Bionature, Lisbon, March 2013
Keynote Presentation

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

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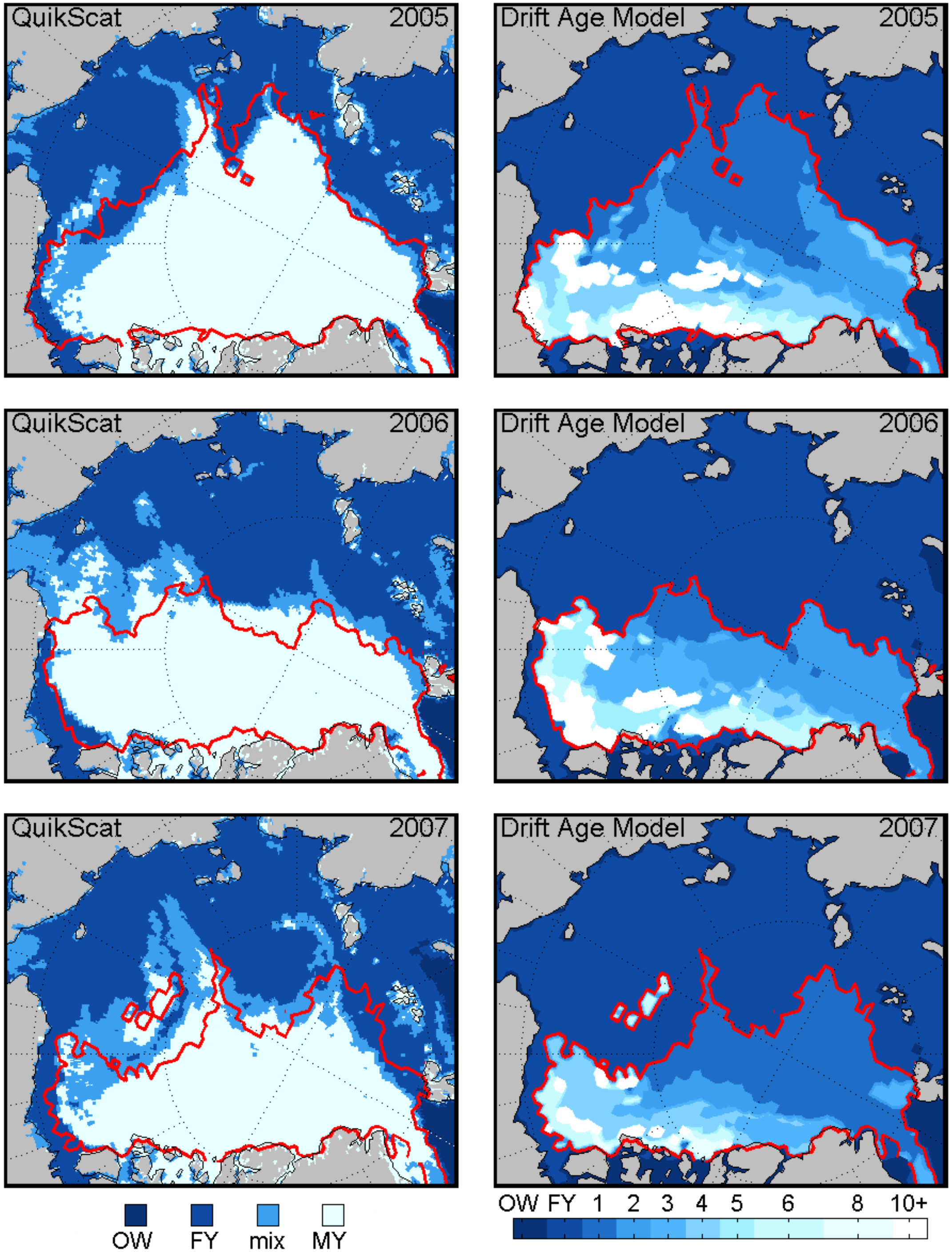
Outline

- 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.

Sea Ice Composition



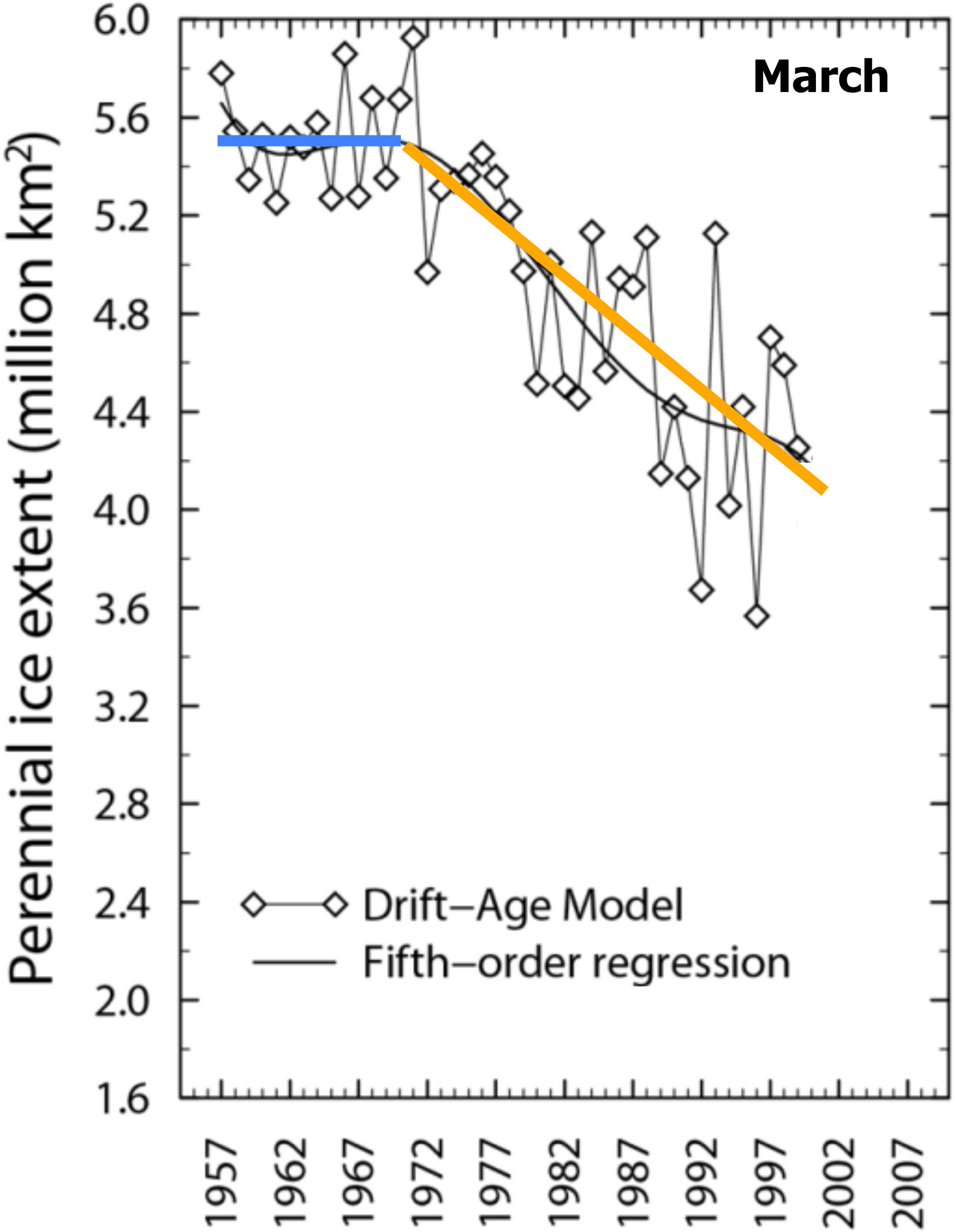
Comparison of:

- Satellite results (left column).
- Drift-age model from buoys data (right column).

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

Nghiem, Rigor, Perovich, Clemete-Colón, Weatherly, and Neumann, GRL, 2007.

Perennial Sea Ice Change 1957-1999



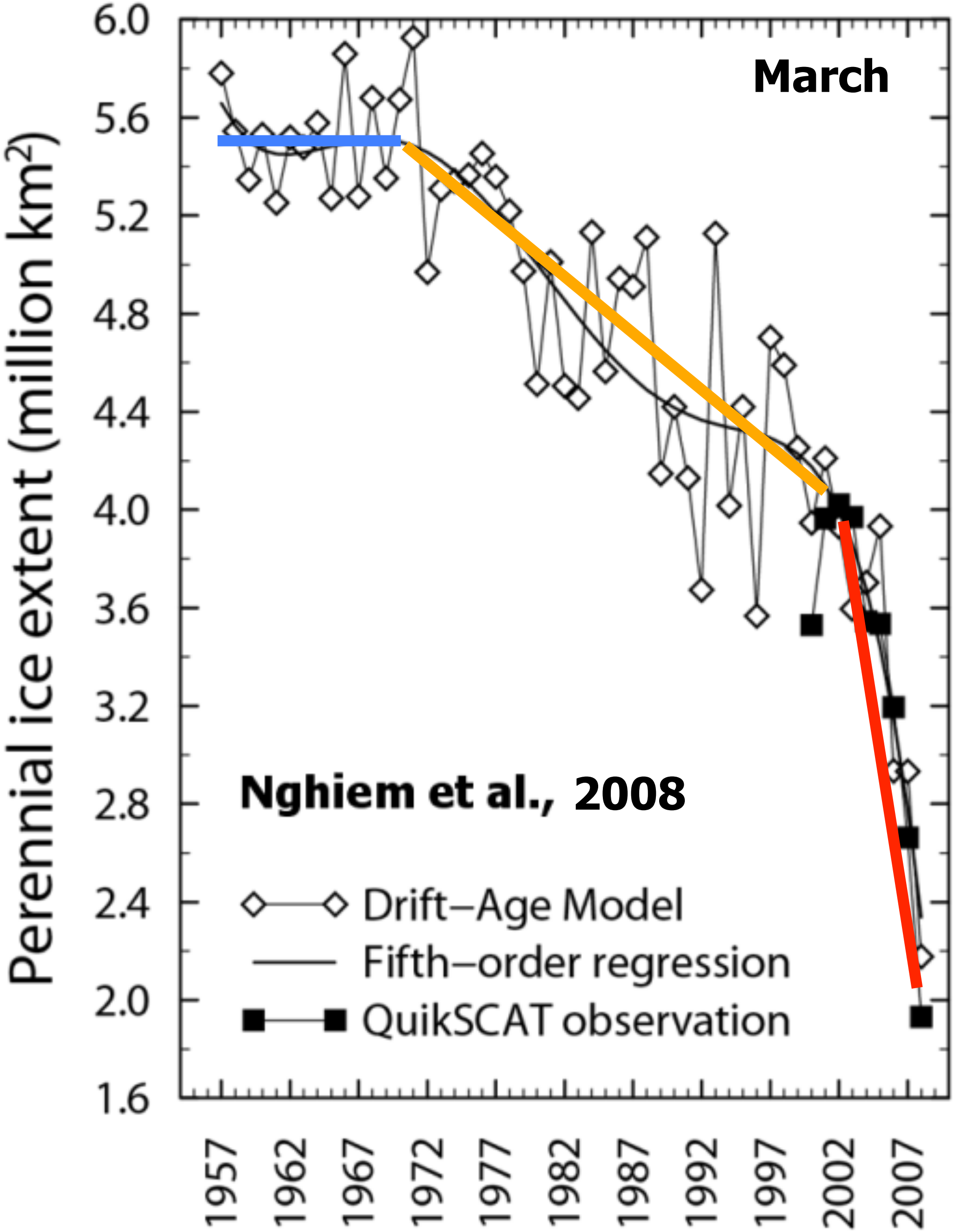
Before 1970:

No discernable trend in March perennial ice extent.

1970-1999:

Decrease of 0.5×10^6 km^2 per decade in March perennial ice extent as estimated from the Drift-Age model.

Perennial Sea Ice Change 1957-2008



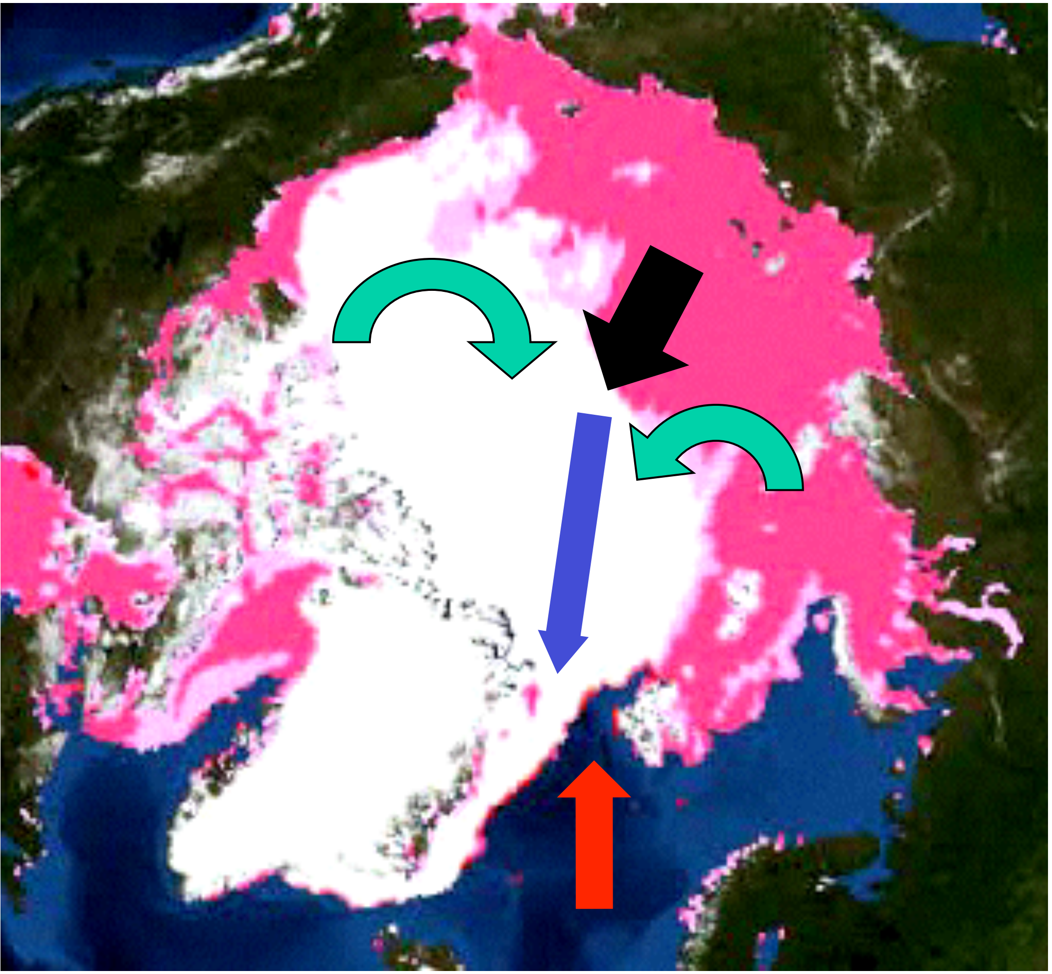
2000-2008:

Decrease of 1.5×10^6 km² per decade in March perennial ice extent as measured from <u>QuikSCAT data</u> and estimated from the Drift-Age model.

<u>TRIPLE THE LOSS RATE</u> 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)

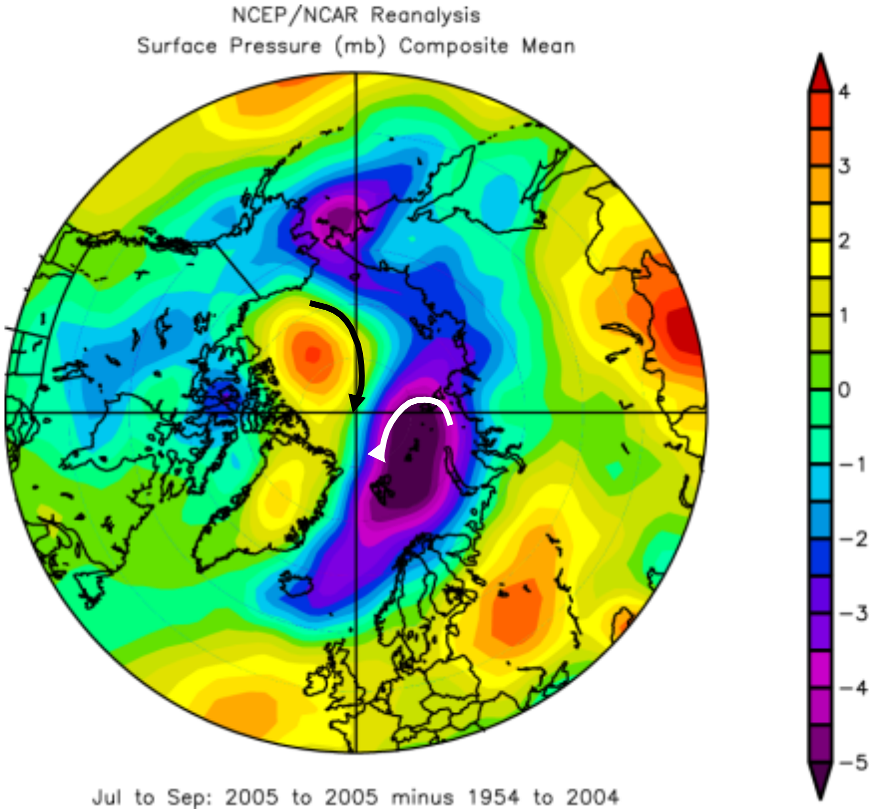
Acceleration of TD[1] carrying ice out of Arctic via Fram Strait

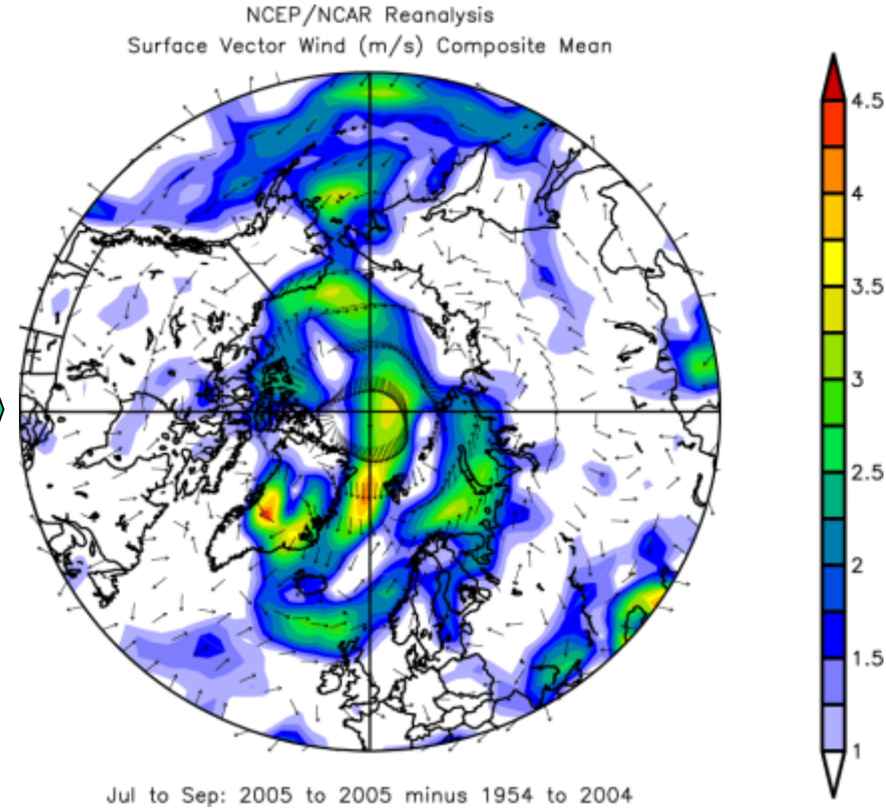
Warm Atlantic water effectively melted ice in Greenland Sea

Nghiem, Rigor, Perovich, Clemete-Colón, Weatherly, Neumann, GRL, 2007

The Polar Express in 2005

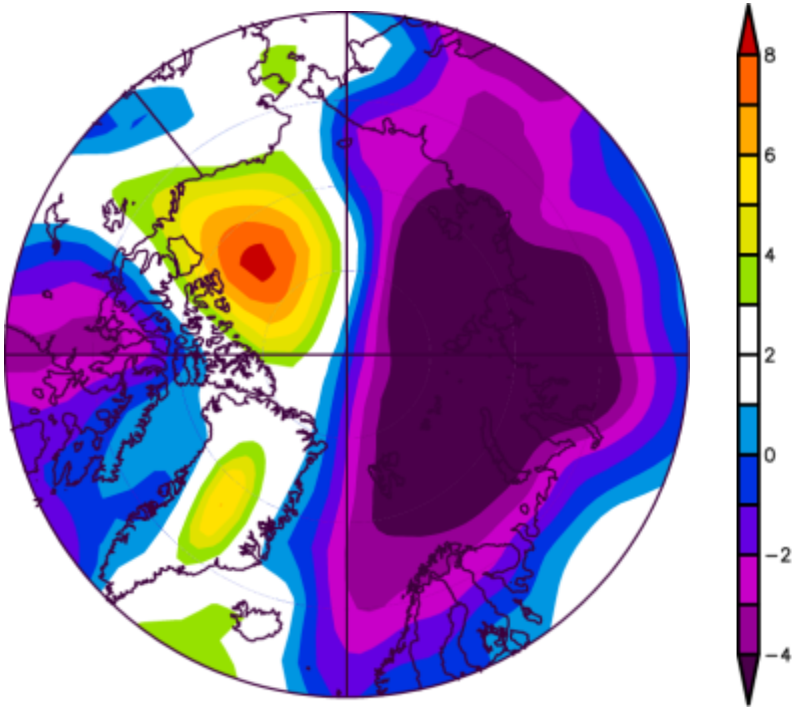
Barents-Sea low and Canadian-Basin high anomalies set up anomalous winds over Fram Basin and Greenland Sea



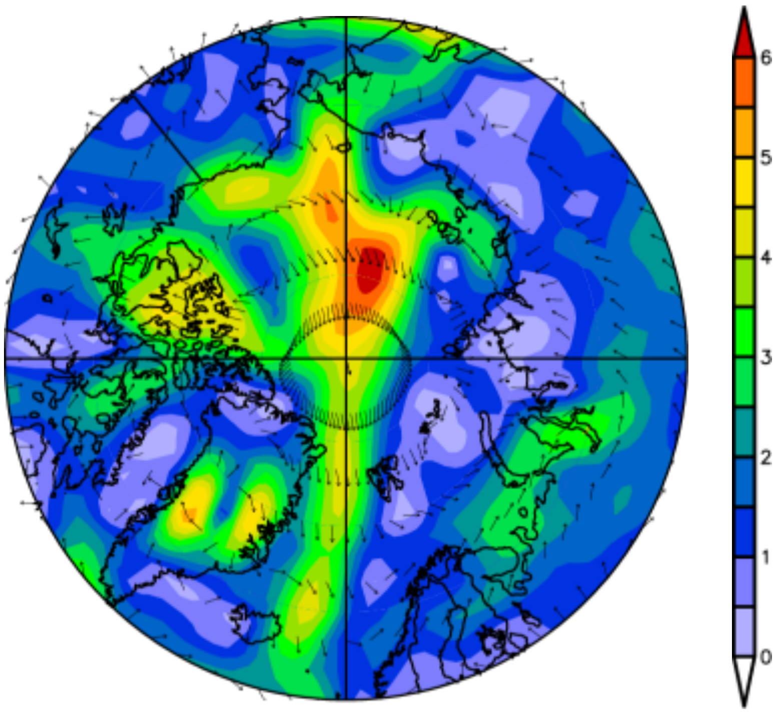


Dipole anomaly

The Polar Express in 2007



Aug: 2007 to 2007 minus 1950 to 2006



Aug: 2007 to 2007 minus 1950 to 2006

Dipole anomaly

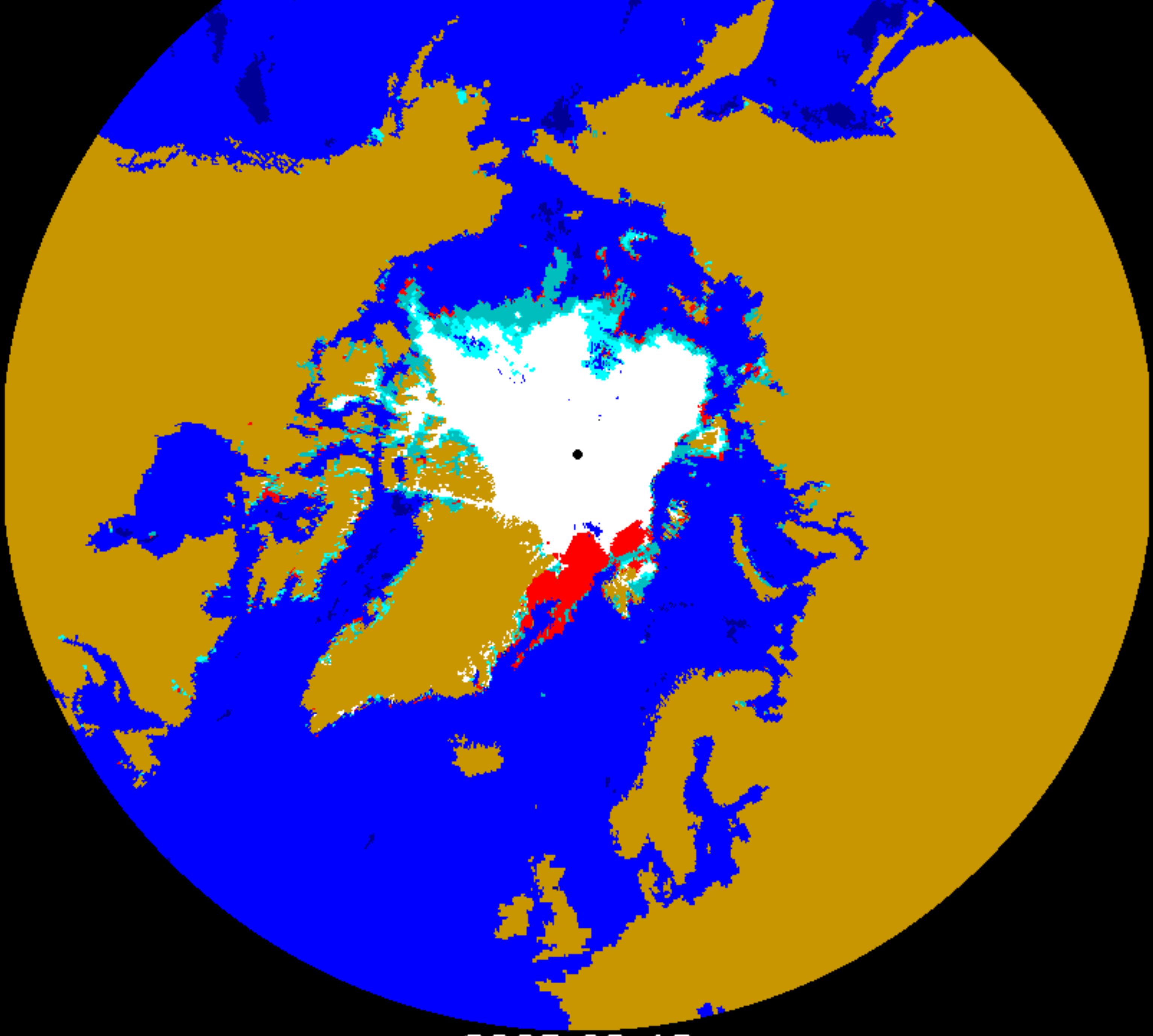
ICE LOSS IN WINTER AND SPRING

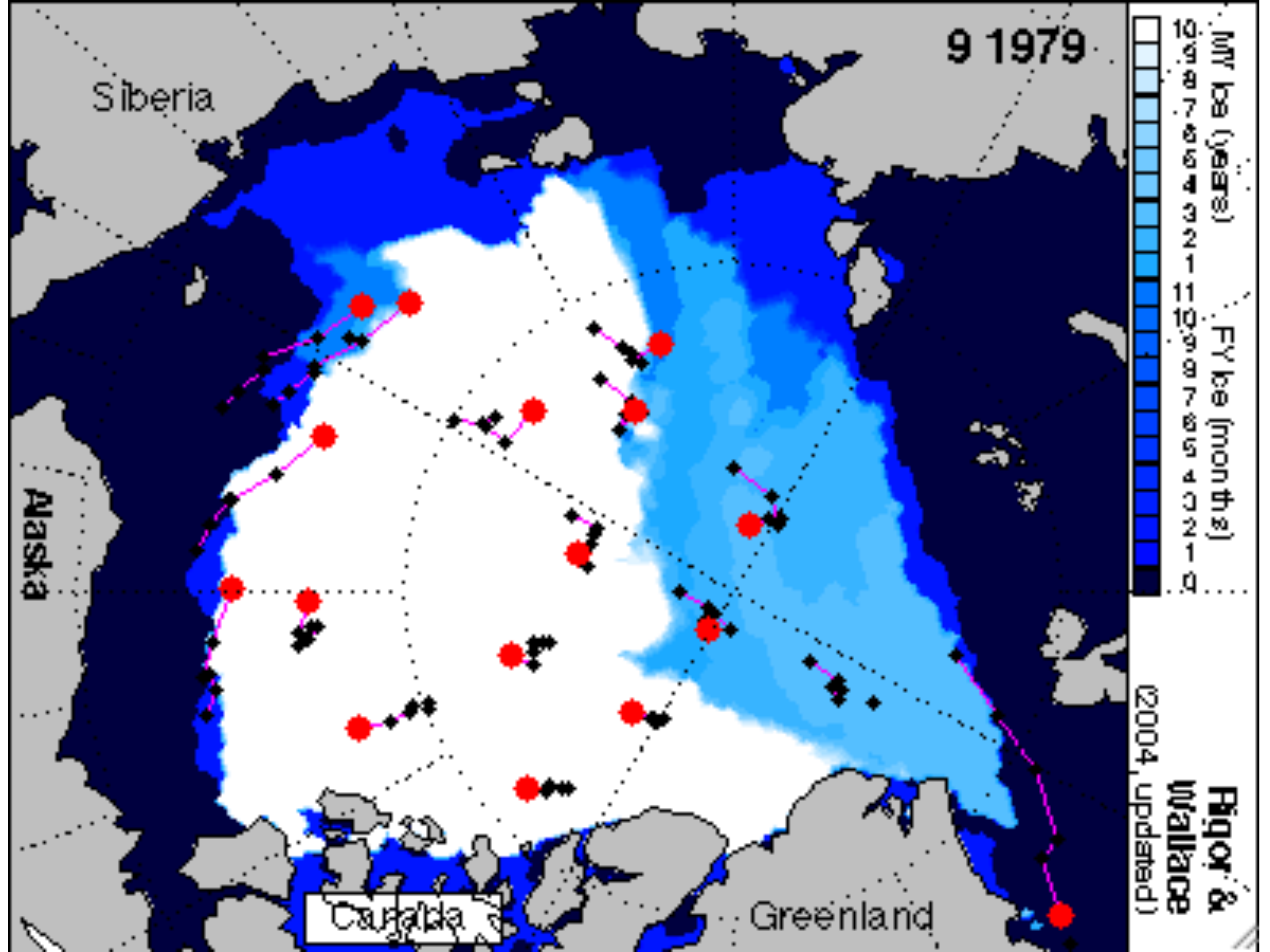
Animation of sea ice 20 frames per second

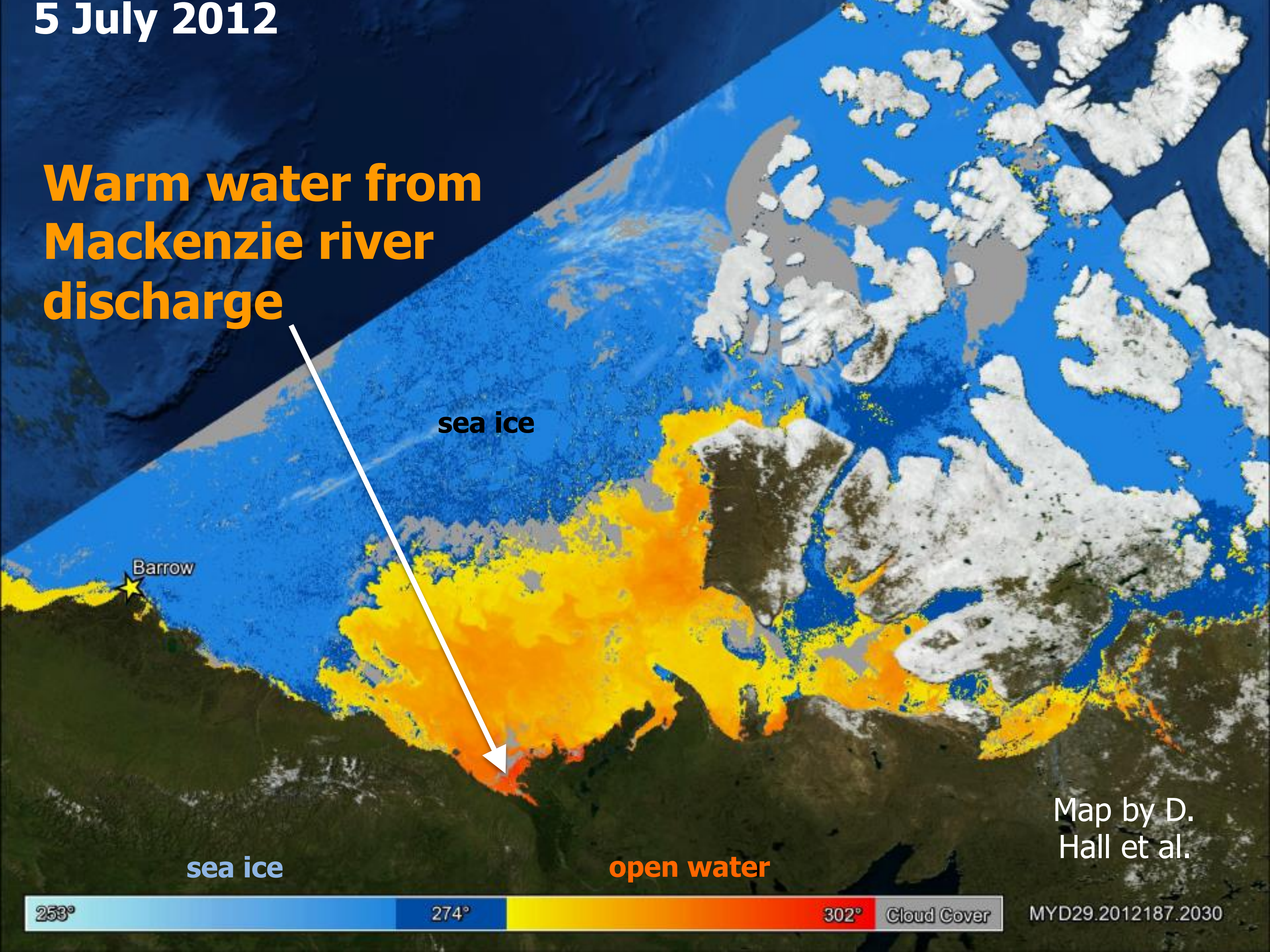
9/2008 to 5/2009

SEA ICE CLASSES

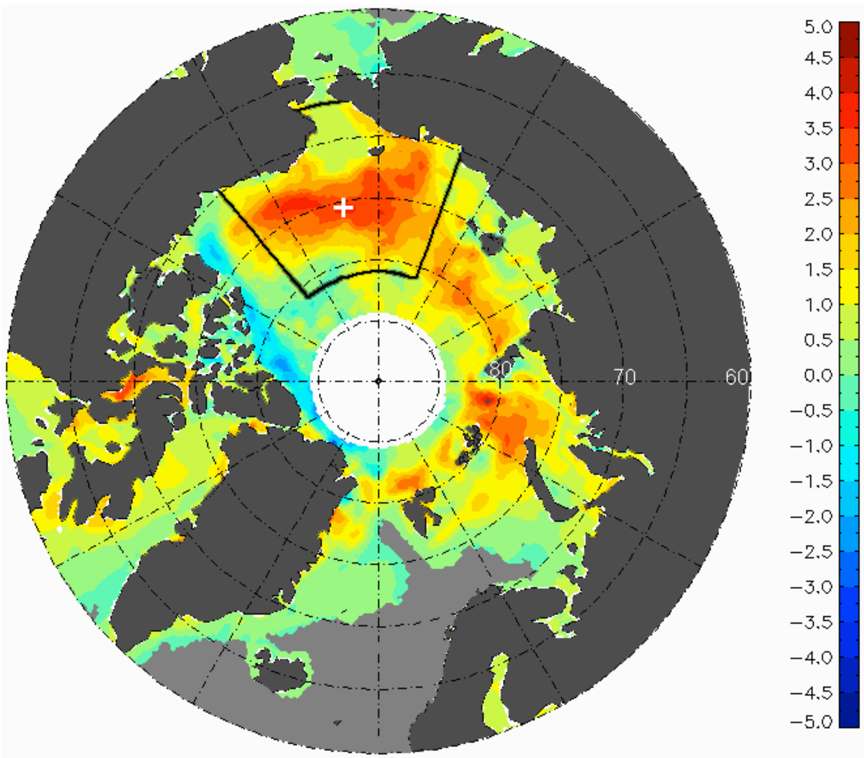
- Seasonal
- Mixed ice
- Perennial
- Melt




9 1979
Siberia
Alaska
Canada
Greenland
MY ice (years)
FY ice (months)
Rigor & Wallace (2004, updated)


5 July 2012
Warm water from Mackenzie river discharge
sea ice
Barrow
sea ice
open water
Map by D. Hall et al.
253°
274°
302°
Cloud Cover
MYD29.2012187.2030

Impacts of Rapid Decrease of Arctic Perennial Sea Ice



Trend of annual solar heat input to ocean in % (1979-2005). Perovich, Light, Eicken, Jones, Ruciman, and Nghiem (GRL, 2007).

- **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

$$Br_2 + h\nu \rightarrow Br + Br \quad (1)$$
$$2(Br + O_3 \rightarrow BrO + O_2) \quad (2)$$
$$2[BrO + HO_2 \rightarrow HOBr(g) + O_2] \quad (3)$$
$$2[HOBr(g) \rightarrow HOBr(l)] \quad (4)$$
$$2[HOBr(l) + HBr(l) \rightarrow H_2O(l) + Br_2(g)] \quad (5)$$

Net: $2HO_2 + 2HBr + 2O_3 + h\nu \rightarrow 2H_2O + Br_2 + 4O_2$

Photochemical Processes

Cycle 2:

$BrCl + h\nu \rightarrow Cl + Br$ (6)

$Br + O_3 \rightarrow BrO + O_2$ (2)

$Cl + O_3 \rightarrow ClO + O_2$ (7)

$BrO + HO_2 \rightarrow HOBr(g) + O_2$ (3)

$ClO + HO_2 \rightarrow HOCl(g) + O_2$ (8)

$HOBr(g) \rightarrow HOBr(l)$ (4)

$HOBr(l) + HCl(l) \rightarrow H_2O(l) + BrCl(g)$ (9)

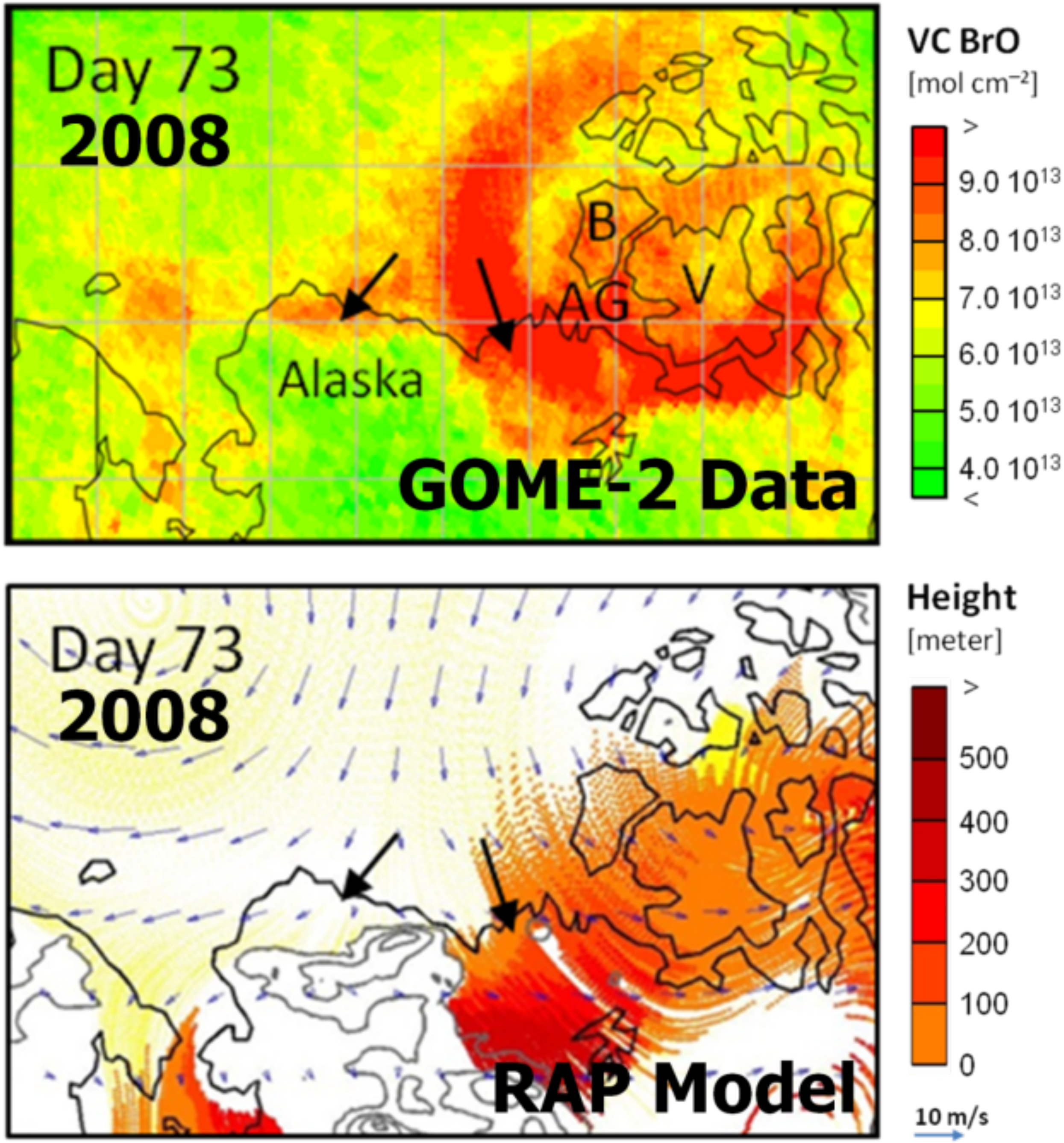
Net: $2HO_2 + HCl(l) + 2O_3 + h\nu \rightarrow H_2O$
$+ HOCl(g) + 4O_2$

Photochemical Processes

Equilibria (5) and (9) are complex:

$$H^+ + Cl^- + HOBr(l) \rightarrow H_2O + BrCl(l)$$
$$BrCl(l) \rightarrow BrCl(g)$$
$$BrCl + Br^- \rightarrow Br_2Cl^- \qquad (10)$$
$$Br_2Cl^- \rightarrow Br_2 + Cl^-$$

Net: $H^+ + Br^-/Cl^- + HOBr \rightarrow H_2O + Br_2/BrCl$



Nghiem and 17 co-authors, JGR, 2012

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

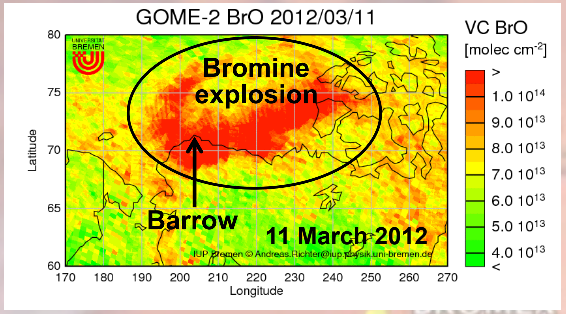
(2) high mountains limit BrO to the Alaskan North Slope and in the Canadian Shield to the east of Richardson and McKenzie mountains.

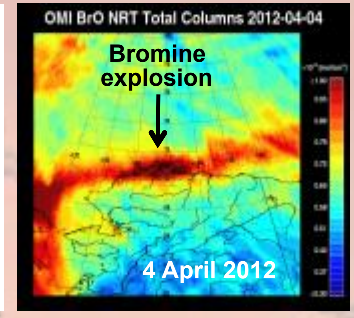
Bromine, Ozone, and Mercury EXperiment (BROMEX)
Chukchi Sea, Beaufort Sea, Alaskan Arctic, February-April 2012

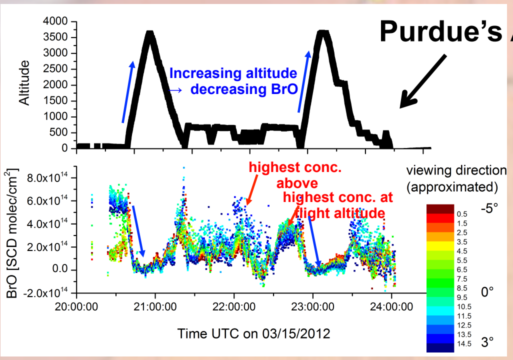
Investigators: PI Son V. Nghiem - JPL; Co-Is from CRREL, Purdue, U. Alaska, U. Washington; Collaborators from > 15 institutions (U.S., Canada, Germany, U.K.)

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
- **Publication:** Nghiem and 17 coauthors, J. Geophys. Res., volume 117, D00S05, doi:10.1029/2011JD016268, 2012 (in press).
- **Outreach:** NASA Press Release March 2012; outreach activities in Barrow

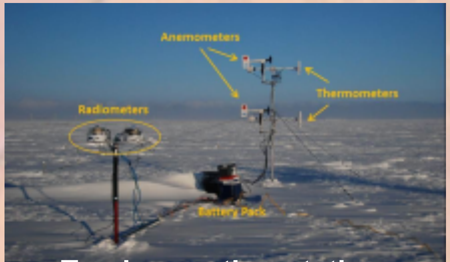






Purdue's ALAR

NASA P3 IceBridge



Tundra weather station

Tundra surface sensors

Icelanders on sea ice: Chukchi Sea and Beaufort Sea

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

USNA buoy

Ice coring

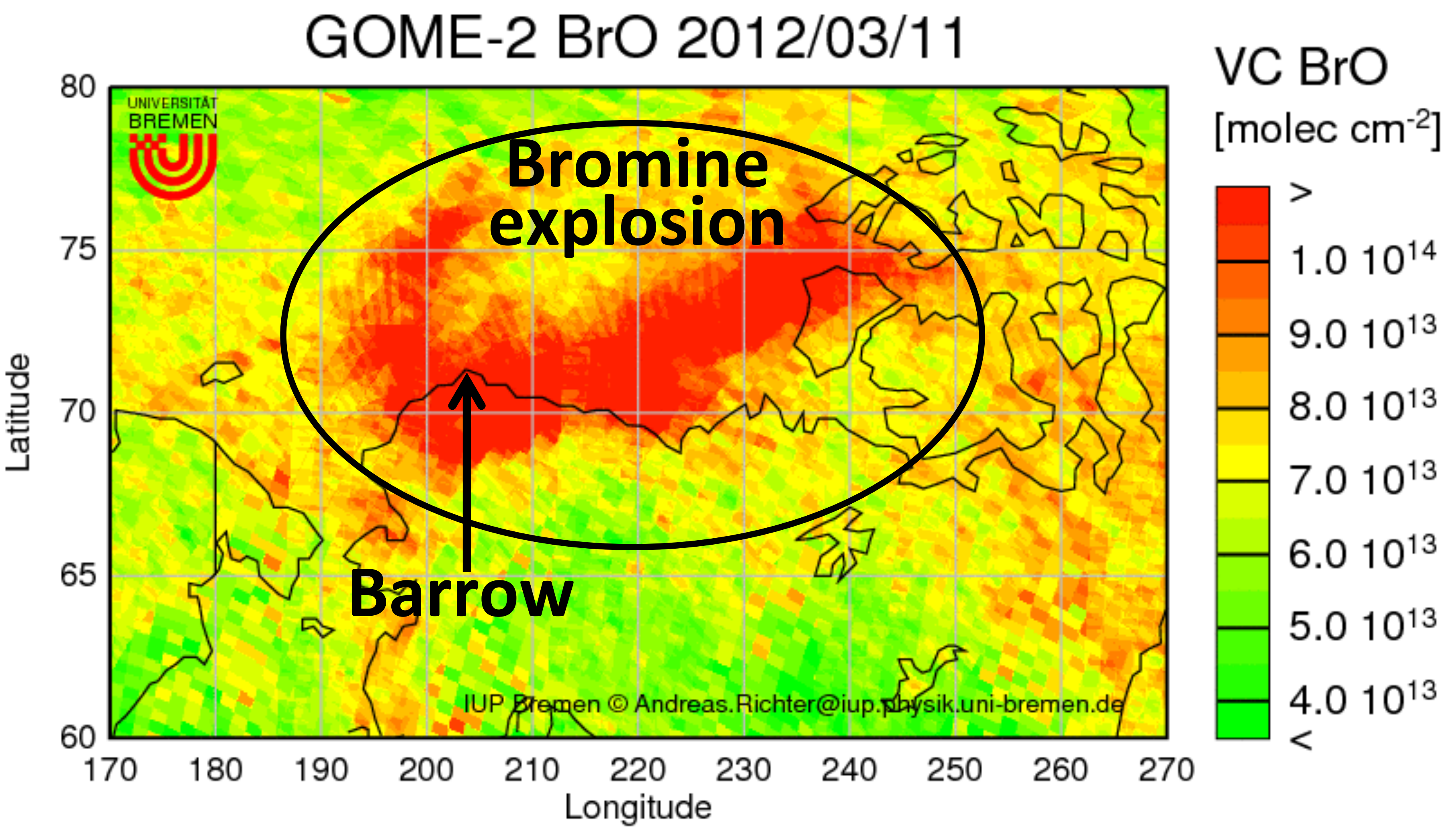
Snow sampling

Land station center

Chemistry instrument

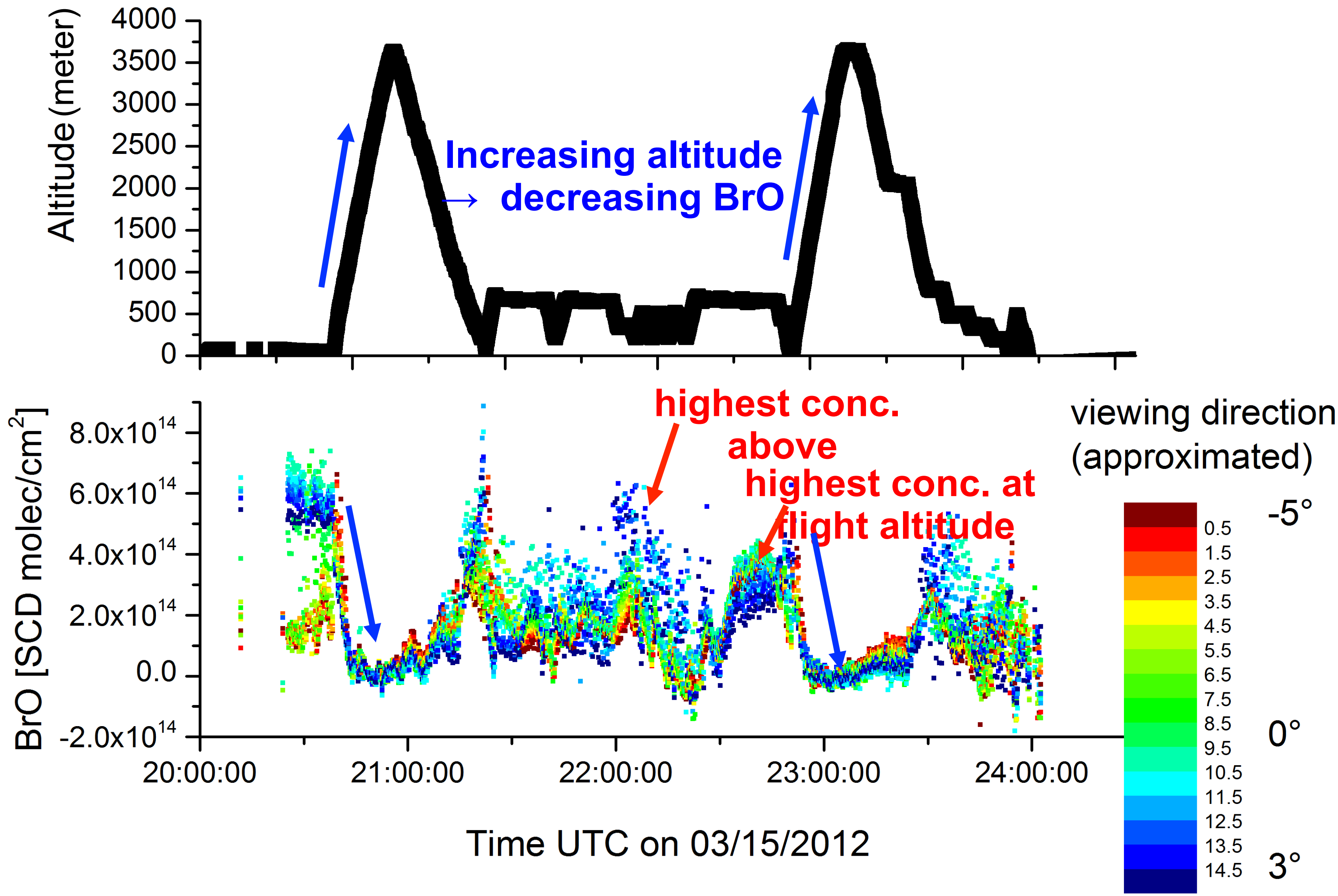
Satellite Observation of BrO

Global Ozone Monitoring Experiment-2 (GOME-2)

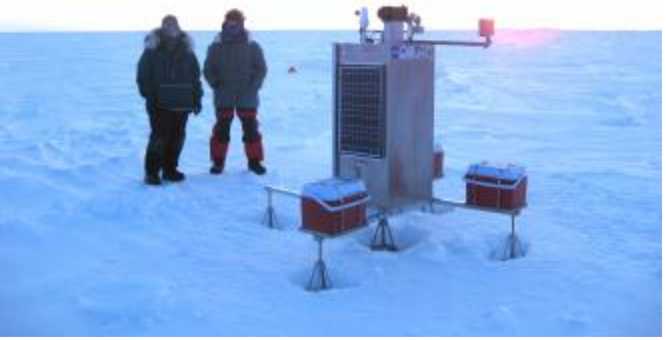


Aircraft Observation of BrO

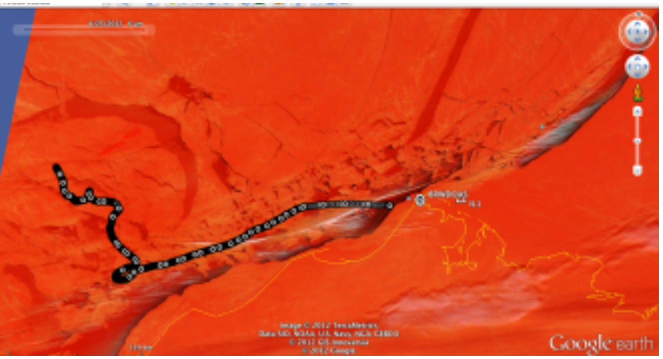
P. Shepson of Purdue U., U. Heidelberg, and BROMEX Team



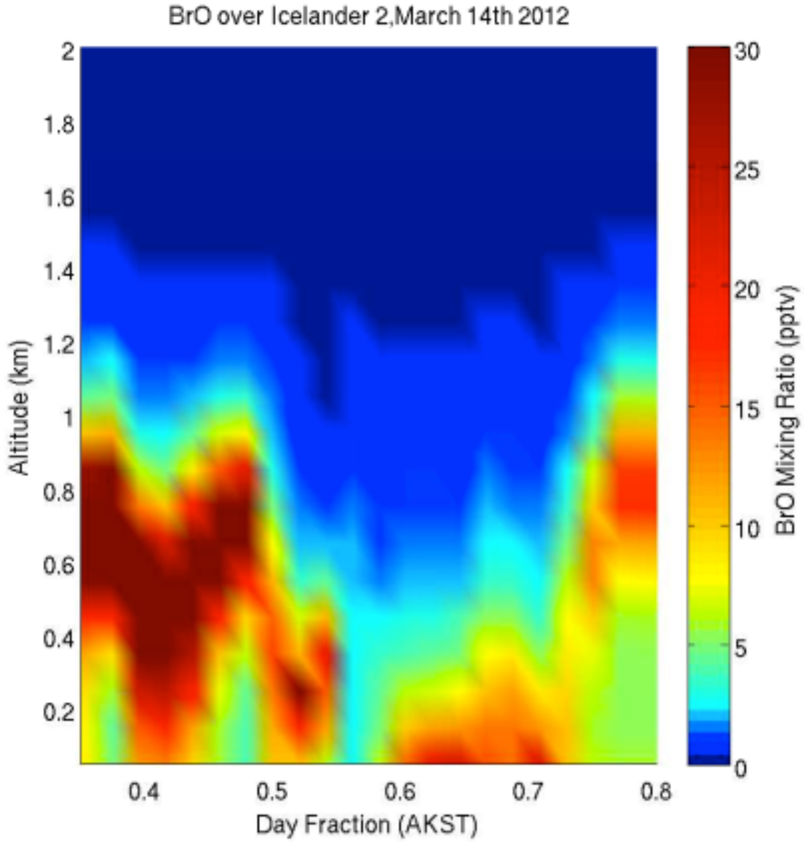
Halogen Activation in the Arctic Boundary Layer



IceLander-2 on Sea Ice



IceLander-2 drift across lead



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

Polar Bear at IL2

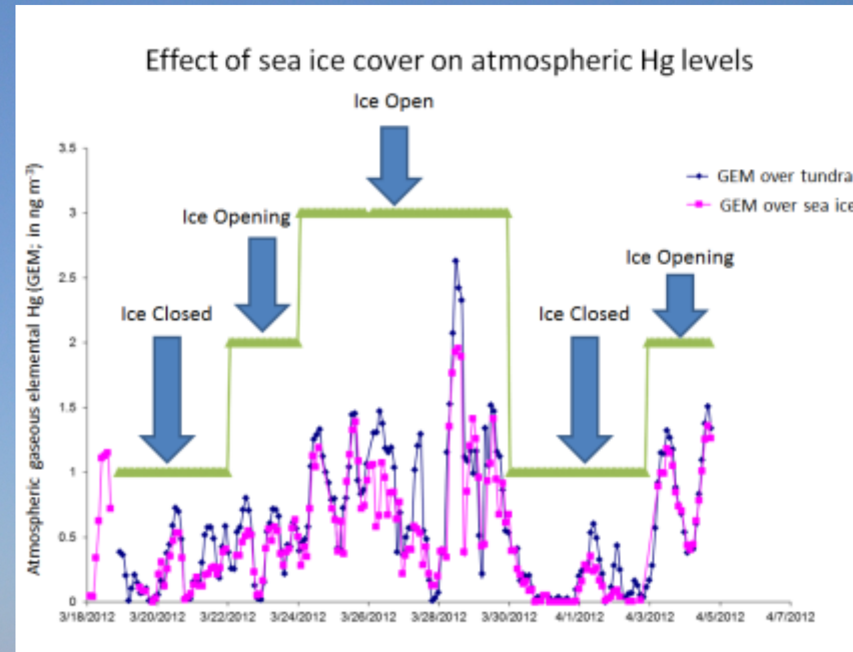
William R. Simpson, Steven J. Walsh, Peter Peterson, and the BROMEX team

Department of Chemistry and Biochemistry and Geophysical Institute, University of Alaska Fairbanks

Environment Canada Environnement Canada

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



Sandy Steffen, Ralf Staebler, John Deary (Environment Canada)
Daniel Obrist and Chris Moore (Desert Research Institute)
Tom Douglas (Cold Regions Research and Engineering Laboratory)

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