Present-day sources and past variability of mercury in the Arctic atmosphere and ocean

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Mercury in the Arctic Ocean: an ecological and human health concern

Methylmercury is a potent neurotoxin that bioaccumulates in marine food webs.

High mercury concentrations have been observed in Arctic species that make up traditional northern diets.

Atmospheric transport brings mercury to the Arctic, but atmosphere-ocean cycling is uncertain.

Goal:
Understand the factors contributing to elevated mercury in the Arctic atmosphere & ocean

AMAP 2011
The atmosphere-ocean mercury cycle - an Arctic perspective

Mid-latitudes

Arctic

The diagram illustrates the atmospheric-ocean mercury cycle with a focus on different regions: Mid-latitudes and Arctic. It shows the transformation of mercury between its elemental (Hg0) and inorganic (HgII) forms. The cycle includes processes such as geogenic and anthropogenic emissions, biomass burning, and vegetation, soil, and snow contributions. The ocean surface and subsurface are also depicted, highlighting the exchange of mercury between these compartments.
The atmosphere-ocean mercury cycle - an Arctic perspective

Mid-latitudes

Ocean subsurface

Arctic

Snow/ice

Hg$^0$ ↔ Hg$^{II}$

Hg$^0$ ↔ Hg$^{II}$
The atmosphere-ocean mercury cycle - an Arctic perspective
The unique seasonal cycle of Arctic mercury

Observations: multi-year mean over three Arctic sites (Alert, Amderma, Zeppelin)

Can we explain the summer peak using our standard understanding of mercury cycling?
The GEOS-Chem biogeochemical mercury model:

- Global, gridded model
- Driven by input meteorology from an assimilated GCM
- 3-D atmosphere: emissions, chemistry, transport, and deposition
- 2-D slab ocean mixed layer: chemistry, evasion, subsurface mixing and export
- Cryospheric processes: AMDEs, snowpack re-emission, snowmelt delivery to ocean

Represents our best *a priori* understanding of mercury sources & processes
Testing our current understanding: model comparison to atmospheric observations

Observations: multi-year mean over three Arctic sites

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Testing our current understanding: model comparison to atmospheric observations

**Observations:** multi-year mean over three Arctic sites

**Model:** GEOS-Chem at these sites in 2008

Can we explain the summer peak using our standard understanding of mercury cycling?
Hypothesis 1: atmospheric transport from mid-latitudes

The Arctic atmosphere is a net exporter -- not a net importer -- of mercury in summer.
Hypothesis 2: re-emission from snowpack and ice

Mercury does not remain in snow long enough to explain peak
Hypothesis 3: chemical kinetics in the Arctic surface ocean

Total Hg pool is depleted in summer, so ocean chemistry cannot create enough Hg$^0$
Hypothesis 4: a large source from circumpolar rivers

With a large river / coastal erosion source included, GEOS-Chem can reproduce the observed summer peak — a promising hypothesis, but more data are needed!
Proposed budget of mercury in the Arctic surface ocean

Atmosphere

- Snowpack emission: 31 Mg
- Deposition to snow/ice: 61 Mg

Snow on Land and Sea Ice

- Soil accumulation: 10 Mg
- Deposition to snow/ice: 61 Mg

Surface Ocean Mixed Layer

- $[\text{Hg}_0] = 0.15 \text{ pM}$
- $[\text{THg}] = 2.7 \text{ pM}$

- Meltwater: 20 Mg
- Net exchange: 2 Mg

Subsurface Waters

- $[\text{Hg}_0] = 0.12 \text{ pM}$
- $[\text{THg}] = 1.6 \text{ pM}$

Rivers & Coasts

- River delivery and erosion: 95 Mg
- Net atmospheric export: 34 Mg

All fluxes in Mg a$^{-1}$
Factors affecting Arctic mercury have changed dramatically. Factors affecting Arctic mercury have changed dramatically.

Hg emissions growth: 1979-2010

Air temperature change: 1979-2010

May sea ice extent trend: 1979-2010

What are the implications for past — and future — variability in Arctic Hg?
Combined model-observation analysis lends insight

1. 30-year GEOS-Chem simulation of Arctic Hg (1979-2008)

2. Evaluated by long-term atmospheric observations
   Alert, Canada (1995-2008)
   Zeppelin, Ny Ålesund (2000-2008)
   Pallas, Finland (1996-2008)

3. Extended to simulation of surface ocean, where long-term records unavailable
We use interannual variability to identify drivers of change

Focus on unique Arctic signatures in spring and summer

Spring-summer trends are negligible, but IAV is large in observations & model
Atmospheric Hg variability governed by a combination of meteorological drivers

Impacts of high T + low sea ice + high radiation + shallow PBL

Environmental drivers of IAV identified using a principal component analysis (PCA).
Dominant mode explains 80% IAV in spring, 43% in summer.
Surface ocean mercury driven by snowmelt & rivers

Arctic ocean mercury and IAV peak in summer

No trends in surface ocean mercury
Surface ocean mercury driven by snowmelt & rivers

Arctic ocean mercury and IAV peak in summer

No trends in surface ocean mercury

Surface ocean inputs increase with:
- Meltwater
  - ↑ summer solar radiation (↓ cloudiness)
  - ↑ spring-summer T difference = ΔT
- Rivers
  - ↑ May river flow
- Deposition
  - ↑ summer wind speed
Surface ocean mercury driven by snowmelt & rivers

Arctic ocean mercury and IAV **peak in summer**

No trends in surface ocean mercury

**SUMMER**

Surface ocean inputs increase with:

- **Meltwater**
  - ↑ summer solar radiation (↓ cloudiness)
  - ↑ spring-summer T difference = ΔT

- **Rivers**
  - ↑ May river flow

- **Deposition**
  - ↑ summer wind speed

**GCMs predict future ↑ cloudiness & ↓ ΔT → less Hg may be added to the Arctic Ocean in future!**