The Arctic Ocean volume, heat and freshwater transports during 2004-2010

ARCGATE: Maximizing the potential of Arctic Ocean Gateway array

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Arctic boundary observation

Fig. Mooring array during 2008-09, modified from Dickson et al. [2009]
The heat budget in the Arctic Ocean

Little is known about oceanic heat temporal variability

\[ \dot{E} = \dot{E}_o + \dot{E}_l = \nabla B^{oi}_E + Q \]

- \( \dot{E}_o \): Sensible heat in Ocean
- \( \dot{E}_l \): Latent heat in sea ice
- \( Q \): Air-Sea heat flux
- \( \nabla B^{oi}_E \): Boundary heat flux by ocean + sea ice
The pan-Arctic approach: progress so far

- Quasi-synoptic estimate in summer 2005 [Tsubouchi et al., 2012].
- First seasonal cycle during 2005-06 [Tsubouchi et al. under review].

Tsubouchi et al. [2012, JGR]
Objective of this study


Focus period: Oct. 2004 - May 2010 (68 months)
Data during 2004-2010

- ~1,000 moored instruments: microCAT (T, S: blue), RCM (T, (S), V: red), ADCP (V: green).
- 37 Repeat CTD sections in south of BSO.
- PIOMAS sea ice thickness & velocity data [Zhang and Rothrock, 2003]

Fig. Mooring array in the Arctic four main gates
Filtering and Gridding

- De-tided and smoothed with Butterworth filter (27 days cutoff).
- Data gaps (> 30 days) are filled by its mean annual cycle.
- Linear interpolation is applied vertically and horizontally.

N-S velocity (cm s\(^{-1}\))

Daily de-tided (black)
Daily smoothed (green)
Monthly mean (red)
Monthly Temperature fields

- Captures major water mass distributions & variabilities
- AW in WSC and BSO, Polar water, large variability in Bering Strait.

Temperature at 50m. Monthly in black, average in red.
Monthly initial volume transport imbalance

- Initial imbalances is \(-3.0\pm2.2\) Sv.
- Of which, below 1,500m accounts for \(-2.4\pm0.9\) Sv.

Full depth (black), above 1,500m (grey).
Inverse model: unknowns & constraints

Obtain volume and salt conserved monthly velocity field for consecutive 68 months.

- 1287 unknowns are derived from 12 constraints.
- Bottom vel (639), Sea ice (639), FW input (1), Diapycnal (8)
- Volume & Salt: 5 layers and whole layer
Results

pan-Arctic volume, heat & FW boundary transports
Mean velocity field during 2004-2010

- Captures major current system.
- Polar water outflow, AW inflow, PW inflow.

Table: volume transport comparison

<table>
<thead>
<tr>
<th></th>
<th>This study</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davis</td>
<td>-1.9±1.0</td>
<td>-1.6±0.5(*1)</td>
</tr>
<tr>
<td>Fram</td>
<td>-1.4±1.2</td>
<td>-2.0±2.7 (*2)</td>
</tr>
<tr>
<td>BSO</td>
<td>2.2±1.0</td>
<td>2.0 (*3)</td>
</tr>
<tr>
<td>Bering</td>
<td>1.0±0.5</td>
<td>0.8 (*4)</td>
</tr>
<tr>
<td>Net</td>
<td>-0.10±0.06</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

*1 Curry et al., 2014, *2 Schauer et al., 2008, *3 Smerduskud et al., 2010, *4 Woodgate et al., 2005

Fig. (top) mean volume & salt closed velocity field. (Bottom) cumulative full depth volume transport.
Volume transports: each gateway

- Net transport is almost zero in each month.
- Seasonality.
  - Strong BSO inflow in winter.
  - Strong Bering inflow in summer.

<table>
<thead>
<tr>
<th></th>
<th>long term</th>
<th>JFM</th>
<th>JAS</th>
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<tr>
<td>Davis</td>
<td>-1.9±1.0</td>
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<td>+2.2</td>
</tr>
<tr>
<td>Bering</td>
<td>1.0±0.5</td>
<td>+0.8</td>
<td>+1.4</td>
</tr>
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</table>
Volume transports: water mass

- Double cell overturning structure.
- AW inflow: strong in winter, weak in summer.
- DW outflow (-1.4±0.8 Sv) may be too strong.

<table>
<thead>
<tr>
<th></th>
<th>(Sv)</th>
<th>mean</th>
<th>JFM</th>
<th>JAS</th>
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</thead>
<tbody>
<tr>
<td>SURF+UAW</td>
<td></td>
<td>-1.0</td>
<td>-1.8</td>
<td>-0.3</td>
</tr>
<tr>
<td>AW</td>
<td></td>
<td>+4.5</td>
<td>+6.0</td>
<td>+3.2</td>
</tr>
<tr>
<td>IW+DW</td>
<td></td>
<td>-3.5</td>
<td>-4.3</td>
<td>-2.9</td>
</tr>
</tbody>
</table>
The Heat transports

- The heat transport is $180\pm57$ TW (68 monthly ave & std).
- Seasonality: $\sim250$ TW in Nov, $\sim100$ TW in May.
- Inter-annual variability: $196\pm56$ TW in 2004-05, $165\pm71$ TW in 2007-08.

*12 monthly ave & std from Oct to following Sep.
The FW transports

- The FW transport is $156\pm91$ mSv (68 monthly ave & std).
- Seasonality: $\sim250$ mSv in Nov-Mar, $\sim50$ mSv in Jun-Aug.
- Inter-annual variability: $163\pm79$ mSv in 2004-05, $121\pm103$ mSv in 2007-08.

*12 monthly ave & std from Oct to following Sep.*
Putting into a big picture

- Heat budget
  - $180 \pm 57 \text{TW} \sim 15.9 \pm 5.0 \text{Wm}^{-2}$
  - MERRA has the best agreement.

Long-term air-sea heat fluxes north of 70°N (Wm$^{-2}$)

<table>
<thead>
<tr>
<th>NRA</th>
<th>ERA40</th>
<th>JRA25</th>
<th>MERRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>11</td>
<td>14</td>
<td>19</td>
</tr>
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Porter et al. [2010], Cullather & Bosilovich [2012]

Note that 10W/m$^2$ is equivalent to 1m sea ice melt in a year.
Putting into a big picture

- FW budget
  - Boundary: 156±91 mSv
  - Surface: ~214 mSv. Haine et al. [2015]
  - FW content: ~25 mSv. Rabe et al. [2014]
  - Imbalance of ~33 mSv - significant?

\[
\dot{E} = \dot{E}_o + \dot{E}_l = \nabla B_E^{oi} + Q
\]
What changes by changing $T_{\text{ref}}$?

- Total heat transport DOES NOT change.
- Temperature transport in each piece of section DOES change.
- e.g. WSC: $33 \pm 14$ TW-eq ($1.01 \pm 0.18$˚C), $113 \pm 34$ TW-eq ($-1.8$˚C).

\[
F_H^j = \iint \rho c_p (\theta - \theta_{\text{ref}}^j) v \, dx \, dz
\]

Fig. Accumulative full depth heat transport along sections.
What changes by changing $S_{\text{ref}}$?

- Total FW transport DOES NOT change (almost).
- FW transport in each piece of section DOES change.
- e.g. EGC: $-4\pm11$ mSv-eq ($34.70\pm0.02$), $95\pm21$ mSv-eq (35.2).

**Fig.** Accumulative full depth FW transport along sections.
Take home message

• Mass & salt conserved velocity field is crucial to calculate heat & FW transport.

• Choice of reference value is arbitrary.
  • For heat, any value is possible.
  • For FW, sensible values (34.7-35.2) only introduce error of ~1%.

• Recognise the impact of choice of reference values.
  • Total heat & FW DOES NOT change (For FW, almost).
  • Partial sectional values DOES change.
Data on PANGAEA

- One year data is available.
- Search Tsubouchi, then you will find it.
- 68 month data will be available in this summer.
ASOF’s role to promote this study

• Endorsement
• Gateway to the PANGAEA web link
• Present the time series as scientific deliverable
What is next break though?

- Include Greenland-Scotland Ridge section in the box inverse model.
- Two boxes - Arctic Ocean & Nordic Seas.
- Initial focus period would be 2004-2010 (same as this study).

Tsubouchi et al. [2012, JGR]

Eldevik & Nilsen. [2013, JC]
Summary


- Volume tra. has Seasonality in each gateway and water masses.

- Double cell over-turning structure and its seasonality.

- Heat transport is $180\pm57$ TW $\sim 15.9\pm5.0 \text{ Wm}^{-2}$

- FW transport is $156\pm91$ mSv.

- The seasonal & interannual variability in the Heat & FW transports

- I am looking for a job. - ideally related work.
Acknowledgement

• The Arctic main gateways have been measured by six research institutes in the world: UW for Davis Strait and for the US side of Bering Strait; NPI and AWI for Fram Strait; IMR for BSO; UAF and AARI for the Russian side of Bering Strait.

• The pan-Arctic approach is developed under two UK NERC projects, ASBO and TEA-COSI.

• This work is supported by EU Marie Curie project, ARCGATE.