Tidal Energy and the 18.6 Year Cycle in the Bering Sea

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Outline:
- Background
- Tidal model & inverse
- Energy fluxes and dissipation
- 18.6 year cycle
- Summary

Acknowledgements:
- Andrew Bennett, Boon Chua, Gary Egbert
- David Greenberg, Dan Lynch, Chris Naimie
Background & Motivation

- complex tidal elevations & flows in the Bering Sea
  - Large elevation ranges in Bristol Bay
  - Large currents in the Aleutian Passes
  - both diurnal & semi-diurnal amphidromes
  - Large energy dissipation (Egbert & Ray, 2000)
  - Interactions with seasonal ice cover
  - Internal tide generation from Aleutian passes (Cummins et al., 2001)
Background & Motivation

- Wide shelf, complex bathymetry, narrow entrances
- Relatively large diurnal currents that will have 18.6 year modulations

- Difficult to get currents & energy balance right with only a forward model
- Need to incorporate observations
  - Data assimilation
The Numerical Techniques

- Barotropic finite element method FUNDY5SP (Greenberg et al., 1998):
  - linear basis functions, triangular elements
  - $e^{-i\omega t}$ time dependency, $\omega = \text{constituent frequency}$
  - solutions ($\eta, u, v$) have form $Ae^{ig}$
  - Provides an initial solution

- FUNDY5SP adjoint model
  - development parallels Egbert & Erofeeva (2002)
  - representers: Bennett (1992, 2002)
  - allows improvement of initial solution by assimilating observations
Grid & Forcing

- **variable resolution:**
  - 50km to less than 1.5km
  - 29,645 nodes, 56,468 triangles
- **Forcing:**
  - Tidal elevation boundary conditions from Topex Poseidon crossover analysis
  - Tidal potential, earth tide, self-attraction & loading
Assimilated Tidal Observations

- from tidal analysis at T/P crossover sites
  (Cherniawsky et al. 2001)
Elevation Amplitude & Major Semi-axis of a sample $M_2$ Representer

(amplitude normalized to 1 cm)

- these fields are used to correct initial model calculation
Model Accuracy Assessment:

average $D$ (cm) at 288 T/P crossover sites

$$D = \left\{ (A_0 \cos g_0 - A_m \cos g_m)^2 + (A_0 \sin g_0 - A_m \sin g_m)^2 \right\}^{1/2}$$

<table>
<thead>
<tr>
<th></th>
<th>$M_2$</th>
<th>$K_1$</th>
<th>$N_2$</th>
<th>$O_1$</th>
<th>$S_2$</th>
<th>$P_1$</th>
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<tr>
<td>Prior model</td>
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<td>1.8</td>
<td>2.9</td>
<td>4.0</td>
<td>1.3</td>
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<td>With T/P assimilation</td>
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<td>2.1</td>
<td>1.1</td>
<td>1.6</td>
<td>1.0</td>
<td>1.0</td>
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</table>
Corrected Elevation Amplitudes
$M_2$ vertically-integrated energy flux

(each full shaft in multi-shafted vector represents 100KW/m)
$K_1$ vertically-integrated energy flux
(each full shaft in multi-shafted vector represents 100KW/m)
Energy Flux Through the Aleutian Passes & Bering Strait
(Vertically integrated tidal power (GW) normal to transects)

<table>
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<th>Pass(es)</th>
<th>M\textsubscript{2}</th>
<th>N\textsubscript{2}</th>
<th>S\textsubscript{2}</th>
<th>K\textsubscript{1}</th>
<th>O\textsubscript{1}</th>
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<tr>
<td>Samalga</td>
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<tr>
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<td>-0.4</td>
<td>7.3</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Seguam</td>
<td>1.6</td>
<td>0.1</td>
<td>-0.1</td>
<td>-2.7</td>
<td>-1.8</td>
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<td>-0.1</td>
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<td>-0.1</td>
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<td>12.2</td>
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<td>Buldir</td>
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<td>7.9</td>
<td>1.6</td>
<td>0.9</td>
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<tr>
<td>Near</td>
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<td>0.0</td>
<td>-4.8</td>
<td>0.2</td>
<td>-0.6</td>
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<tr>
<td>Kamchatka</td>
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<td>-0.3</td>
<td>-0.4</td>
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<td>Bering Strait</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>31.2</strong></td>
<td><strong>3.3</strong></td>
<td><strong>-0.9</strong></td>
<td><strong>24.9</strong></td>
<td><strong>13.0</strong></td>
<td><strong>2.3</strong></td>
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</table>
M₂ Dissipation from Bottom Friction (W/m²)

- Mostly in Aleutian Passes & shallow regions like Bristol Bay
- Bering Sea accounts for about 1% of global total of 2500 GW
- $K_1$ dissipation mostly in Aleutian Passes, along shelf break, & in shallow regions
  - Strong dissipation off Cape Navarin as shelf waves try to turn corner
  - Enhances mixing and nutrient supply → biological implications
- Bering $K_1$ dissipation accounts for about 7% of global total of 343GW
18.6 Year Nodal Cycle

- Declination of moons’ orbit to equator varies between 18.3° and 28.6° over 18.61 year period
- leads to a small tidal constituent with 18.6 yr period & modulation of most major constituents
  - ~ ±4% for M₂
  - ~ ±13% for K₁
  - ~ ±19% for O₁
- K₁/O₁ modulations synchronous but out of phase with M₂
- K₁/O₁ modulations: max in 2006, min in 1997
18.6 Year Nodal Cycle

- Model estimates 19% increase in incoming tidal energy flux to Bering Sea from 1997 to 2006
  - Regional variations with relative magnitude of constituent amplitudes
  - 36% increase in Amchitka Pass

- Expect variations in energy dissipation, mixing, ice cover, and biological productivity
  - Dissipation varies as cube of velocity
  - Parker et al. (1995) found correlation with Pacific halibut recruitment

Pacific Halibut
Hippoglossus stenolepis
Ratio of average bottom friction dissipation in April 2006 to that in April 1997
Summary

- many interesting physical & numerical problems associated with tides in the Bering Sea
- representer approach is instructive way to solve the inverse problem
- 18.6 year nodal cycle
  - significant variation in energy dissipation in regions where diurnal tides dominate
  - should correlate with water properties (next speaker) & biological productivity
- More details in Foreman et al., Nov 2006 issue of *Journal of Marine Research*