Warm Deep Water and OHC changes in the Weddell Sea - 20th and 21st C
CMIP5 and Ocean-reanalysis

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Southern Ocean = large uncertainties in climate models

Region of dense water mass formation

- Icy wind flows from the Antarctic continent
- Salt is expelled as sea ice forms
- Cold, salty water sinks
- Warmer water flows from the equator
- Antarctic bottom water flows toward the equator
Focus on the Atlantic sector of the Southern Ocean
Southern Ocean

Climate Hotspot

- Source (and export) region for Antarctic Bottom Water (AABW);
- AABW becoming fresher and lighter (Schmidkto et al., 2014);
- Processes such as ice shelves desintegration; shelf Water Freshening (Van Wijk & Rintoul, 2014);
- We want to know how Weddell Sea water masses are represented in large-scale climate models.
Motivation
Weddell Sea Water Masses - CMIP5
Ocean Heat Content - CMIP5
Appendix: Description of methods

Weddell Sea Water Masses

Observations

Warm Deep Water and OHC changes in the Weddell Sea - 20th
Interest is in the Warm Deep Water (WDW)

Robertson et al., 2002
Water masses are excellent indicators for climate change

Warm Deep Water along SR4 - WOCE data
Evaluate the dense water masses in climate models.

Separation of water masses using OMP (optimal multiparameter) method

- OMP is based on simple linear mixing, starting from observed values of water mass parameters.

- Determine the contributions (in percentage) from predefined source water types (SWT).
OMP results

Weddell Sea - WOCE data
Weddell Sea Water Masses

CMIP5 models intercomparison
CanESM, CCSM4, CESM1-CAM5, GFDL-CM3, Hadgem2-ES, IPSL-CM5A-MR, MIROC5, MIROC-ESM, MPI-ESM-MR

- Locate **WDW** highest percentage and track:
  - temperature changes
  - salinity changes
  - core depth changes
RESULTS: Weddell Sea Water Masses

T-S for historical (blue) and RCP8.5 (red)

- CanESM2
- CCSM4
- CESM1
- HadGEM
Weddell Sea Water Masses - RESULTS

T-S for historical (blue) and RCP8.5 (red)

- IPSL-CM5
- WDW
- MIROC5
- MPI-ESM-MR
- MIROC-ESM
- WDW
All models show warming, however, their representation of the water masses is very different
Motivation
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Weddell Sea Water Masses

WDW salinity: some models show freshening

![Graph showing WDW salinity changes with years for different models.](image-url)
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Weddell Sea Water Masses

WDW core depth changes

![Graph showing WDW core depth changes over time for different models.](image-url)
How well are CMIP5 models doing w/r WDW core depth?

1. CanESM2
2. CCSM4
3. CESM1-CAM5
4. GFDL-CM3
5. HadGEM2-ES
6. IPSL-CM5A-MR
7. MIROC5
8. MIROC-ESM
9. MPI-ESM-MR

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Changes in CMIP5 models - Conclusions

- all models show warming
- most models show freshening 0.2 decrease (max)
- all models show WDW core is moving up (less dense)
- note: GFDL and HadGEM - poor WDW representation (historical)
Ocean Heat Content

(Global OHC) ORAS4 Reanalysis *Balmaseda et al., 2013*
Time series of OHC

Reanalysis vs. CMIP5 for SO, SATL and Regional Seas

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Warm Deep Water and OHC changes in the Weddell Sea - 20th
### OHC trends

<table>
<thead>
<tr>
<th>Southern Ocean [W/m²]</th>
<th>South Atlantic [W/m²]</th>
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<tbody>
<tr>
<td><strong>0-2000m</strong></td>
<td><strong>0-2000m</strong></td>
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<tr>
<td>ORAS4</td>
<td>1.23</td>
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<tr>
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<td>IPSL</td>
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### Weddell [-W/m²]

<table>
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### Ross [-W/m²]

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<td>CanESM2</td>
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### Bellingshausen-A. [-W/m²]

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<td>CanESM2</td>
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Is OHC and SIE correlated?

Annual avg - Weddell Sea from 1982

ORAS4 and summer SIE: $r = -0.60$ (99% confidence interval)
SODA and summer SIE: $r = -0.42$ (95% confidence interval)
ECCO2 and summer SIE: $r = -0.48$ (90% confidence interval)
Correlation of reanalysis OHC and satellite SIE

Annual avg - Ross Sea from 1982

ORAS4 and winter SIE: \( r = -0.37 \) (90% confidence interval)
SODA and summer/winter SIE: \( r = -0.56 \) (99% confidence interval)
ECCO2 and SIE: no significant correlation
What is the *Bottom-line*?

**Southern Ocean is Warming**

- Warming of the deep water in the Weddell Sea has important implications for AABW formation, melting of pack ice, and the regional ocean–atmosphere heat transfer.
- Negative OHC trend in ice formation regions (WS and Ross) not captured by Cmip5 - How to explain the negative trend, is it real?
- Models missing important processes?
Ice shelves?

Regional hydrography

- Continental & ice shelf region:
  - Ice shelf
  - ISW
  - HSSW

- Ocean:
  - AASW
  - MWDW
  - WSDW
  - WSBW

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OMP calculations

\[
\begin{align*}
x_1 \theta_1 + x_2 \theta_2 + x_3 \theta_3 + x_4 \theta_4 + 0 &= \theta_{\text{Obs}} + R_\theta \\
x_1 S_1 + x_2 S_2 + x_3 S_3 + x_4 S_4 + 0 &= S_{\text{Obs}} + R_S \\
x_1 O_1 + x_2 O_2 + x_3 O_3 + x_4 O_4 - \Delta O &= O_{\text{Obs}} + R_O \\
x_1 N_1 + x_2 N_2 + x_3 N_3 + x_4 N_4 + \Delta N &= N_{\text{Obs}} + R_N \\
x_1 P_1 + x_2 P_2 + x_3 P_3 + x_4 P_4 + \Delta P &= P_{\text{Obs}} + R_P \\
x_1 Si_1 + x_2 Si_2 + x_3 Si_3 + x_4 Si_4 + \Delta Si &= Si_{\text{Obs}} + R_{Si} \\
x_1 + x_2 + x_3 + x_4 + 0 &= 1 + R_{\text{CMass}}
\end{align*}
\]
OMP calculations

The Method

\[ \begin{align*}
\theta_1 & \quad \theta_2 & \quad \theta_3 & \quad \theta_4 & \quad 0 \\
S_1 & \quad S_2 & \quad S_3 & \quad S_4 & \quad 0 \\
O_1 & \quad O_2 & \quad O_3 & \quad O_4 & \quad -rO/P \\
P_1 & \quad P_2 & \quad P_3 & \quad P_4 & \quad 1 \\
N_1 & \quad N_2 & \quad N_3 & \quad N_4 & \quad -rO/P \\
S_1 & \quad S_2 & \quad S_3 & \quad S_4 & \quad 1
\end{align*} \]

\[ 
\begin{bmatrix}
\theta_{\text{Obs}} \\
\phi_{\text{Obs}} \\
\omega_{\text{Obs}} \\
\tau_{\text{Obs}} \\
\theta_{\text{obs}} \\
\phi_{\text{obs}} \\
\omega_{\text{obs}} \\
\tau_{\text{obs}} \\
\end{bmatrix}
\]
OHC calculations

\[ HC_m = \int_{z_1}^{z_2} \int_{y_1}^{y_2} \int_{x_1}^{x_2} \rho_0 c_p (T_m - T_c) \, dx \, dy \, dz \]  

- \( HC_m \) is the monthly Ocean Heat Content value;
- \( \rho_0 \) the average density;
- \( c_p \) the specific heat of water;
- \( T_m \) the temperature at a given point \((x,y,z,t)\);
- \( T_c \), the climatological temperature for the specific month.