Do the volumes work out?

Volume PW at 33.1 psu per year
~ 6x $10^{12}$ m$^3$/yr (0.6 Sv for 4 months)
In Arctic ~ half pure, half mixed with AW (1:1)
Thus need 3 x $10^{12}$ m$^3$/yr AW to be raised onto shelf

Observed upwelling events in Barrow Canyon
= 2-3 x $10^{11}$ m$^3$ per event
Therefore need 10 events
and there are multiple wind events, and multiple canyons

So – plausible

Also, this ventilation rate is an order of magnitude higher than estimates of polynya water formation

Woodgate et al, 2005, GRL
The Eddy Band-wagon
Eddies in the Beaufort Sea

e.g., Hunkins and Manley, Plueddemann and MANY others

http://www.whoi.edu/science/PO/arcticgroup/projects/eddies.html

Figure 2. Drift tracks for three Ice-Ocean Environmental Buoy (IOEB) deployments where subsurface velocity data were available: Beaufort Gyre 1992 (B92, solid), Beaufort Gyre 1997 (B97, dashed) and SHEBA 1997 (S97, dotted). Drift tracks have been smoothed over 6 days. The 78 eddy encounters are separated into 62 with complete statistics (filled circles) and 16 with only position information (open circles).

Predominantly Anticyclonic

Figure 3. Physical properties of 62 eddies encountered during 10,000 km of buoy drift in the Beaufort Gyre. Shown are histograms of (a) center depth (the depth of maximum velocity), (b) thickness (the depth range with velocity greater than 8 cm/s), (c) maximum azimuthal velocity, and (d) radius of maximum velocity.
Eddy Census

- XBT lines

1 eddy =
(10 km radius, 50m)
~ $2 \times 10^{10}$ m$^3$

Flux through Bering Strait ~ 1 Sv
~ $3 \times 10^{13}$ m$^3$ per yr

If all eddies, makes ~1000 eddies a year.

Do we see 1000 eddies??? - no
Flow of winter-transformed Pacific water into the Western Arctic

Robert S. Pickart*, Thomas J. Weingartner, Lawrence J. Pratt, Sarah Zimmermann, Daniel J. Torres

Fig. 1. (A) Study area in the Eastern Chukchi and Western Beaufort Sea. (B) Detailed view of study area, showing the hydrographic stations occupied by DEDC-Polar Star in summer 2002. The survey consisted of six sections. Station numbers are included on the two Barrow Canyon sections: the head of the canyon (stations 42-52) and the mouth of the canyon (stations 78-80). The location of the eddy observed during the 1997 Sibell expedition is indicated by the triangle.

Fig. 12. Vertical sections of properties overlaid on potential density (kg/m³). The top panel shows potential temperature (color, °C); the bottom panel shows turbidity (color, volts). (A) Section 5, west of Barrow Canyon and (B) Section 3, east of Barrow Canyon.
Eddies in the non-Beaufort Arctic
(Woodgate et al, 2001)

TWO EDDY TYPES
Cold (Tf), Fresh, near surface, AC,
- likely from shelf polynyas

Warm, Salty, ~ 1000m deep, AC
- instabilities on upstream front
  (e.g. St Anna)

40 cm/s; ~ 10km radius, but volume flux ~ 0.1 Sv or less
Kugmallit Valley as a conduit for cross-shelf exchange on the Mackenzie Shelf in the Beaufort Sea

JGR, 2008

William J. Williams, Humfrey Melling, Eddy C. Carmack, and R. Grant Ingram

Figure 3. A wind rose of wind stress over the Mackenzie Shelf for the period of the mooring deployment calculated from NCEP 10-m wind and ignoring the presence of ice. For each direction the black arrows show the mean wind stress, and the thick red line shows its probability relative to the reference thin red circle that would be obtained if each direction was equally likely. The blue line marks the cross-shelf direction for the Mackenzie Shelf, so that winds either side of the line are either upwelling or downwelling favorable. The green line is the along-shelf direction.

Figure 8. A comparison between mean water velocity profiles at site 1 during two upwelling events, one with ice and one without. The colors from deep to shallow are shaded from dark red to dark blue, respectively. Wind and ice velocities are also shown, but note that wind velocity is plotted in m/s and ice and water velocities are plotted in cm/s. True north is toward the top of the plot.
Figure 4. Various time series plots. (a) Along-shelf and (b) cross-shelf surface stresses. Red and blue bars are NCEP wind stress (calculated ignoring the presence of ice), and the black line is ice stress at site 1 (represented by |U_{ICE}|U_{ICE}). (c) Site 9 minus site 1 bottom pressure difference relative to the mean difference. Low-passed currents (true north is upward) at (d) site 1 at 46.2 m (the lowest-depth bin of the ADCP), (e) site 2 at 105.2 m (the lowest-depth bin of the ADCP), (f) CA1 at 49.1 m, and (g) CA2 at 51.4 m. (h) Salinity and (i) potential temperature (referenced to the surface) at site 1 at 54 m (black line), site 2 at 114 m (pink line), CA1 at 49.1 m (blue line), and CA2 at 51.4 m (green line).
DISSOLVED OXYGEN
- High at surface (ventilated from atmosphere)
- Low = OLD water (long time since at surface)
  or
  = Evidence of high biological activity
THUS – Pacific Water has LOW Dissolved Oxygen

Falkner et al, 2005 DSR
SILICATE, NITRATE, PHOSPHATE
- High from source in Pacific
  BUT – not conservative

PW - Hi Nutrients

Redfield-Ketchum-Richards Model (Redfield et al, 1963)

\[(\text{CH}_2\text{O})_{106}(\text{NH})_{16}(\text{H}_3\text{PO}_4) + 138 \text{ O}_2 = 106 \text{ CO}_2 + 122 \text{ H}_2\text{O} + 16 \text{ HNO}_3 + \text{ H}_3\text{PO}_4\]

**Biogenic matter** + oxygen = **Carbon Dioxide** + **Water** + **NUTRIENTS**

Try to create a “tracer” that is conservative “Quasi-conservative Tracer”

“NO” and “PO” – Broecker, 1974
- cope with growth and decay
  \[\text{NO} = 9 \text{ NO}_3 + \text{ O}_2\]
  \[\text{PO} = 135 \text{ PO}_4 + \text{ O}_2\]

N:P ratios
NO:PO ratios

N* (N star) – Gruber and Sarmiento, 1997
- indicates nitrogen fixation and denitrification
  \[N* = 0.87 [N - \text{ 16 P} + 2.9 \mu\text{mol kg}^{-1}]\]
PW versus AW in N:P space

- For a Nitrate value, PW have more Phosphate
- Slope set by Redfield
- Exact lines may change
  \[ \text{NO}_3(pw) = 14.828 \times \text{PO}_4(pw) - 12.16 \] (Falck, 2001)

BUT work out % influence of PW and AW
(…but certainly no better than 10%
.... assumes ice melt, P and runoff same as AW
.... denitrification .. and other such processes)

% PW in upper 30m

Figure 2. Nitrate vs. phosphate from AOS94 Stations 4 to 12 (triangles) and St. Anna Trough, ARKTIS XII Stations 3 to 19 (circles). Freshwater is represented by a cross.

Jones, Anderson and Swift, GRL, 1998
Distribution of Atlantic and Pacific waters in the upper Arctic Ocean: Implications for circulation
Upper Arctic Ocean Circulation and Ventilation

HALOCLINE BASICS
Formation possibilities
Western versus Eastern Arctic
Different branches of PW

CIRCULATION CHANGES
Shift in rivers outflow
Retreat and recovery of CHL
Shift of Pacific/Atlantic Front

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MECHANISMS OF SHELF-BASIN EXCHANGE
Winddriven upwelling and mixing of AW with PW
Potential vorticity conservation, following topography
Dense water outflow from polynyas
Eddies (AC, ~ scale of Rossby radius)
Winddriven undercurrents (Yoshida jet)
Tides and inertial oscillations

TRACING PW versus AW HALOCLINE
PW lower salinity, smoother TS
PW lower dissolved oxygen
PW higher nutrients (esp Silicate)
AW/PW NO3:PO4 ratio

Rudels et al, 1996
TRACING PW versus AW HALOCLINE
PW lower salinity, smoother TS
PW lower dissolved oxygen
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