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

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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 from Large Point Sources

Emissions (kg/yr)
- ▲ 5–10
- ○ 10–50
- △ 50–100
- □ 100–300
- □ 300–500
- □ 500–1000
- ○ 1000–3000

Type of Emissions Source
- Orange: coal-fired power plants
- Green: other fuel combustion
- Blue: waste incineration
- Purple: metallurgical
- Black: manufacturing & other
2005 Atmospheric Mercury Emissions
(Direct Anthropogenic + Re-emit + Natural)

Atmospheric mercury emissions (kg/yr)
from all sources in each 2x2 degree grid cell

// Map showing global distribution of atmospheric mercury emissions in 2005, with color coding to represent different emission levels.

// The map illustrates the emissions from various sources across the globe, with concentrations varying significantly from region to region.

// The data is likely derived from a comprehensive dataset that integrates direct anthropogenic sources, natural re-emissions, and other factors contributing to atmospheric mercury levels globally.

// The map can be used to analyze the spatial distribution of mercury emissions, identify hotspots, and inform policy and mitigation strategies to control or reduce these emissions.
To simulate the global transport of mercury, puffs are transferred to an Eulerian grid after a specified time downwind (~3 weeks), and the mercury is simulated on that grid from then on.

This is how we model the local & regional impacts.

But for global modeling, puff splitting overwhelms computational resources.

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

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**

Impact of source 4 estimated from weighted average of impacts of nearby explicitly modeled sources

Impacts from Sources 1-3 are Explicitly Modeled

RECEPTOR
**Chemical Interpolation**

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

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

- MDN sites in the "western" Great Lakes region
- MDN sites in the "eastern" Great Lakes region
- 1:1 line
- Linear (MDN sites in the "western" Great Lakes region)
- Linear (MDN sites in the "eastern" Great Lakes region)

Error bars shown are the range in model predictions obtained with different precipitation adjustment schemes (none, all, EDAS only, NCEP/NCAR only)
Overestimates for wet deposition found for these sites
2005 Atmospheric Mercury Emissions (Direct Anthropogenic + Re-emit + Natural)

Atmospheric mercury emissions (kg/yr) from all sources in each 2x2 degree grid cell
Keep track of the contributions from each source, and add them up.

Geographical Distribution of 2005 Atmospheric Mercury Deposition Contributions to Lake Erie

Atmospheric mercury deposition contribution (g/yr) to Lake Erie from all emissions sources in each 2x2 degree grid cell.
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

Based on estimated 2005 mercury emissions, e.g., from the 2005 USEPA National Emissions Inventory, and atmospheric fate and transport simulations with the NOAA HYSPLIT-Hg model.
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)

- **U.S.**: 45%
- **China**: 11%
- **Canada**: 4%
- **Mexico**: 1%
- **India**: 1%
- **Other countries**: 9%
- **Ocean re-emission**: 11%
- **Natural**: 18%

Contributions to 2005 Atmospheric Mercury Deposition to the Great Lakes Basin (EDAS met data)

- **U.S.**: 23%
- **China**: 17%
- **Canada**: 2%
- **Mexico**: 1%
- **India**: 2%
- **Other countries**: 13%
- **Ocean re-emission**: 16%
- **Natural**: 26%

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

- **U.S.**: 34%
- **China**: 16%
- **Canada**: 3%
- **Mexico**: 1%
- **India**: 2%
- **Other countries**: 12%
- **Ocean re-emission**: 16%
- **Natural**: 20%

Contributions to 2005 Atmospheric Mercury Deposition to the Great Lakes Basin (NARR met data)

- **U.S.**: 19%
- **China**: 20%
- **Canada**: 1%
- **Mexico**: 1%
- **India**: 3%
- **Other countries**: 16%
- **Ocean re-emission**: 20%
- **Natural**: 20%
Thanks!

This work was partially funded through the Great Lakes Restoration Initiative.
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](http://www.arl.noaa.gov/documents/reports/GLRI_Atmos_Mercury_Summary.pdf)

- **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:

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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
Dry and wet deposition of the pollutants in the puff are estimated at each time step.

The puff’s mass, size, and location are continuously tracked…

Phase partitioning and chemical transformations of pollutants within the puff are estimated at each time step.

Centerline of puff motion determined by wind direction and velocity

= mass of pollutant
(changes due to chemical transformations and deposition that occur at each time step)

Initial puff location is at source, with mass depending on emissions rate

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

Deposition (ng/m^2-hr) at ground-level
Integrated from 0000 01 May to 0100 01 May 05 (UTC)
RGM Release started at 0000 01 May 05 (UTC)

Results scaled to actual RGM emissions of 43.6 g/hr

1 ng/m^2-hr = 8.8 ug/m^2-yr (if it persisted the entire year)

Total deposition to Lk Erie is ~20 ug/m^2-yr
an example for one source... the Monroe coal-fired power plant on the shore of Lake Erie
- 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

- **HYSLIT**

- **HYSLIT-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

- **Evaluate** overall model results: compare against ambient measurements

- **Source-attribution** results for deposition to selected receptors
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

Evaluate overall model results: compare against ambient measurements

Source-attribution results for deposition to selected receptors
Cumulative Fraction of Total Modeled Mercury Deposition to Lake Erie (2005)

Rank of Source's Atmospheric Mercury Deposition Contribution to Lake Erie

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[Graph showing cumulative fraction of modeled mercury deposition to Lake Erie (2005)]
Sources of Mercury Deposition to the Great Lakes Basin 2005 Baseline Analysis

- Natural: 23%
- Ocean Re-emission: 14%
- U.S.: 32%
- China: 14%
- India: 2%
- Canada: 3%
- Other Countries: 12%

Total = 11,300 kg/yr
Sources of Mercury Deposition to the Lake Erie Basin
2005 Baseline Analysis

- U.S.: 49%
- China: 10%
- Canada: 4%
- India: 1%
- Other Countries: 9%
- Natural: 17%
- Ocean Re-emission: 10%

Total = 2,300 kg/yr
ARL’s GLRI Atmospheric Mercury Modeling Project

A multi-phase project

Jan 1, 2009
Initial Inter- and Intra-Agency Planning for FY10 GLRI Funds

Jan 1, 2010
FY10 $ Baseline Analysis for 2005

Jan 1, 2011
FY11 $ Sensitivity Analysis + Extended Model Evaluation

Jan 1, 2012
FY12 $ Scenario Analysis

Jan 1, 2013
FY13 $(proposed) Update Analysis (~2008)

Jan 1, 2014
FY14 $(proposed) Update Analysis (~2011)

Jan 1, 2015

Jan 1, 2016

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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.


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.
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

Release height 50 m vs 250 m

Met data (EDAS vs. NARR)

Fortran compilation

Time step

Puff lifetime

Number of puffs

Deposition modeling

Chemistry and Partitioning

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

- Release height: 50 m vs 250 m
- Met data (EDAS vs. NARR)
- Fortran compilation
- Time step
- Puff lifetime
- Number of puffs
- Deposition modeling
- Chemistry and Partitioning

- Fraction of RGM deposited
- Fortran compilation
- Time step
- Puff lifetime
- Number of puffs
- Deposition modeling
- Chemistry and Partitioning
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.
Atmospheric Mercury Deposition

<table>
<thead>
<tr>
<th>Great Lake</th>
<th>Atmospheric Mercury Deposition (ug/m²-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erie</td>
<td>Natural: 5, Ocean Re-Emit: 3, All Other Countries: 2, Canada: 1, China: 1, United States: 8</td>
</tr>
<tr>
<td>Ontario</td>
<td>Natural: 7, Ocean Re-Emit: 2, All Other Countries: 2, Canada: 1, China: 2, United States: 6</td>
</tr>
<tr>
<td>Michigan</td>
<td>Natural: 3, Ocean Re-Emit: 1, All Other Countries: 1, Canada: 1, China: 1, United States: 4</td>
</tr>
<tr>
<td>Huron</td>
<td>Natural: 4, Ocean Re-Emit: 1, All Other Countries: 1, Canada: 1, China: 1, United States: 3</td>
</tr>
<tr>
<td>Superior</td>
<td>Natural: 4, Ocean Re-Emit: 1, All Other Countries: 1, Canada: 1, China: 1, United States: 3</td>
</tr>
</tbody>
</table>
Atmospheric Mercury Fate Processes

Upper atmospheric halogen-mediated oxidation?

Polar sunrise “mercury depletion events”

Vapor phase:
Hg(0) oxidized to RGM and Hg(p) by O₃, H₂O₂, Cl₂, OH, HCl

Primary Anthropogenic Emissions

Natural emissions
Re-emission of previously deposited anthropogenic and natural mercury

Multi-media interface

Wet deposition
Dry deposition

Hg(II) reduced to Hg(0) by SO₂ and sunlight

Hg(0) oxidized to dissolved Hg(II) species by O₃, OH, HOCI, OCl⁻

Adsorption/desorption of Hg(II) to/from soot

Cloud droplet

Elemental Mercury [Hg(0)]
Hg(II), ionic mercury, RGM
Particulate Mercury [Hg(p)]
### GAS PHASE REACTIONS

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate</th>
<th>Units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Hg}^0 + \text{O}_3 \rightarrow \text{Hg}(p) )</td>
<td>3.0E-20</td>
<td>cm(^3)/molec-sec</td>
<td>Hall (1995)</td>
</tr>
<tr>
<td>( \text{Hg}^0 + \text{HCl} \rightarrow \text{HgCl}_2 )</td>
<td>1.0E-19</td>
<td>cm(^3)/molec-sec</td>
<td>Hall and Bloom (1993)</td>
</tr>
<tr>
<td>( \text{Hg}^0 + \text{H}_2\text{O}_2 \rightarrow \text{Hg}(p) )</td>
<td>8.5E-19</td>
<td>cm(^3)/molec-sec</td>
<td>Tokos et al. (1998) (upper limit based on experiments)</td>
</tr>
<tr>
<td>( \text{Hg}^0 + \text{Cl}_2 \rightarrow \text{HgCl}_2 )</td>
<td>4.0E-18</td>
<td>cm(^3)/molec-sec</td>
<td>Calhoun and Prestbo (2001)</td>
</tr>
<tr>
<td>( \text{Hg}^0 + \text{OH} \rightarrow \text{Hg}(p) )</td>
<td>8.7E-14</td>
<td>cm(^3)/molec-sec</td>
<td>Sommar et al. (2001)</td>
</tr>
<tr>
<td>( \text{Hg}^0 + \text{Br} \rightarrow \text{HgBr}_2 )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### AQUEOUS PHASE REACTIONS

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate</th>
<th>Units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Hg}^0 + \text{O}_3 \rightarrow \text{Hg}^{+2} )</td>
<td>4.7E+7</td>
<td>(molar-sec(^{-1}))</td>
<td>Munthe (1992)</td>
</tr>
<tr>
<td>( \text{Hg}^0 + \text{OH} \rightarrow \text{Hg}^{+2} )</td>
<td>2.0E+9</td>
<td>(molar-sec(^{-1}))</td>
<td>Lin and Pehkonen (1997)</td>
</tr>
<tr>
<td>( \text{HgSO}_3 \rightarrow \text{Hg}^0 )</td>
<td>( T \times e^{((31.971 \times T) - 12595.0)/T} ) sec(^{-1})</td>
<td>Van Loon et al. (2002)</td>
<td></td>
</tr>
<tr>
<td>( \text{Hg(II)} + \text{HO}_2 \rightarrow \text{Hg}^0 )</td>
<td>~ 0</td>
<td>(molar-sec(^{-1}))</td>
<td>Gardfeldt &amp; Jonnson (2003)</td>
</tr>
<tr>
<td>( \text{Hg}^0 + \text{HOCl} \rightarrow \text{Hg}^{+2} )</td>
<td>2.1E+6</td>
<td>(molar-sec(^{-1}))</td>
<td>Lin and Pehkonen (1998)</td>
</tr>
<tr>
<td>( \text{Hg}^0 + \text{OCl}^{-1} \rightarrow \text{Hg}^{+2} )</td>
<td>2.0E+6</td>
<td>(molar-sec(^{-1}))</td>
<td>Lin and Pehkonen (1998)</td>
</tr>
<tr>
<td>( \text{Hg(II)} \leftrightarrow \text{Hg(II)} \text{(soot)} )</td>
<td>9.0E+2</td>
<td>liters/gram; ( t = 1/\text{hour} )</td>
<td>eqlbrm: Seigneur et al. (1998) rate: Bullock &amp; Brehme (2002).</td>
</tr>
<tr>
<td>( \text{Hg}^{+2} + \text{hv} \rightarrow \text{Hg}^0 )</td>
<td>6.0E-7</td>
<td>(sec(^{-1})) (maximum)</td>
<td>Xiao et al. (1994); Bullock and Brehme (2002)</td>
</tr>
</tbody>
</table>
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)

2005 chosen for baseline analysis

Dataset Available for 2005

Need all of these datasets for the same year
Over the entire modeling period (e.g., one year), puffs are released at periodic intervals (e.g., once every 7 hours).

Each released puff is advected and dispersed, and the pollutant within the puff is transformed and deposited.
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
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.
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:

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

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

\[
= \text{transfer flux coefficient} \left( \frac{1}{\text{km}^2} \right) \times \text{source mercury emissions} \left( \frac{g}{\text{yr}} \right)
\]
\[
\text{deposition flux rate} = \frac{\text{grams Hg deposited per year}}{\text{km}^2 \text{ of receptor area}} \left( \frac{g}{\text{km}^2 \text{yr}} \right)
\]

\[
= \text{transfer flux coefficient} \left( \frac{1}{\text{km}^2} \right) \times \text{source mercury emissions} \left( \frac{g}{\text{yr}} \right)
\]
Transfer Flux Coefficients for Pure Elemental Mercury Emissions from Selected Locations to Lake Erie

Transfer Flux Coefficient "X" for Elemental Mercury Emissions

\[ X = \frac{\text{grams Hg deposited per year}}{(\text{km}^2)} \]  

\[ \text{[}\text{grams Hg emitted per year from the source]} \]  

\[ \text{[=]} \text{1/km}^2 \]
Transfer Flux Coeff. "X" for Reactive Gaseous Mercury Emissions from Selected Locations to Lake Erie

$$X = \frac{\text{grams Hg deposited per year}}{\text{(km2)}}$$

$$\text{grams Hg emitted per year from the source}$$

[=] 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.
The “Transfer Flux Coefficient” is calculated as the atmospheric deposition flux to a given receptor (in this case, Lake Erie) in units of $g/km^2 \cdot yr$, 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)

Atmospheric mercury emissions (kg/yr) from direct anthropogenic sources in each 2x2 degree grid cell
Natural mercury emissions

Atmospheric mercury emissions (kg/yr) from natural sources in each 2x2 degree grid cell
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

- max sample or rain gauge precip
- sample precip
- rain gauge precip
- NCEP/NCAR Reanalysis precip
- EDAS precip

Measured and Modeled Precipitation (m/yr)

NOAA Air Resources Laboratory

Discussion July 5, 2012
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

![Graph showing modeled vs. measured wet deposition of mercury](image)

- **Modeled Mercury Wet Deposition (ug/m^2-yr)**
- **Measured Mercury Wet Deposition (ug/m^2-yr)**

- Model result (136 std pts)
- 1:1 line
- Linear Regression

Error bars shown are the range in model predictions obtained with different precipitation adjustment schemes (none, all, EDAS only, NCEP/NCAR only)

NOAA Air Resources Laboratory

Discussion July 5, 2012
Modeled vs. Measured Wet Deposition of Mercury at Sites in the Great Lakes Region

Error bars shown are the range in model predictions obtained with different precipitation adjustment schemes (none, all, EDAS only, NCEP/NCAR only).

- **measurement**
- **model result (136 std pts)**

### 2005 Total Wet Mercury Deposition (ug/m²-yr)

- **MDN sites in the "western" Great Lakes region**
- **MDN sites in the "eastern" Great Lakes region**

**Mercury Deposition Network Site**

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### Summary of Mercury Emissions Inventories Used in GLRI Analysis

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