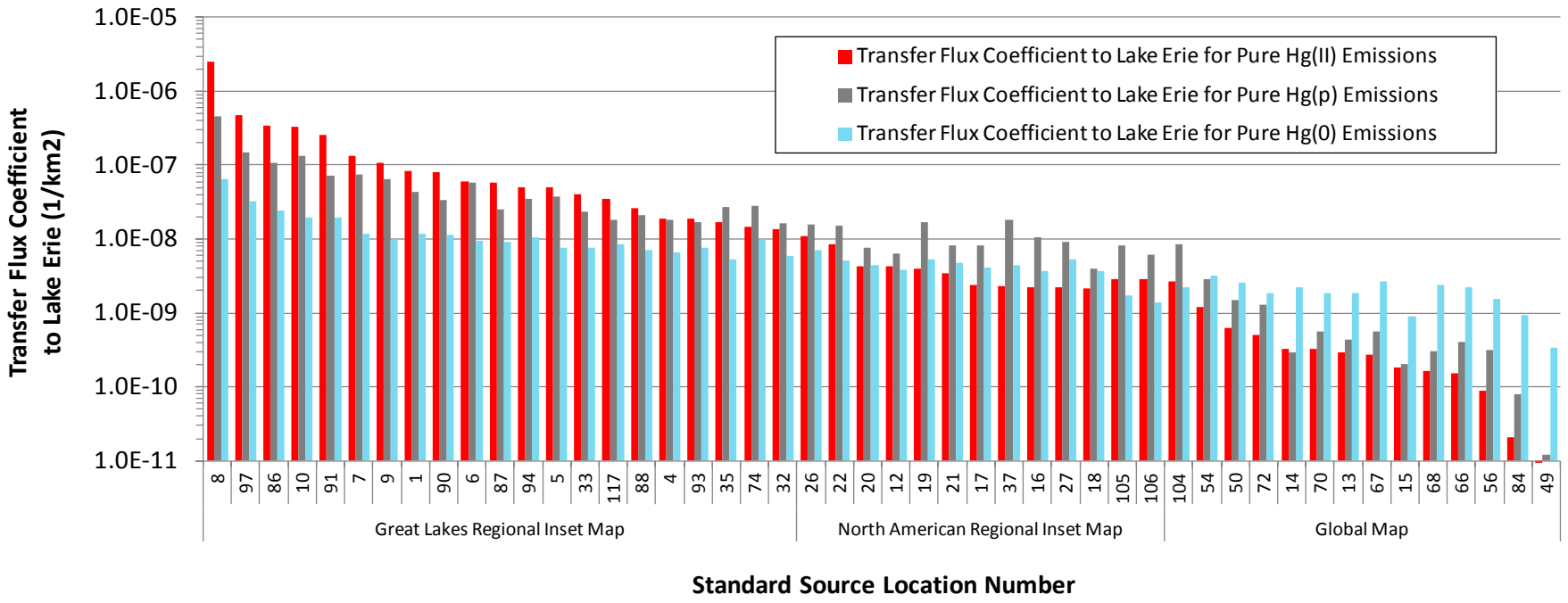
Transfer Flux Coefficients For Pure Reactive Gaseous Mercury Emissions at an Illustrative Subset of Standard Source Locations, for Deposition Flux Contributions to Lake Erie

Transfer Flux Coeff. "X" for Reactive Gaseous Mercury Emissions from Selected Locations to Lake Erie

$$X = \frac{\text{(grams Hg deposited per year) / (km2)}}{\text{(grams Hg emitted per year from the source)}} \quad [=] \ 1/km2$$



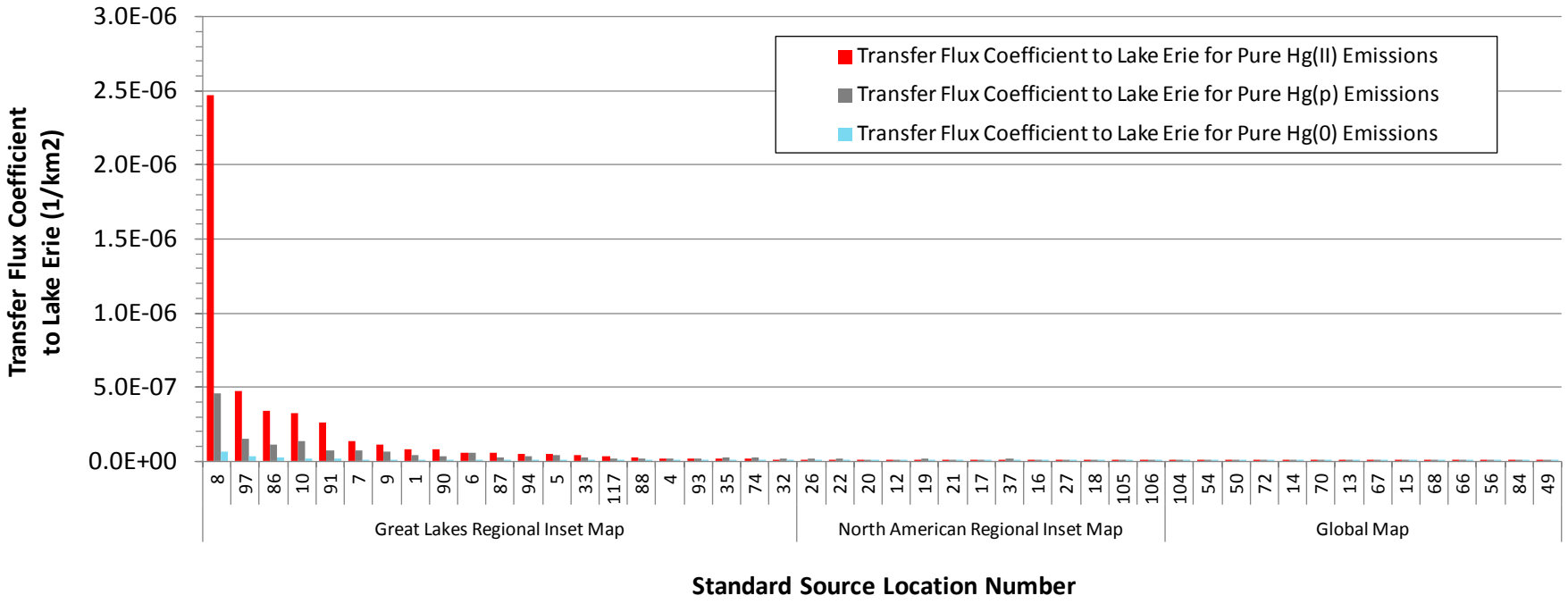
Transfer Flux Coefficients For Hg(0), Hg(II), and Hg(p) to Lake Erie (logarithmic scale)



The "Transfer Flux Coefficient" is calculated as the atmospheric deposition flux to a given receptor (in this case, Lake Erie) in units of g/km2-yr, divided by the total emissions from the source, in units of g/yr.

With this transfer flux coefficient, if one knows the emissions of the source in the given location, then the atmospheric deposition flux impact of the source on the receptor can be estimated, by simply multiplying the emissions by the transfer flux coefficient.

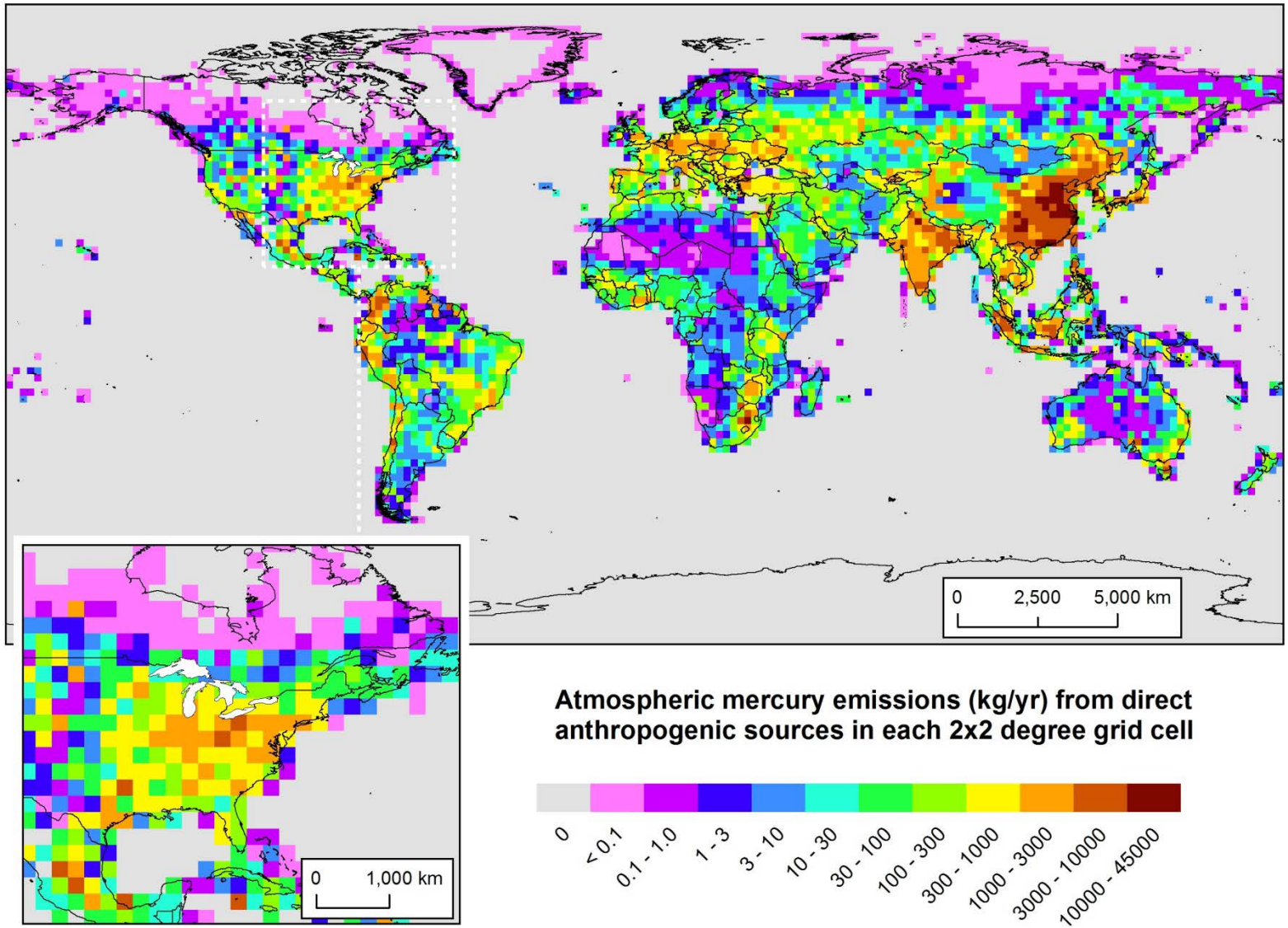
Transfer Flux Coefficients For Hg(0), Hg(II), and Hg(p) to Lake Erie (linear scale)



The "Transfer Flux Coefficient" is calculated as the atmospheric deposition flux to a given receptor (in this case, Lake Erie) in units of g/km2-yr, divided by the total emissions from the source, in units of g/yr.

With this transfer flux coefficient, if one knows the emissions of the source in the given location, then the atmospheric deposition flux impact of the source on the receptor can be estimated, by simply multiplying the emissions by the transfer flux coefficient.

Anthropogenic Mercury Emissions (ca. 2005)



Natural mercury emissions

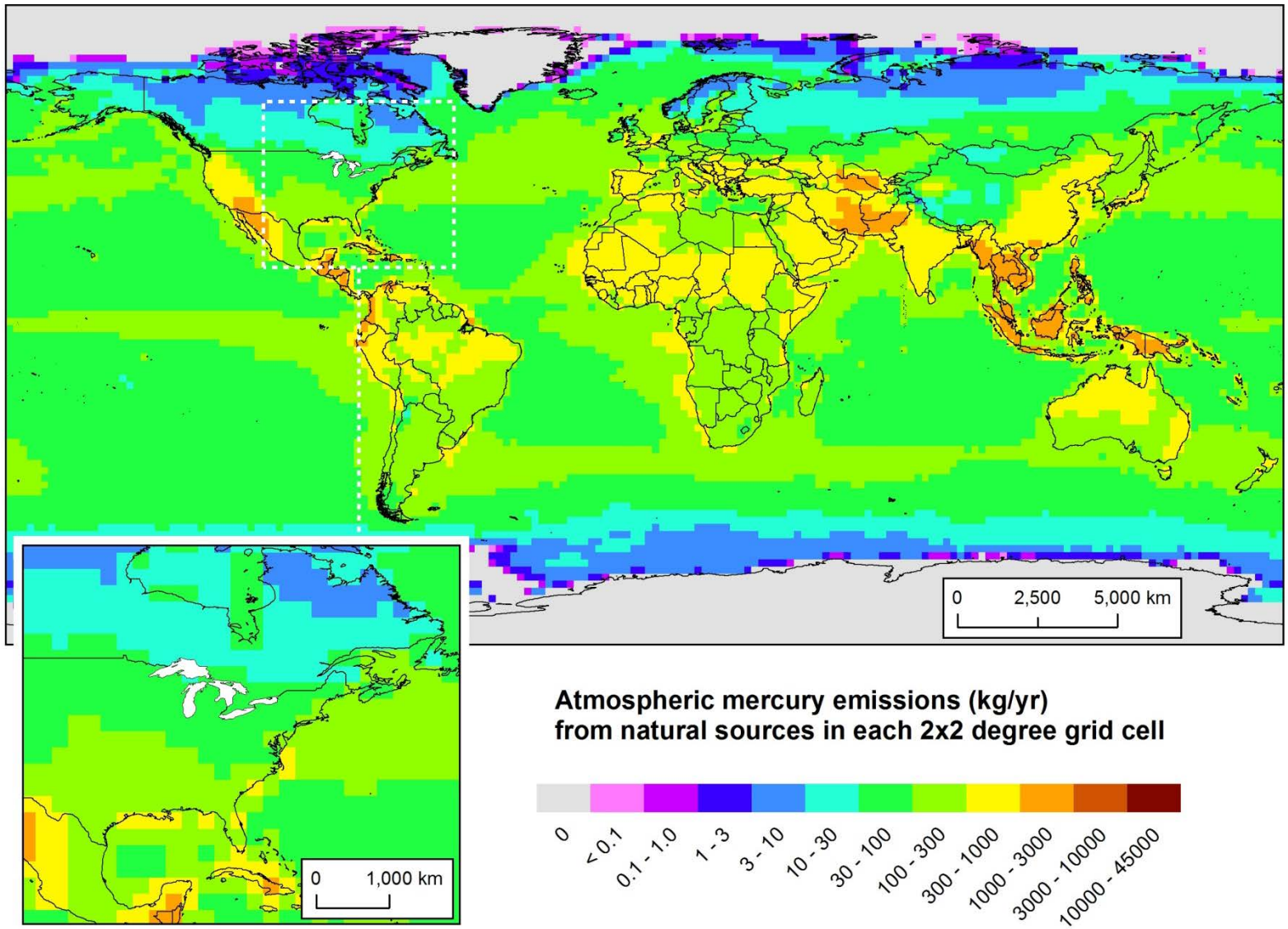


Figure 55. Mercury Deposition Network Sites in the Great Lakes Region Considered in an Initial Model Evaluation Analysis

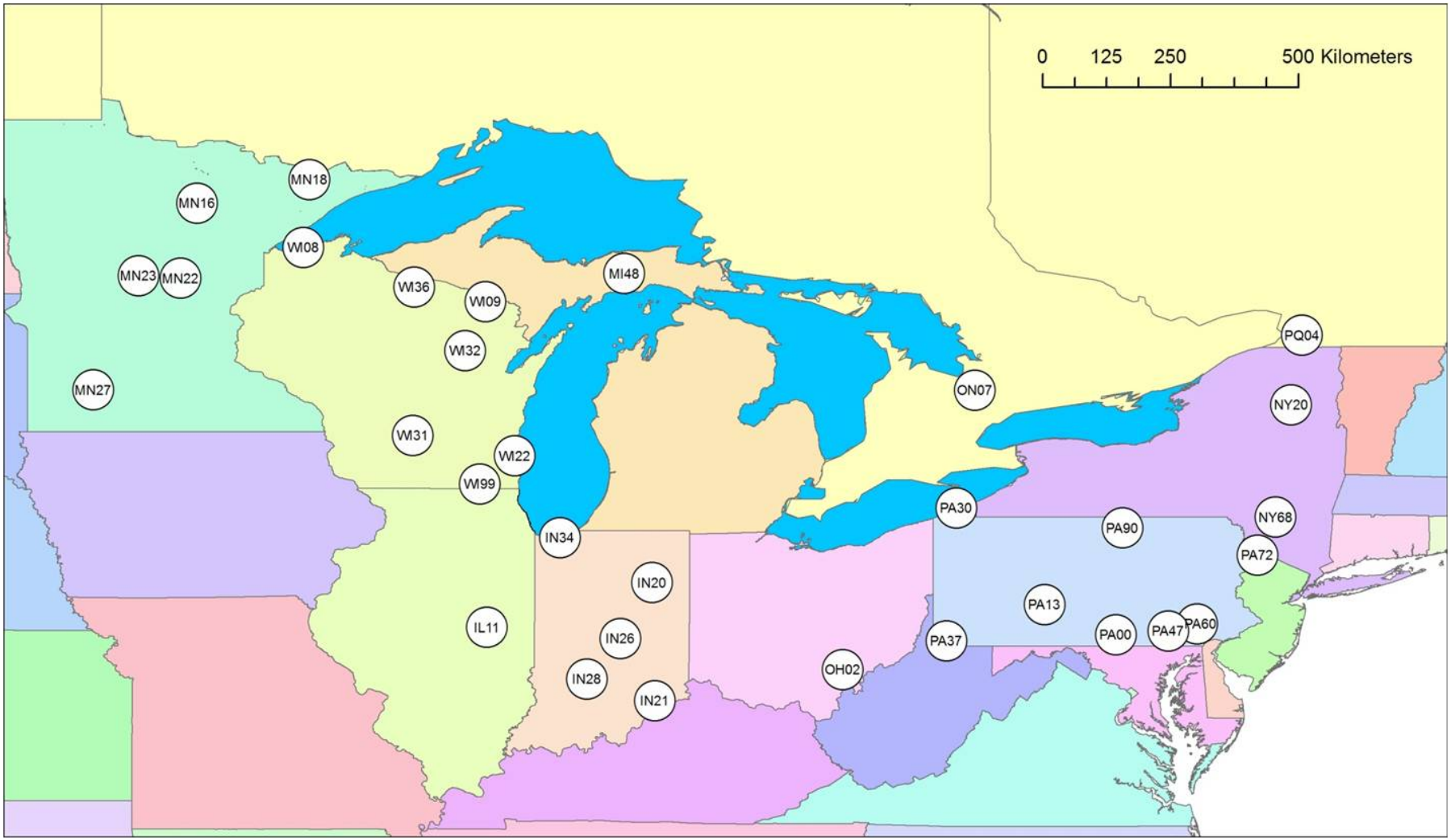
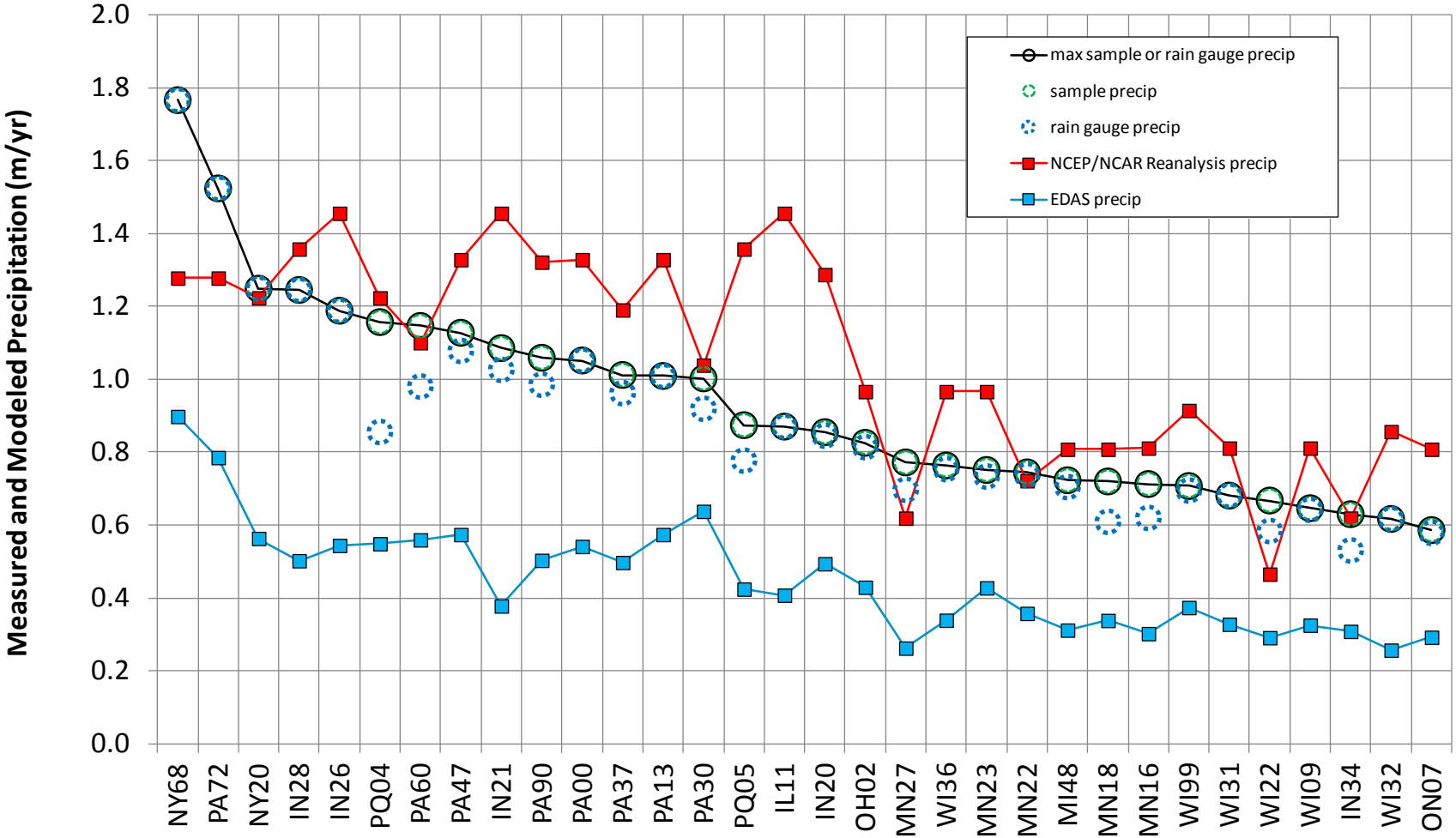
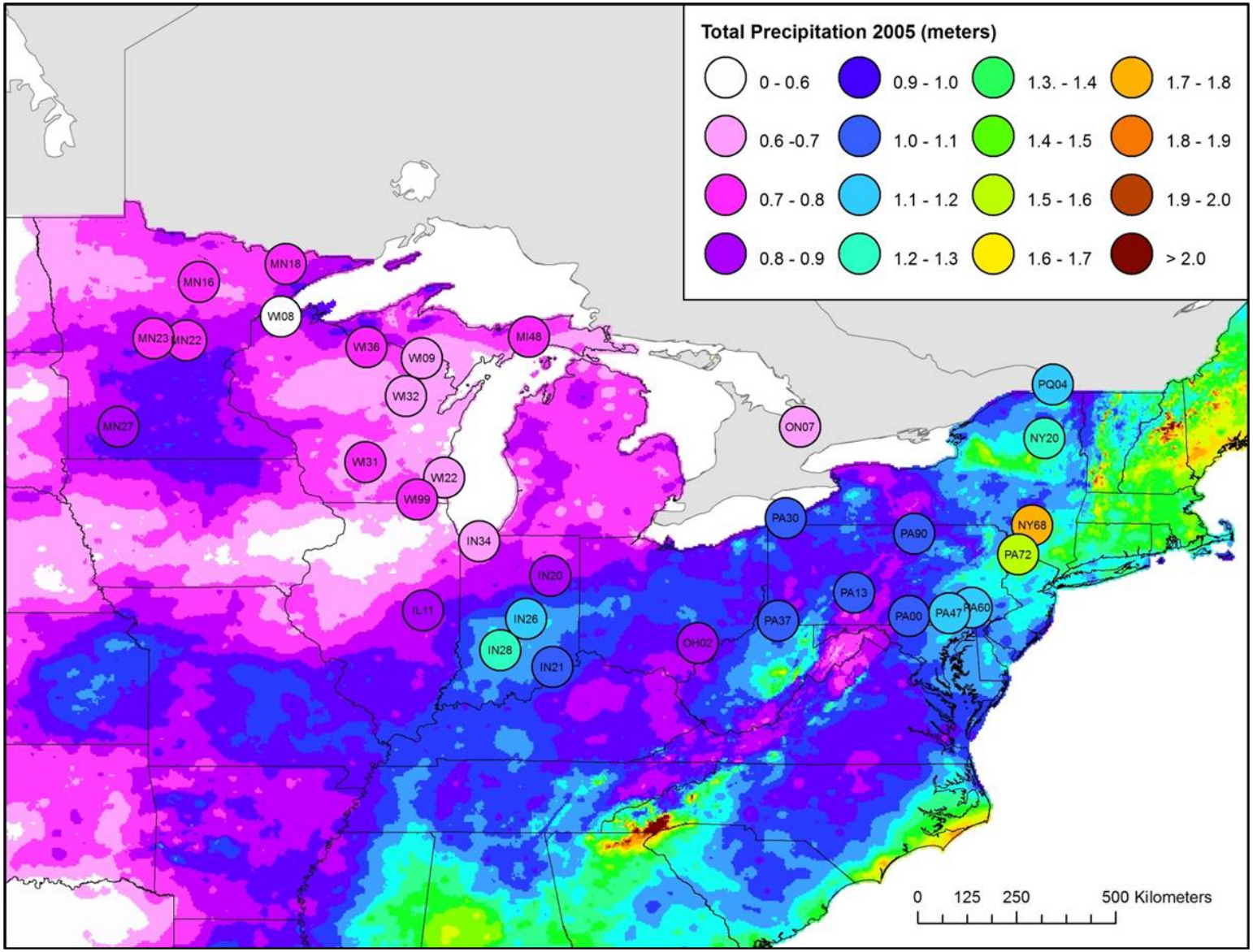


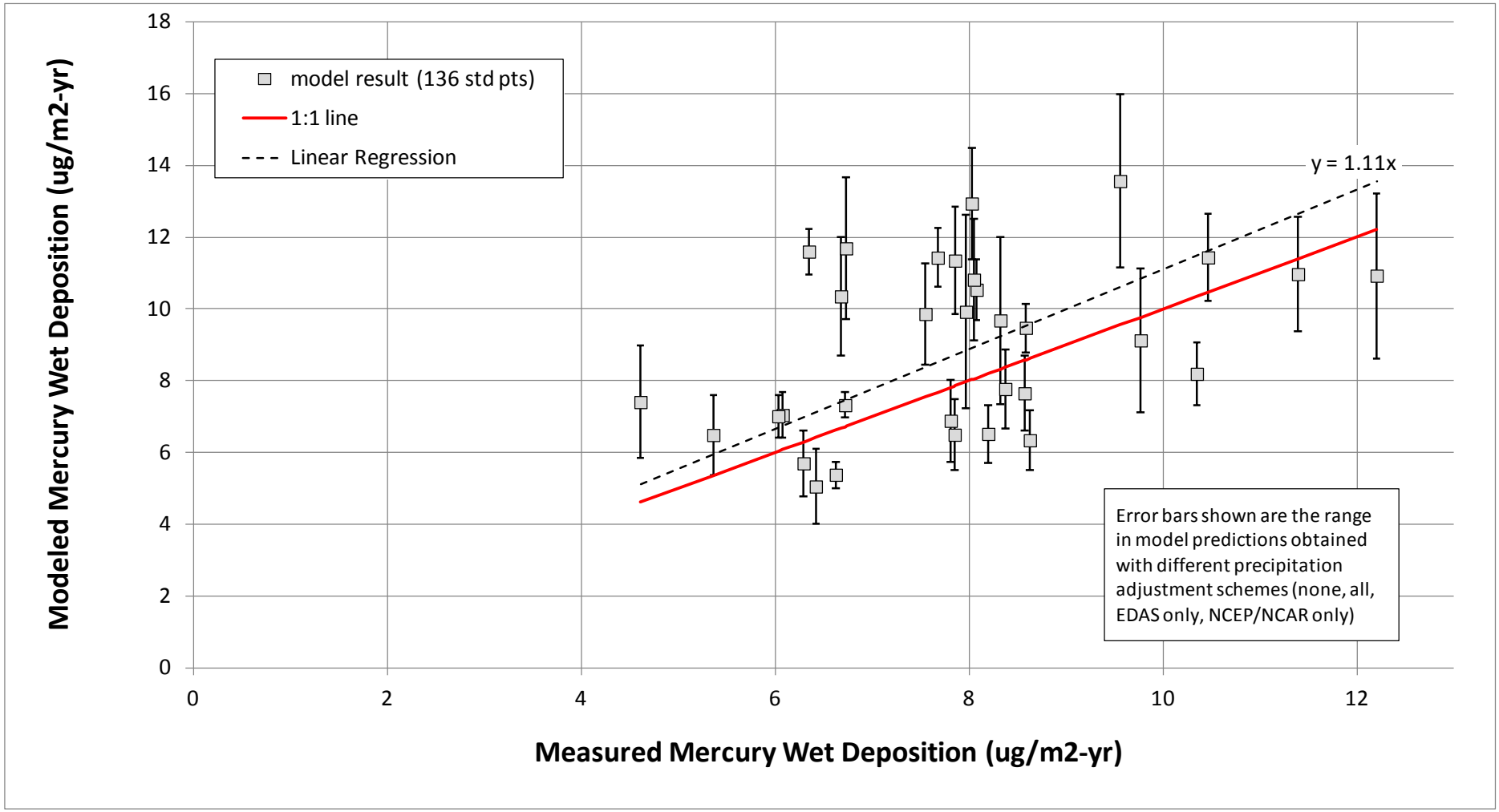
Figure 56. Comparison of Total 2005 Precipitation Measured at each of the Great-Lakes Region MDN Sites with the Precipitation in the Meteorological Datasets Used as Inputs to this Modeling Study



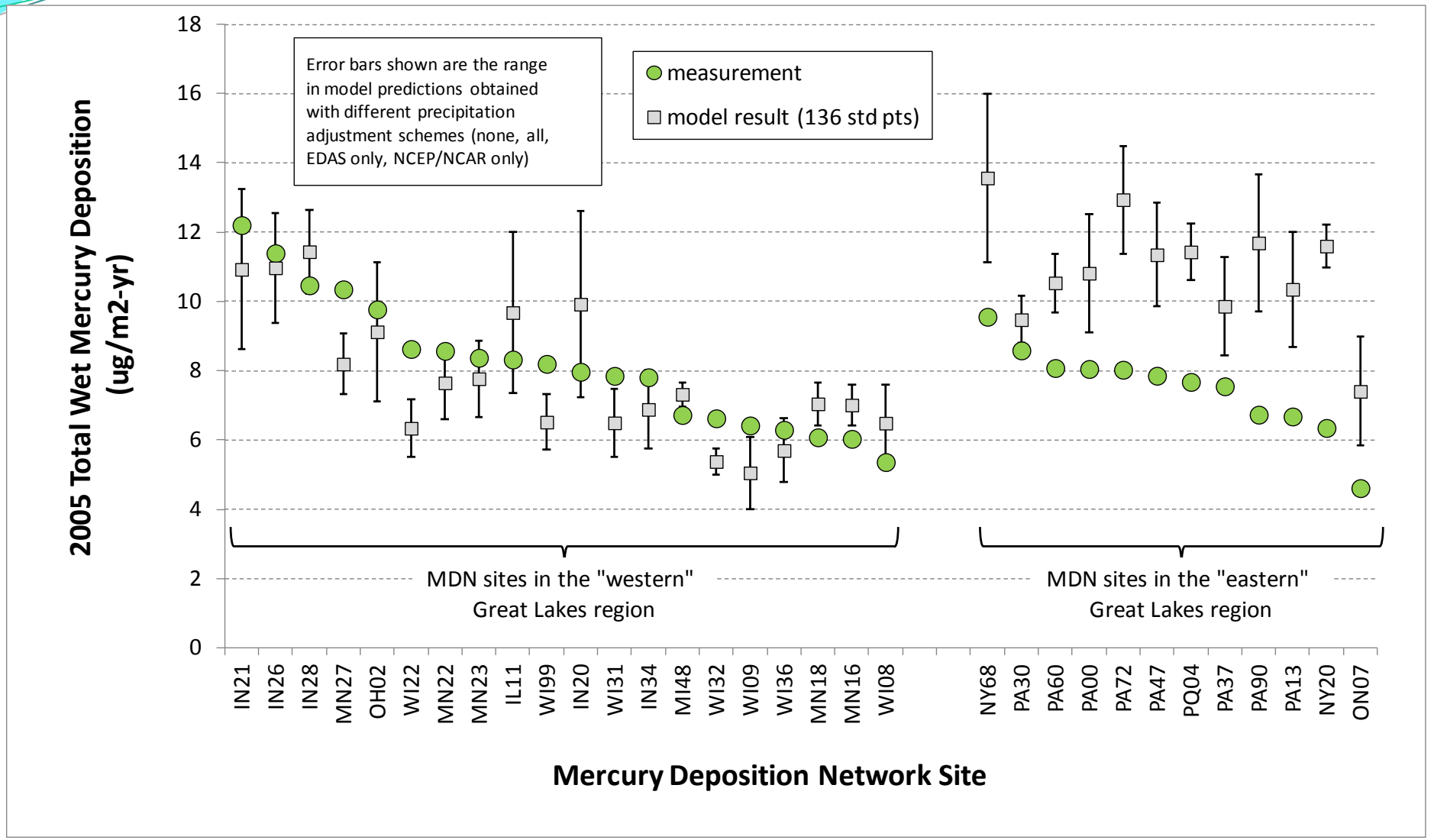
Comparison of 2005 precipitation total as measured at MDN sites in the Great Lakes region (circles) with precipitation totals assembled by the PRISM Climate Group, Oregon State University



Modeled vs. Measured Wet Deposition of Mercury at Sites in the Great Lakes Region



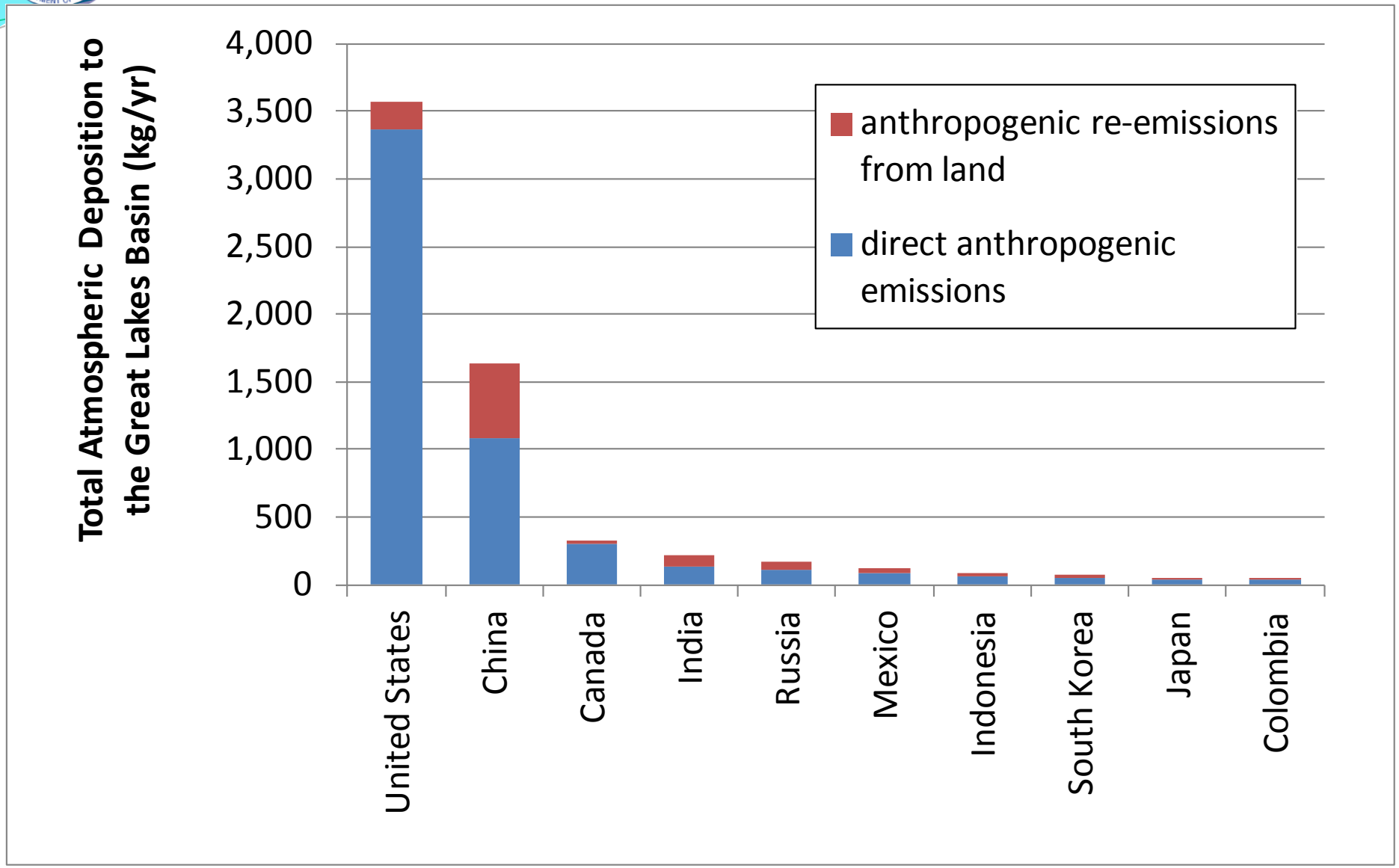
Modeled vs. Measured Wet Deposition of Mercury at Sites in the Great Lakes Region



Summary of Mercury Emissions Inventories Used in GLRI Analysis

Inventory	domain	Number of records	Hg(0) emissions (Mg/yr)	RGM emissions (Mg/yr)	Hg(p) emissions (Mg/yr)	Total mercury emissions (Mg/yr)
U.S. Point Sources	United States	19,353	50.6	35.5	9.1	95
U.S. Area Sources	United States	44,848	4.5	1.8	1.1	7.4
Canadian Point Sources	Canada	166	3.0	1.7	0.4	5.1
Canadian Area Sources	Canada	12,372	1.0	0.96	0.42	2.4
Mexican Point Sources	Mexico	268	28	0.81	0.46	29
Mexican Area Sources	Mexico	160	1.25	0.38	0.25	1.9
Global Anthropogenic Sources not in U.S., Canada, or Mexico	Global, except for the U.S., Canada, and Mexico	52,173	1,239	434	113	1,786
Global Re-emissions from Land	Global land (and freshwater) surfaces	129,180	750	0	0	750
Global Re-emissions from the Ocean	Global oceans	43,324	1,250	0	0	1,250
Global Natural Sources	Global	64,800	1,800	0	0	1,800
Total		366,804	5,127	475	125	5,728

Model-estimated 2005 deposition to the Great Lakes Basin from countries with the highest modeled contribution from direct and re-emitted anthropogenic sources



Model-estimated *per capita* 2005 deposition to the Great Lakes Basin from countries with the highest modeled contribution from direct & re-emitted anthropogenic sources