Significance of curl-driven upwelling to production in the Coastal Gulf of Alaska

Albert J. Hermann (UW/JISAO, NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115)

S. Hinckley (NOAA/AFSC)
E. L. Dobbins (UW/JISAO)
D. B. Haidvogel (Rutgers U.)
N. A. Bond (UW/JISAO)
P. J. Stabeno (NOAA/PMEL)
C. Mordy (UW/JISAO)
- Two major currents: Alaskan Stream and Alaska Coastal Current
- ACC forced by downwelling-favorable winds and distributed runoff
- Downwelling-favorable winds, yet very productive!
Average surface chlorophyll from SeaWifs data in the CGOA for late July, 1998-2002 (data from S. Salo, PMEL)
Why so productive? Alternate sources of new nitrogen

- "Traditional" 2D upwelling in the summer
- Upwelling driven by wind stress curl
- Onshore flux of HNLC waters
- Vertical mixing (deep pool replenished each year)
- Others!

Here, we seek to begin *quantifying* these candidates with a coupled biophysical model
Nested Biophysical Models for GLOBEC:
NCEP/ MM5 -> ROMS/ NPZ -> IBM
The Circulation Models

- Regional Ocean Modeling System (ROMS)
- Primitive Equations
- Terrain-following vertical coordinates (30 vertical levels)
- LMD mixed layer physics
- COADS/NCEP/MM5 wind and heat forcing
- Implemented on massively parallel (distributed memory) computers
Nested model results (SSS)
Detail of CGOA results (SSS)
10 Component model
Includes iron limitation

(diagram from G. Blamey, UAF)
Daily velocity at GB-1

DATA

LONGITUDE: 149.4E
LATITUDE: 59.7N
DEPTH (m): 42

MODEL

LONGITUDE: 149.4W (-149.4)
LATITUDE: 59.7N
DEPTH (m): 42

Data: data/home/galatea3/mooring_data/2001/globe1/01gbla_en7_6042m.nc

Model: 01GB-1.nc
Mean velocity at 40 m on the CGOA shelf for May-September, computed from drifter data (black) vs model output (red).
S, T, NO3 along the GAK line in 2001

MAY

DATA

MODEL

SEPT

DATA

Seward Line Salinity (PSU)
17-18 May 2001

Seward Line Temperature (°C)
17-18 May 2001

Seward Line NO3 (μmol kg⁻¹)
17-18 May 2001

Seward Line Salinity (PSU)
27-28 Sept. 2001

Seward Line Temperature (°C)
27-28 Sept. 2001

Seward Line NO3 (μmol kg⁻¹)
27-28 Sept. 2001

S, T, NO3 along the GAK line in 2001
Rings of chlorophyll are a dominant feature
Shelf budgets (top 15m)

Calculate the fluxes into and out of a control volume spanning the top 15m of the shelf waters.

This construction is equivalent to a volume integral (from 15 m below mean sea level, up to the sea surface) of the local balance of terms:

\[
C_{\text{box}} = \iiint \left[ -uC_x - vC_y - wC_z + (kC_z)_z \right] \, dx \, dy \, dz \\
= C_{\text{east}} + C_{\text{west}} + C_{\text{north}} + C_{\text{south}} + C_{\text{vertadv}} + C_{\text{vertdiffu}} \\
+ \iiint (\text{nonconservative terms}) \, dx \, dy \, dz
\]
Physical sources for nitrate

- Horizontal advection
- Vertical advection
- Vertical diffusion

- Seek to quantify these basic terms across the faces of a control volume
- Note: result depends on the dimensions of the box!
Monthly average wind stress vectors (N m\(^{-2}\)) and wind stress curl (N m\(^{-3}\) x 10\(^3\), shaded)

May 2001

Aug 2001
Calculated Ekman pumping from winds (black line) vs ROMS vertical velocities at 15 m (red line) integrated over the control volume
First, look at the *water* budget:

*upwelling in spring, onshore flux*

![Graph showing water budget with labels for Adv in from E, Adv in from basin, Vert adv, Sum of adv, and Adv out to W.]

**Labels:**
- Adv in from E
- Adv in from basin
- Vert adv
- Sum of adv
- Adv out to W

**Axes:**
- Y-axis: $5.0 \times 10^5$ to $-5.0 \times 10^5$
- X-axis: March 2001 to September 2001

**Legend:**
- Black line: Adv in from E
- Green line: Adv in from basin
- Blue line: Adv out to W
- Purple line: Vertical adv
- Red line: Sum of adv
Modeled surface nitrate and velocity

May 15 2001

Aug 15 2001
Modeled monthly average horizontal flux of nitrate at 15 m depth (millimole m\(^{-2}\) s\(^{-1}\))

May 15 2001

Aug 15 2001
May 2001 average vertical advection and vertical diffusion of nitrogen across the 15m depth horizon (millimole m$^{-2}$ s$^{-1}$ x $10^3$)
Nitrate flux summary (30-d lowpass)
Monthly average fluxes of nitrate into the control volume for the advective and diffusive terms (millimole s\(^{-1}\) x 10\(^5\))

<table>
<thead>
<tr>
<th></th>
<th>Advec east</th>
<th>Advec west</th>
<th>Advec south</th>
<th>Advec north</th>
<th>Advec below</th>
<th>Diffu below</th>
<th>Advec Total</th>
<th>A+D Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar</td>
<td>42.82</td>
<td>-51.98</td>
<td>-3.34</td>
<td>-1.63</td>
<td>15.53</td>
<td>28.18</td>
<td>1.39</td>
<td>29.57</td>
</tr>
<tr>
<td>Apr</td>
<td>28.89</td>
<td>-40.45</td>
<td>10.02</td>
<td>-0.43</td>
<td>8.29</td>
<td>62.14</td>
<td>6.32</td>
<td>68.46</td>
</tr>
<tr>
<td>May</td>
<td>12.12</td>
<td>-31.63</td>
<td>20.44</td>
<td>-0.07</td>
<td>-0.35</td>
<td>73.28</td>
<td>0.52</td>
<td>73.80</td>
</tr>
<tr>
<td>Jun</td>
<td>3.71</td>
<td>-12.65</td>
<td>9.81</td>
<td>1.36</td>
<td>-4.80</td>
<td>59.12</td>
<td>-2.56</td>
<td>56.56</td>
</tr>
<tr>
<td>Jul</td>
<td>1.96</td>
<td>-7.74</td>
<td>5.83</td>
<td>-0.19</td>
<td>-2.06</td>
<td>28.97</td>
<td>-2.20</td>
<td>26.77</td>
</tr>
<tr>
<td>Aug</td>
<td>0.68</td>
<td>-4.36</td>
<td>4.33</td>
<td>-0.88</td>
<td>-3.51</td>
<td>22.93</td>
<td>-3.73</td>
<td>19.19</td>
</tr>
</tbody>
</table>

Time average value is 4.0 mmol nitrate m\(^{-2}\) d\(^{-1}\)

Childers et al. [2005] report 2.46-6.97 mmol nitrate m\(^{-2}\) d\(^{-1}\)
Alongshore Wind Stress and Wind Stress Curl EOFs

J. Fiechter, pers. comm.
Surface Chlorophyll EOFs: NEMURO-Fe vs. SeaWiFS

J. Fiechter, pers. comm.
Spring Bloom Variability and Winter Ekman Pumping

J. Fiechter, pers. comm.

[Graph showing amplitude and anomaly over years 1998-2002, with data points labeled as Wind Stress Curl, NEMURO-fe, and SEAWIFS.]
Mean summertime (May-July) wind stress and upwelling rate from 1984 to 2004. (Rykaczewski and Checkley, 2008)
Upwelling and surplus production per unit biomass of Pacific sardine (Rykaczewski and Checkley, 2008)
SUMMARY

- Nitrate flux can be consistently budgeted using coupled circulation/NPZ models. These indicate:
  - Tidally-driven mixing
  - A patchy pattern of vertical velocity.
  - Net upwelling of water and nutrients during spring (March and April)

- Conclude: wind stress curl is an important contributor to Gulf of Alaska production; apparently true in other coastal regions as well!
FUTURE WORK

• Improved circulation/NPZ models
• Data assimilation
• Different coordinate systems (e.g. isopycnal layers)
FIN!
Nested model domains with SSH

NPAC

NEP with CGOA

Prince William Sound

Shelikof Strait

Sitka AK

CGOA
NESTED CIRCULATION MODEL DOMAINS

Delta x = 20-40 km  Delta x = 10 km  Delta x = 3 km  Delta x = 1 km
NPZ model
(arrows indicate nitrogen flux)

- **Nutrients** (Nitrate, Ammonium, Iron)
- **Phytoplankton** (Small and Large)
- **Microzooplankton** (Small and Large)
- **Copepods** (Small, Large Oceanic)
- **Euphausiids**
- **Detritus**
How well do NEP and CGOA models replicate flow thru Shelikof Strait?

2001

model-data comparison (sv) (NEP - red; CGOA - green; data - black)

Flux through Shelikof Strait (sv) (NEP model)
Amatouli Trough May 01, 2001

Horizontal advection

Vertical advection

Vertical diffusion
Amatouli NO3 flux summary (lowpass)

- Adv in from E
- Vert adv
- Vert diff
- Adv in from basin
- Sum of adv
- Adv out to W
- ADV
- DBELOW
- DABOVE

Graph showing the flux summary from March to September 2001.
Amatouli NO3 flux summary (unfiltered)
Why upwelling in spring? The cross-shelf scenario

- Western outflow > Eastern inflow
- Input of water from deep basin
- Flow at mid-depth goes up canyons
- Upwelling in spring!
Summary: fluxes of no3 in the upper 15m of the shelf indicate

- Patchy w with upwelling in the spring!
- Vertical diffusion is the biggest term on the shelf as a whole
- Advective balance: onshelf flow and vertical advection feed the alongshelf deficit
Compare density at GAK line with CGOA model
Mar 2001
Compare velocity in Shelikof Strait with NEP model

LONGITUDE : 155E(155)
LATITUDE : 57.6N
DEPTH (m) : 249

rsq=0.6456

MM5-DRIVEN MODEL (red) vs DATA (black)

TOTAL depth-integrated flux (m^3/s)