Implications of Arctic sea ice reduction on bromine explosion, ozone depletion, and mercury deposition


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Outline

• Arctic sea ice reduction
• Impacts on tropospheric chemical processes
Sea Ice Composition: Two Major Ice Classes

• Perennial sea ice: Surviving at least a summer melt, multi-year age, thick ice, important to ice mass and ice pack stability.

• Seasonal sea ice: Thinner ice, forming and melting away seasonally.
Comparison of:
- Satellite results (left column).
- Drift-age model from buoys data (right column).

Red line represents the boundary of perennial ice from the Drift-Age Model (>1 year)

Perennial Sea Ice Change 1957-1999

Before 1970:
No discernable trend in March perennial ice extent.

1970-1999:
Decrease of $0.5 \times 10^6$ km$^2$ per decade in March perennial ice extent as estimated from the Drift-Age model.
2000-2008: Decrease of $1.5 \times 10^6$ km$^2$ per decade in March perennial ice extent as measured from QuikSCAT data and estimated from the Drift-Age model.

TRIPLE THE LOSS RATE in the previous three decades
‘The Polar Express’

Ice loss mechanism in any season (not just summer)

Ice compression from East to West Arctic

Ice compression into Transpolar Drift (TD)

Acceleration of TD\(^1\) carrying ice out of Arctic via Fram Strait

Warm Atlantic water effectively melted ice in Greenland Sea

Nghiem, Rigor, Perovich, Clemente-Colón, Weatherly, Neumann, GRL, 2007
The Polar Express in 2005

Barents-Sea low and Canadian-Basin high anomalies set up anomalous winds over Fram Basin and Greenland Sea.
The Polar Express in 2007

Dipole anomaly
ICE LOSS IN WINTER AND SPRING

Animation of sea ice
20 frames per second
9/2008 to 5/2009

SEA ICE CLASSES

Seasonal
Mixed ice
Perennial
Melt
Warm water from Mackenzie river discharge

5 July 2012

Map by D. Hall et al.
Impacts of Rapid Decrease of Arctic Perennial Sea Ice

- **Regime shift**: Arctic is dominated by seasonal sea ice.
- **Seasonal ice**: Younger, thinner, weaker, unstable.
- **Lower albedo and more solar heat**: Equivalent to ice thinning capacity of 1 m. (Perovich and Polashenski, GRL, 2012).

Implications

Perennial sea ice reduction

Arctic dominated by seasonal ice

Saltier ice surface over vast region with more: FY, leads, polynyas, frost flowers

More sources for bromine explosion causing more ozone depletion/mercury deposition
Photochemical Processes

**Cycle 1**: destroys O$_3$ and is autocatalytic in that it releases one additional Br atom to the gas phase

Br$_2$ + $h\nu$ → Br + Br \hspace{1cm} (1)

2(Br + O$_3$ → BrO + O$_2$) \hspace{1cm} (2)

2[BrO + HO$_2$ → HOBr(g) + O$_2$] \hspace{1cm} (3)

2[HOBr(g) → HOBr(l)] \hspace{1cm} (4)

2[HOBr(l) + HBr(l) → H$_2$O(l) + Br$_2$(g)] \hspace{1cm} (5)

**Net**: 2HO$_2$ + 2HBr + 2O$_3$ + $h\nu$ → 2H$_2$O + Br$_2$ + 4O$_2$
Photochemical Processes

Cycle 2:

\[
\begin{align*}
\text{BrCl} + h\nu & \rightarrow \text{Cl} + \text{Br} \\
\text{Br} + \text{O}_3 & \rightarrow \text{BrO} + \text{O}_2 \\
\text{Cl} + \text{O}_3 & \rightarrow \text{ClO} + \text{O}_2 \\
\text{BrO} + \text{HO}_2 & \rightarrow \text{HOBr(g)} + \text{O}_2 \\
\text{ClO} + \text{HO}_2 & \rightarrow \text{HOCl(g)} + \text{O}_2 \\
\text{HOBr(g)} & \rightarrow \text{HOBr(l)} \\
\text{HOBr(l)} + \text{HCl(l)} & \rightarrow \text{H}_2\text{O(l)} + \text{BrCl(g)}
\end{align*}
\]

Net: \[2\text{HO}_2 + \text{HCl(l)} + 2\text{O}_3 + h\nu \rightarrow \text{H}_2\text{O} + \text{HOCl(g)} + 4\text{O}_2\]
Equilibria (5) and (9) are complex:

\[ H^+ + Cl^- + HOBr(l) \rightarrow H_2O + BrCl(l) \]
\[ BrCl(l) \rightarrow BrCl(g) \]
\[ BrCl + Br^- \rightarrow Br_2Cl^- \]
\[ Br_2Cl^- \rightarrow Br_2 + Cl^- \]

Net: \[ H^+ + Br^-/Cl^- + HOBr \rightarrow H_2O + Br_2/BrCl \]
Comparison of pattern of vertical-column BrO observed by GOME-2 satellite (upper panel) with pattern of rising air pattern from model overlaid on topography (lower panel). Results show:

1. BrO pattern is consistent with RAP in the lower troposphere, and

2. high mountains limit BrO to the Alaskan North Slope and in the Canadian Shield to the east of Richardson and McKenzie mountains.

Nghiem and 17 co-authors, JGR, 2012
Objective: Understand and assess the impact of Arctic sea ice reduction on bromine explosion, ozone depletion, and mercury deposition in the Arctic environment.

- **Satellites:** OMI, GOME-2, SCIAMACHY, MODIS (Aqua/Terra), OLS, Oceansat-2, SSMIS, SMOS, TanDEM-X, Envisat ASAR, RADARSAT-2.

- **Airborne Components:**
  - Purdue Airborne Laboratory for Atmospheric Research (ALAR) Aircraft: Bromine, ozone, aerosol, temperature, pressure, wind, vertical profiling.
  - NASA P3 IceBridge – flight coordinated with IceBridge; data collected for BROMEX over Barrow, AK (BROMEX has > 5000 surface truths).

- **Surface Components:**
  - IceLanders (chemistry buoys), SVPs/USNA (meteorological buoys) in Chukchi/Beaufort Seas: Bromine, ozone, wind, temperature, radiation.
  - Sea Ice Site: Full mercury speciation/fluxes, forced condensation, snow tower/sampling, sea ice coring, seawater, meteorology, bio., acoustics.
  - Tundra/Land Site: Full mercury speciation/fluxes, bromine/chloride/ozone suite, radiation tower, weather station, and snow tower/sampling.

- **Events occurred during BROMEX for new science discoveries:**
  - Major lead formations (as wide as 50 km), frost flowers, multiple sea ice mixtures (frazil ice, nilas, first-year ice, multi-year ice, ridges).
  - Wind change (0 to >20 knots), clear sky, extensive plumes from leads.
  - Bromine explosions (like firework), ozone and mercury depletion events


- **Outreach:** NASA Press Release March 2012; outreach activities in Barrow

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**Icelanders on sea ice: Chukchi Sea and Beaufort Sea**

**Sea Ice Site:** mercury, sea ice snow, seawater, meteorology biochemistry, acoustics, and optics

**Tundra weather station**

**Tundra surface sensors**

**Snow sampling**

**Land station center**

**Chemistry instrument**
Satellite Observation of BrO
Global Ozone Monitoring Experiment-2 (GOME-2)

GOME-2 BrO 2012/03/11

Bromine explosion

Barrow
Aircraft Observation of BrO

P. Shepson of Purdue U., U. Heidelberg, and BROMEX Team

Increasing altitude → decreasing BrO

highest conc. above

highest conc. at flight altitude

viewing direction (approximated)

Time UTC on 03/15/2012
Halogen Activation in the Arctic Boundary Layer

Vertical structures of BrO show high levels of BrO that are aloft at times

IceLander-2 on Sea Ice

IceLander-2 drift across lead

Polar Bear at IL2

William R. Simpson, Steven J. Walsh, Peter Peterson, and the BROMEX team

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Mercury Measurements

• Investigate how sea ice affects deposition and emission of Hg along the coast and over sea ice
• Quantify Hg in the atmosphere and in surface snow over sea ice and the tundra
• Results
  – Direct links between atmospheric Hg dynamics and open leads in sea ice
  – Snow over sea ice retains more deposited Hg than over tundra
• Importance
  – Climate change is altering sea ice distribution which will alter Hg deposition and retention in the Arctic

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