Global ocean reanalyses for the Arctic

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Learning goals

After this presentation, you

- know what Ocean Retrospective Analyses (ORAs) are,
- can tell what they are used for,
- understand why they are important in polar research,
- can, to some extent, estimate their usefulness,
- and
- consider starting to use ORAs in your research.
What is an analysis?

- Weather map is a familiar example, representing the state of atmosphere.
- It typically is the initial condition of a forecast.
What is reanalysis?

Analysis of past, where old observations and a non-changing analysis system are used.
What are ORAs?

- Similar to familiar atmospheric reanalyses (ERA, NCEP, JRA, ...) which consist of multidecadal meteorological model simulations with assimilated observations.
- ORAs are often used to generate initial conditions to long-term coupled model forecasts, such as decadal.
- As here, they are also used to describe and study the state and evolution of the ocean.
Special issue in *Climate Dynamics* (August 2017) with 21 articles.

However, leaves the polar regions largely out, except Chevallier et al. (2017).

Data repository established at [https://icdc.cen.uni-hamburg.de/1/daten/reanalysis-ocean/oraip.html](https://icdc.cen.uni-hamburg.de/1/daten/reanalysis-ocean/oraip.html).
Why polar regions?

- Very few observations, particularly under ice.
- Dynamical model with physics is a better 'interpolator' than statistical methods.
- Estimates for non-measurable quantities.

Polar ORA-IP group at BSC, Barcelona in June 2017
First discussions in late 2015.

Three face-to-face meetings (in Helsinki and Barcelona) and several on-line gatherings.

Review process was rather smooth.
Material and methods
Mostly eddy-permitting models with level vertical coordinates.

Many configurations of NEMO.

One regional model, others global.

One coupled atmosphere-ocean model, others mainly driven by ERA-Interim.
**Data assimilation (DA) in ORAs**

<table>
<thead>
<tr>
<th>Name</th>
<th>C-GLORS025v5</th>
<th>ECDA3</th>
<th>GECCO2</th>
<th>GLORYS2v4</th>
<th>GloSea5-GO5</th>
<th>MOVE-G2i</th>
<th>ORAP5</th>
<th>SODA3.3.1</th>
<th>TOPAZ4</th>
<th>UR025.4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ocean restoring</strong></td>
<td>Large scale bias correction to EN4v2a</td>
<td>Fully coupled</td>
<td>None</td>
<td>T, S restoring towards EN4.1.1 for z &gt; 2000 m and lat &lt; 60°S (τ = 20 years)</td>
<td>Surface Haney SSS restoring (− 33.333 mm/day/PSU), 3D T/S to ENACT3 2004–2008 climatology (τ = 1 year)</td>
<td>Relaxing (by IAU) T/S to merged PHC3- WOA13 climatology (τ = 5 years)</td>
<td>Relaxation to OSTIA/NOAA O1v2d SST</td>
<td>Restoring to mean T and S (τ = 10 years). Relaxation to WOA SSS (τ = 3 months)</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Sea-ice DA method</strong></td>
<td>Nudging</td>
<td>None (SST)</td>
<td>None (SST)</td>
<td>Reduced order KF</td>
<td>3DVAR</td>
<td>3DVAR</td>
<td>3DVAR-FGAT</td>
<td>None (SST)</td>
<td>EnKF</td>
<td>OI</td>
</tr>
<tr>
<td><strong>Sea-ice DA variables</strong></td>
<td>SIC, Arctic SIT</td>
<td>–</td>
<td>–</td>
<td>SIC</td>
<td>SIC</td>
<td>SIC</td>
<td>SIC</td>
<td>–</td>
<td>SIC, SIV</td>
<td>SIC</td>
</tr>
<tr>
<td><strong>Sea-ice DA sources</strong></td>
<td>NOAA O1v2d, PIOMAS</td>
<td>–</td>
<td>–</td>
<td>CERSAT</td>
<td>OSISAfv2</td>
<td>MGDSST</td>
<td>OSTIA, NOAA O1v2d</td>
<td>–</td>
<td>OSISAfv</td>
<td>OSISAf</td>
</tr>
<tr>
<td><strong>Ocean DA method</strong></td>
<td>3DVAR</td>
<td>EnKF</td>
<td>4DVAR (adjoint)</td>
<td>Reduced order KF + 3DVAR large scale bias correction to in-situ T, S</td>
<td>3DVAR</td>
<td>3DVAR</td>
<td>3DVAR</td>
<td>OI</td>
<td>EnKF</td>
<td>OI</td>
</tr>
<tr>
<td><strong>Ocean DA variables</strong></td>
<td>T, S, SSH, SST</td>
<td>T, S, SST</td>
<td>T, S, SSH, SST</td>
<td>T, S, SST, SSH</td>
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</tr>
</tbody>
</table>

**DA changes the physics:**

\[
\frac{dx}{dt} = \cdots + G w_i (x^0 - x)
\]
Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS)

- PIOMAS sea-ice thickness and volume are used widely.
- However, Polar ORA-IP did not include PIOMAS. Why?
  - PIOMAS was not a part of the original ORA-IP.
  - Its ocean output is not publicly available.
- PIOMAS ORA sea-ice volume was compared with others (slide later).

http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/
Statistical analysis

- Sea-ice variables: snow volume and thickness; sea-ice concentration, thickness, extent, area and volume
- Ocean variables: mixed layer depth, transports (heat, volume and freshwater), heat and salinity contents and hydrography (temperature and salinity).
- Mean states, biases and spread (1993 – 2010)
- Trends and variability (in progress)

\[
\text{SIA} = \int_A SIC \, dA, \quad \text{OHC} = \int_{-H}^{\eta} \theta(z) \, dz
\]
Arctic and Antarctic basin masks used for ORA ensemble statistics (left).

Arctic sections for ocean transport calculations (below).

Antarctic results not presented (unless you ask for it).

Table 2 Sections used for calculating net lateral volume, heat and freshwater exchange between the Arctic and Sub-Arctic

<table>
<thead>
<tr>
<th>Section</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fram strait</td>
<td>N79°30'</td>
<td>W20°–E11°</td>
</tr>
<tr>
<td>Barents sea opening</td>
<td>N70°30’–N74°30’</td>
<td>E20°</td>
</tr>
<tr>
<td>Davis strait</td>
<td>N66°40’</td>
<td>W53°30’–W61°</td>
</tr>
<tr>
<td>Bering strait</td>
<td>N66°45’</td>
<td>W168°–W170°30'</td>
</tr>
</tbody>
</table>
Recap: Arctic Ocean circulation

Talley et al. 2011
Selected results
Snow on sea ice

Sea-ice extent and area

- **MIZ = Marginal Ice Zone**, where sea-ice concentration is 90–15%.
- In pack ice, concentration is \( \geq 90\% \).
2000 – 2012 mean difference of ORA sea-ice thickness to Thickness Regression Procedure (ITRP; Lindsay and Schweiger 2015) thickness in February – March.
March mixed layer depth

As with sea-ice thickness, differences between models are large.

Deep mixed layers in the Nordic Seas indicate strong convection.
Mixed layer depth biases

Observed (MIMOC; Schmidtko 2013) and ORA MMM mixed-layer depths and their difference.
Mean 1993 – 2010 heat transport through main Arctic Ocean openings.
Eurasian basin temperature profile

Cold AW bias to Sumata.
Evolution of sea-ice volume

Integrated over the ITRP-region.

PIOMAS included.

Fig. 3 Arctic sea-ice volume in October/November.

Frank Kauker/AWI
Temperature and salinity trends

Amerasian basin:

- Amerasian and Eurasian basins are getting fresher and warmer.
- Warming clearest in Eurasian basin in top 100 m, and in Amerasian basin in 100–300 m layer.
- Freshening clearest in top 100 m layer.
Conclusions – common issues

- Sea-ice edge is largely unaffected by heat anomalies due to DA, but MIZ is too narrow.
- Summer mixed layer is too shallow, associated with sea-ice biases and poorly represented mixing processes.
- Sea-ice thickness has a dipole bias, which could be related to too fast moving ice.
- Heat transport is too weak to the Arctic Ocean, related to strong cooling in the North Atlantic and Barents Sea.
- Atlantic Water in the Arctic Ocean is too cold and fresh.
Other conclusions

- Snow volume differences are large due to uncertain precipitation, and deviations in ice formation, melt and sublimation.
- In the Greenland Sea, too far east extending ice may reduce heat transport through Fram Strait.
- Eddy-permitting resolution helps to resolve transports through openings, such as in St. Anna Trough and Fram Strait.
- Multi-ORA mean performs better than most individual ORAs.
- Despite biases in mean states, sea-ice and upper ocean temperature and salinity trends seem rather well captured.
Future of ORAs looks bright

More observations from polar oceans.

More variables are being assimilated, such as sea-ice thickness and velocity.

Models, their coupling and data-assimilation methods are improving.

Research using ocean-ice models remains important.

New physical processes, for example ice-waves, and improving resolution better resolve ocean eddies, mixing and transports.
Thank you!

Any questions?


Supplementary figures
Synthesis of mean states

- MMM performs better than individual ORAs.
- MMM is a useful product.
- No ORA stands superior to the others.
Arctic sea-ice trends
Eurasian basin has warmed, especially in 0–100m.
Amerasian basin has warmed.

ORA MMM shows significant trends in 100–3000m.
The Eurasian basin is getting fresher.
Amerasian basin salinity trends

Amerasian basin is getting fresher on top.
Eurasian basin temperature profile

Cold AW bias to Sumata.
Eurasian basin salinity profile

(a) Mean and (b) biases.
Amerasian basin temperature profile

(a) Mean and (b) biases.
Amerasian basin salinity profile

(a) Mean and (b) biases.
Ocean heat content

- Average ORA heat content and spread.
- EN4, WOA13 and Sumata observed hydrographic climatologies.
Ocean salinity content

- Average ORA salinity content and spread.
- EN4, WOA13 and Sumata observations.
Temperature seasonal cycle

Mean monthly temperature (a) in Eurasian and (b) Amerasian basins in 0–100m layer.
Salinity seasonal cycle

Mean monthly salinity (a) in Eurasian and (b) Amerasian basins in 0–100m layer.
Sea-ice concentration

- Number of ORAs per grid cell (up to 10) where their sea-ice concentration is >15% in March (left) and in September (right).
Sea-ice volume

Volume $[\text{km}^3]$ in ICESat domain.

(c) is (a) minus (b).

ENSMEAN is the ORA mean and spread.
Sea-ice thickness

- October–November 1993–2010 sea-ice thickness differences [m] from ITRP.
August mixed layer depth
Arctic mixed layer depth

Mean seasonal cycle - north of 80 °N
Volume transport
Fresh water transport

\[ S_{ref} = 34.8 \]
0 – 100 m heat content
Multi-model mean departures (\( \text{ENS}_{\text{ORA}} \)) of Arctic Ocean Heat (OHC; upper row) and Salt Content (OSC; lower row) from an observational multi-product mean climatology (\( \text{ENS}_{\text{CLIM}} \)). Departures are averaged vertically in 4 layers (0–100 m, 100–300 m, 300–700 m and 700–1500 m). The observational climatology is the mean of Sumata, WOA13 and EN4.2.0.g10 products.