Arctic Ocean circulation patterns using GRACE

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In collaboration with:

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**USF:** Don Chambers and Jennifer Bonin

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mean Arctic Ocean circulation
Goal: Show capability of GRACE to identify variations in Arctic Ocean circulation
ocean bottom pressure (OBP)

\[ P_b'(t) = g \int_{-H}^{0} \rho'(z,t)\,dz + P_a'(t) = g \int_{-H}^{0} \rho'(z,t)\,dz + \rho_o g \eta'(t) + \overline{P_a'}(t) \]

Density, Steric pressure, Sea surface height, SSH, inverted-barometer adjusted

Oceanic mass

Atmos averaged over oceans

No ocean dynamics

\[ \eta'_{steric}(t) = -\frac{1}{\rho_o} \int_{-H}^{0} \rho'(z,t)\,dz = -\frac{P'_{steric}(t)}{\rho_o g} \]

[Gill and Niiler, 1973; Landerer et al., 2007]

OBP units:
1 mbar or 1 hPa \(\rightarrow\) 1 cm
Admittance amplitude and phase between sea level (SSH) and bottom pressure (OBP) anomalies.

**Model-based**

At hourly timescales, Arctic Ocean is barotropic.

At inter-annual scales, Arctic is barotropic only on the shelves.

**Observation-based**

At inter-annual scales, Arctic basin (deep) tends to adjust baroclinically.

[Bingham and Hughes, 2008]

[Morison et al., 2012]
Objective

Identify temporal and spatial patterns of Arctic Ocean circulation at monthly to longer timescales

1. What processes control OBP variations in the Arctic?

2. Where/when are OBP variations dominated by changes in SSH?
data and model output

**GRACE:** Gravity Recovery and Climate Experiment

- U. of Texas, CSR, Release 4
- Monthly OBP observations

http://grace.jpl.nasa.gov/

**Ocean models**

**PIOMAS (UW)**
Pan-Arctic Ice Ocean Modeling Assimilation System

[Zhang and Rothrock, 2003]
- 30 vertical levels
- Horizontal resolution ~22 km
- Forced with NCEP/NCAR

**ECCO2 (JPL)**
Estimating the Circulation and Climate of the Ocean, Phase II Project

[Nguyen, et al., 2011]
- 50 vertical levels
- Horizontal resolution ~18 km
- Forced with JRA-25
18 tide and pressure gauges

ABPR, North Pole (NPEO)
BPR, Beaufort Sea (BGEP)
BPR, Bering Strait (RUSALCA)
TG, Fisheries and Oceans, Canada
PIES, Fram Strait (AWI)
TG, Russian (AARI), through PSMSL at Nat. Oceanography Centre, UK

Thank you so much!!
temporal-spatial modes of variability

- EOFs of GRACE OBP. Mean seasonal variation and long term trend removed. There are 3 significant, independent modes.
Mode 1: basin-wide OBP change

NCEP/NCAR winds (925 hPa) and SLP projected on PC1.

Corr. Coef = 0.67, significant above 95% C.I.
Mode 1: basin-wide OBP change

Normalized principal component time series (PC1)

Corr. Coef = 0.67, significant above 95% C.I.

PC 1 and North Pole in situ OBP

NCEP/NCAR winds (925 hPa)
and SLP projected on PC1.

FORCING:
Northward component of the winds over the Arctic gateways.
Mode 1: basin-wide OBP change

FORCING:
Northward component of the winds over the Arctic gateways.

PROCESS:
Geostrophic slope current through the straits.

NCEP/NCAR winds (925 hPa) and SLP projected on PC1.

Corr. Coef = 0.67, significant above 95% C.I.

Normalized principal component time series (PC1)

Normalized principal component time series (PC1) of GRACE-300 ocean bottom pressure.
Regression maps of GRACE OBP and SLP on PC1.

OBP mode 1: forced by winter dynamics
Modeled OBP and SSH regressed on winter GRACE PC1

- Model captures observed basin-coherent OBP change
- Modeled OBP underestimates observed OBP.

Modeled OBP ≠ SSH → Modeled SSH is partially compensated by steric pressure change.

EOF 1, 49% of variance

- 2 m/s/std
Mode 2: Siberian shelves

Normalized principal component time series (PC2)

NCEP/NCAR winds (925hPa) and SLP regressed on PC2.
Mode 2: Siberian shelves

Normalized principal component time series (PC2)

Corr. Coef R = 0.45, significant above 95% C.I.

NCEP/NCAR winds (925 hPa) and SLP regressed on PC2.

Forcing resembles the Arctic Oscillation!!

T & W, 1998
Mode 2: Siberian shelves

Normalized principal component time series (PC2)

\[ \text{Corr. Coef } R = 0.45, \text{ significant above 95\% C.I.} \]

FORCING:
Positive phase of AO generates eastward alongshore winds.

NCEP/NCAR winds (925 hPa) and SLP regressed on PC2.
Mode 2: Siberian shelves

Normalized principal component time series (PC2)

\[ \text{Corr. Coef } R = 0.45, \text{ significant above } 95\% \text{ C.I.} \]

FORCING:
Positive phase of AO generates eastward alongshore winds

PROCESS:
Surface Ekman transport drives the OBP increase on the Siberian shelves.
Mode 2: seasonal forcing

Regression maps of winds (925 hPa) and SLP on PC2.

Winter (DJFMA)

Summer (JJAS)

Mode 2 is forced similarly in winter and summer...

... except in the Barents Sea: weaker during summer
Mode 2: modeled OBP and SSH

Modeled OBP and SSH regressed on all months GRACE PC2

Models show Siberian shelves OBP increase

OBP = SSH → OBP change on the Siberian shelves is of barotropic character.
Using **GRACE**, 2 modes of circulation and forcing were identified:

<table>
<thead>
<tr>
<th>MODE</th>
<th>FORCING</th>
<th>PROCESS</th>
<th>SSH-OBP RELATION</th>
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<tbody>
<tr>
<td>1</td>
<td>Wintertime southerly winds at straits</td>
<td>Northward slope current</td>
<td>Partially baroclinic (basins)</td>
</tr>
<tr>
<td>2</td>
<td>Arctic Oscillation (+)</td>
<td>Surface Ekman transport</td>
<td>Barotropic (shelves)</td>
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Ocean models capture the large-scale patterns of variability in ocean circulation at these time scales.
• Using **GRACE**, 2 modes of circulation and forcing were identified:

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• Ocean models capture the large-scale patterns of variability in ocean circulation at these time scales.
Gravity Recovery and Climate Experiment
http://grace.jpl.nasa.gov/
GRACE – *in situ* mismatch in Kara & Barents seas

**Why tide gauge – GRACE mismatch in Kara and Barents Sea?**

**a) GRACE may have seasonal leakage from land-hydrology**

**b) Contrary to B&H [2008], Kara and Barents Seas might have strong steric pressure signal, likely due to runoff influence.**

GRACE land mass change of Kara watersheds.

```
<table>
<thead>
<tr>
<th>Year</th>
<th>Equivalent Water Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>-12</td>
</tr>
<tr>
<td>2004</td>
<td>-10</td>
</tr>
<tr>
<td>2005</td>
<td>-8</td>
</tr>
<tr>
<td>2006</td>
<td>-6</td>
</tr>
<tr>
<td>2007</td>
<td>-4</td>
</tr>
<tr>
<td>2008</td>
<td>-2</td>
</tr>
<tr>
<td>2009</td>
<td>0</td>
</tr>
<tr>
<td>2010</td>
<td>2</td>
</tr>
<tr>
<td>2011</td>
<td>4</td>
</tr>
<tr>
<td>2012</td>
<td>6</td>
</tr>
</tbody>
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```

**Lagged-correlation**

```
<table>
<thead>
<tr>
<th>Lag (month)</th>
<th>Correlation Coefficient R</th>
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<tbody>
<tr>
<td>-50</td>
<td>0.7</td>
</tr>
<tr>
<td>-40</td>
<td>0.6</td>
</tr>
<tr>
<td>-30</td>
<td>0.5</td>
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<tr>
<td>-20</td>
<td>0.4</td>
</tr>
<tr>
<td>-10</td>
<td>0.3</td>
</tr>
<tr>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>20</td>
<td>-0.1</td>
</tr>
<tr>
<td>30</td>
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99% C.I.

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Good correlation at no lag $\rightarrow$ land mass change may leak into ocean OBP estimate... but mainly at seasonal timescales!

GRACE-land data from *Landerer and Swenson* [2012]
mean sea level pressure

SLP (mbar)

1004 1006 1008 1010 1012 1014 1016 1018 1020 1022 1024
The AO is the leading EOF mode of the sea level pressure in the northern hemisphere (>30°N) [Thompson and Wallace, 1998].

NCEP/NCAR SLP projected on AO index values from NOAA's Climate Prediction Center

Very high AO!!
A geostrophic slope current due to southerly winds along the Norwegian Sea generates flow into the basin, increasing Arctic OBP.

Hughes C. W. and V. N. Stepanov (2004)
Peralta-Ferriz, C., et al. (2011)
**MODE 3: Shelves dipole**

NCEP/NCAR winds (925 hPa) and SLP regressed on PC3.

**FORCING:**
- Beaufort Gyre spin-up
- Alongshore westerly winds in the Barents Sea.

**PROCESS:**
- Ekman convergence pulls mass away from 'Western' shelves.
- Ekman transport
Mode 3: seasonal forcing

Regression maps of winds (925 hPa) and SLP on PC3.

OBP change from mode 3 is **forced differently** in winter and summer.

Tendency of summer atmospheric circulation toward anticyclonic winds **[Ogi and Wallace, 2012]**

Reflects multi-year variations.

Mode 3: modeled OBP and SSH

Modeled OBP and SSH regressed on GRACE PC3

Winter (DJFMA)

- **OBP**
  - Increased OBP in Barents Sea in winter.

Summer (JJAS)

- **OBP**
  - OBP low on ‘Western’ shelves occurs in winter and summer.

**On the shelves, OBP = SSH → barotropic**

In the basin, OBP ≠ SSH → baroclinic