Increased Freshwater and Biogenic Fluxes: The flip side of Arctic sea-ice retreat

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Sea Ice Concentration
Nimbus-7, 1979-2007

Summer ice extent retreating rapidly:

Mean sea-ice concentration
September, 1987

Mean sea-ice concentration
September, 2007
Seasonal Ice Zone (SIZ): complement of ice changes:
Ice concentration: Mar – Aug

1988

2007

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Want to think about two implications:

• **Freshwater Flux:**
  - Dominates density gradients,
  - Sets stratification,
  - Protecting ice from upwelling heat,
  - Modulating biological productivity,
  - And deep water formation rates,

• **Nutrient fluxes:**
  - Critical to productivity
  - Limited by light and stratification
  - So modulated by sea-ice formation and melt
  - Important tracer for circulation and water masses
In the context of modern hydrographic cruises:

AOS (Oden) 2005

AOS (Polarstern) 1994

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Surface circulation and river basins

Freshwater Sources:

- River runoff
- Bering Strait inflow (N. Pacific is fresher than N. Atlantic)
- Local precipitation
- Annual sea-ice cycle (asymmetry between fate of melt and freeze)
Coastal ice circulation from buoys:
EEZ ice flows from satellite images:
Ice transports fresh water (among other things):

- Changes in summer sea-ice melt locations should change the distribution of salinity and density gradients.
- Increasing area of the seasonal ice zone (SIZ) should increase total sea ice formation.
- A stronger sea ice pump (fresh water up, brine down) should increase stratification.
- Changing density distributions should impact on large-scale circulation ... but how?
To evaluate impact of sea ice, need to separate sea ice meltwater and brines from other fresh/salty water sources:

\[
f_a + f_p + f_r + f_i = 1,
\]

\[
f_a S_a + f_p S_p + f_r S_r + f_i S_i = S_m,
\]

\[
f_a \delta^{18}O_a + f_p \delta^{18}O_p + f_r \delta^{18}O_r + f_i \delta^{18}O_i = \delta^{18}O_m,
\]

\[
f_a PO_4^{*a} + f_p PO_4^{*p} + f_r PO_4^{*r} + f_i PO_4^{*i} = PO_4^{*m},
\]

Note that a nutrient parameter is required to identify Bering Strait inflow (Pacific Water).
Basic water mass de-convolution technique: matrix inversion

- System of tracer equations:
  - $E_f = d$
  - $f = E \backslash d$
- Coefficients in $E$: end-member values
- $d$ are the sample measurements.
- Can be exact ($m = n =$ number of measured parameters) or
- Overdetermined (solved by least-squares minimization of a cost function).
Nutrient tracers are not conservative. Redfield combinations minimize impact of photosynthesis and respiration:

- PO* (Ekwurzel, Schlosser, Newton, Chen)
- N* (Newton)
- NO (Wallace)
- NO/PO (Wallace)
- Empirical N/P (Jones, Anderson, Matsumoto-Kawai)
Physical properties and water mass fractions from AOS-05

Observations

FW Components and water column sum

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Water mass fractions in 2005 and 1994 were comparable ...
As long as one uses the same end-member parameters and values ...
10.0 - 6.5 = 3.5 m

(-5) - (-6) = 1 m

10.5 - 8.0 = 2.5 m

3.5 - 3.5 = 0.0 m

Makarov Basin
2005 - 1994
Difference

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Increased stratification?

- There is a dramatic freshening of the upper layers over the Makarov Basin (3.5 m freshwater anomaly, 2004 – 1994).
- Increased sea-ice meltwater flux is a significant component (~ 1/3).
- But meteoric waters (runoff and local snowfall), driven mainly by changes in wind stress (Ekman transport) continue to dominate the anomalies.
- No convincing evidence of increased salinity in the halocline; residence times ~ 15 years implies this should follow the surface anomalies.
Nutrients on the AOS-2005

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AOS-05 N-P data: 
(well fit to empirical end-members)
But implication is: significant processing on the Arctic shelves.

Bering Strait Inflow: reasonable average of shallow Bering Sea, and intermediate between Atlantic and Pacific N/P relationships.

Transformation from BSI to the “Pacific” end member requires denitrification and/or Phosphate addition in the Chukchi Sea.
So nutrient patterns in the Arctic halocline reflect indigenous (Arctic) processing:
For process rates we need a clock:
Halocline nutrient concentrations asymptote with Tr/He age:

Nitrate  Phosphate

(So implied export productivity varies …
Upper halocline: ~3 gC/m²; Lower halocline: ~6 gC/m²)
The Halocline nutrient system appears supply limited ... and the supply may be increasing:
MODIS-A: Change in Chlorophyll in the E. Siberian Sea, 2007 - 2003:
Fractional change in ChlA:
1 = areas of new production
Increased nutrient flux?

• Nutrient regeneration in the Canadian Basin halocline appears to be limited by POC supply; current (~ last 20 years) limits: 16 mMol N/m$^3$.

• Redfield-derived (using C/N/P and Tr-age) POC export: upper halocline ~ 3gC/m$^2$; lower h.c.: ~ 6gC/m$^2$; mainly from production on shelves.

• Supply of organic material is increasing, perhaps dramatically (30% step in 2006), as the growing season lengthens and the water column is more stratified. Largest absolute increases on the shelves, which feed the halocline.

• New regions of productivity over the deep Canadian Basin ➔ greater vertical flux.