Climate impact on interannual variability of Weddell Sea Bottom Water

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Climate impact on interannual variability of Weddell Sea Bottom Water

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Outline

• Overview of Weddell gyre and oceanographic time series

• Extra-polar climate modes and their regional impacts

• Mechanisms of interannual variability:
  • 1) Modulation of dense shelf water production
  • 2) Spin-up of Weddell gyre and increased export

• Extension of results to the MOC(?)
Bottom waters are formed around Antarctica's margins and spread into the global abyssal ocean.

- Southern limb of the global overturning circulation
- Moderates global heat, carbon, and freshwater budgets
- Formal definition for this study: WSBW is bottom water with $\theta < -0.7^\circ$C (restricted to Weddell basin)
Bottom water production and export

- South Scotia Ridge
- Weddell Sea
- Heat, freshwater
- HSSW
- WDW
- WSBW
- Gravity current
- Helo 3 potemp & sigmas stations
- Ronne Ice Shelf
- Filchner Ice Shelf
- S. Orkney Is.
- Powell Basin
- M2
- M3
WSBW outflow moorings

- Equipped with series of thermistors and current meters (we focus on deepest sensors, ~4500 m at M3)
- Positioned at steep escarpments to sample boundary current and minimize effects of gyre movement
Mooring data

- 8 year record (longer now!) – first record long enough to record interannual variability
Mooring data

- Strong **seasonal variability** (cold pulse in austral winter coincident with velocity and shear maxima)

- Implies export is **episodic** (gravity current export in austral spring with travel time of ~5 months to mooring; related to seasonal cycle of winds and Ekman transport)
Mooring data

- But also distinct **interannual variability**:
  - No cold pulse in 2000.
  - Increased salinification of cold pulse between 1999-2002.
Large-scale climate forcing

- Processes of formation and export are related to regional (Weddell) atmospheric forcing
- Regional atmospheric forcing is largely controlled by extra-polar climate variability
  - ENSO (e.g., Yuan, 2004; Martinson and Iannuzzi, 2003)
  - SAM (e.g., Lefebvre and Goosse, 2005)
- But it is not a simple story...
Large-scale climate forcing

El-Niño – Southern Oscillation (ENSO)

- Joint influence in Western Weddell via Amundsen SLP anomaly and dipole anomalies in wind/sea ice (EN/-SAM or LN/+SAM)

- Potential for modulation of impact

Southern Annular Mode (SAM)
Favorable phase relationship of ENSO/SAM leads to stronger, more persistent dipole anomalies in winds and sea ice.

Explanation: anomalous transient momentum fluxes in the Pacific reinforce the circulation anomalies in the midlatitudes, altering the circulation to maintain the ENSO teleconnection (Fogt et al., 2011).
The period of our hydrographic time series is dominated by favorable ENSO/SAM phase relationships.
Large-scale climate forcing

- MEOF analysis to capture coherent climate variability and obtain “most relevant” forcing index over the 1997-2007 period.

- EOF 1 (22% variance) shown

- Clearly represents simultaneous La Niña / +SAM variability

The period of our hydrographic time series is dominated by favorable ENSO/SAM phase relationships.
Time scale(s) of forcing

- Lagged-correlation analysis between WSBW temperature time series and climate indices to establish time-scale(s) of forcing.

Correlogram PC1 with M3 bottom temperature (solid) and M2 bottom temperature (dashed)
Time scale(s) of forcing

- Lagged-correlation analysis between WSBW temperature time series and climate indices to establish time-scale(s) of forcing.

- 14-20 month: ENSO and 'non-annular' SAM → Time scale for dense water production

- 0-6 month: 'Annular' SAM → Time scale for export
Mechanism I: Production

- Wind anomaly is associated with ENSO/SAM related dipole-pattern of anomalies.
- Controls summertime coastal polynya area and wintertime production of dense water.
Mechanism I: Production

Correlation coefficients

Color: WSBW temperature / Sea ice concentration

Vectors: WSBW temperature / wind

M2 temperature lags 17 months

M3 temperature lags 14 months
Mechanism I: Production

Stronger wind, more ice

Weaker wind, less ice

WSBW $\theta$-anom.

Solid: shelf sea ice conc. anomaly
Dashed: merid. wind anomaly

*If southward wind persists, no HSSW is formed (Timmerman et al., 2002)
Mechanism I: Production

- In particular, the 1999-2002 period is dominated by the very strong 1997/1998 El-Niño.
- Ronne polynya extended $3 \times 10^5$ km$^2$, the largest extent in the satellite record.
- Anomalously large glut of HSSW observed to be produced (Nicholls and Østerhus, 2004).
- Salinity of WSBW increases through 2002, consistent with 3.5 year residence time on shelf (Gill, 1973).
Mechanism II: Export

- WSBW temperature weakly correlated with SAM at 0-6 month lag.
- Stronger westerlies and increased cyclonic forcing may 'spin-up' the Weddell gyre.
- Baroclinicity: isopycnals slump at slope which may facilitate export.
- Also, enhanced cyclonic forcing increases cross-slope flux at zero lag (seen in high-res model; Kerr et al. 2012).

Meredith et al., 2008
Mechanism II: Export

- Use gyre-averaged wind-stress curl as proxy for gyre spin-up.

Mechanism II: Export

- Why should we see an increase in gyre baroclinicity on $O(\text{months})$ when geostrophic adjustment time scales are $O(\text{years})$?

- One idea: *Meredith et al.*, 2011

  Appeal to response of bottom Ekman layer to barotropic changes in deep boundary current on sloping topography:

  $$\tau = 0.5 \, c_d^{-1} \, N^{-1} \, S^{-3/2} \sim 54 \, \text{days}.$$
Mechanism II: Export

- Another (new) idea: Su et al., 2014
  - Wind stress curl drives Ekman pumping in gyre interior.
  - Sloping isopycnals lead to baroclinic instability and rapidly responding mesoscale eddy buoyancy fluxes in the boundary.

- Point of digression: Gyre can respond rapidly to wind forcing.
Synthesis

- ENSO / non-annular SAM dipole anomalies can modulate production of shelf water the year before a pulse is exported.
- Annular SAM related wind anomalies can increase efficacy of export.
  - Construct 2-stage multiple linear regression: (NINO34, SAM index, ADP index) → (shelf sea ice concentration, shelf offshore wind, gyre wind stress curl) → WSBW temperature anomaly.
  - Agreement is best over period of strongest climate forcing and favorable-phasing of ENSO/SAM.

\[ r = 0.66 \]
Potential relation to MOC

- WSDW is derived from WSBW and leaves the Weddell through sills and passages into the Scotia Sea and ultimately the global ocean.

- Stronger gyre $\rightarrow$ less dense (warmer) classes of WSDW escape.

- Isopycnal excursions of 100 m (0.04 °C) possible

- Warming downstream?

Solid: stronger gyre
Dashed: weaker gyre
Potential relation to MOC

- Warming trend is observed in abyssal Atlantic (Johnson and Doney, 2006; shown) and in other basins (Purkey and Johnson, 2010).

  ![Image: Δθ(2000s-1990s)]

- WSDW-source properties do not contain similar trends.

- Related to observed trend in the SAM?
Conclusions

● Strong interannual variability in WSBW temperature is observed to covary with ENSO and SAM related variability.

● Dipole related anomalies modify summer open-water area over the shelf, which dictates the amount of subsequent freeze, shelf water formation and amount of cold-end member available for export.
  • This process is only effective if the dipole teleconnection mechanism is strong (IE, favorable phase relationship between ENSO/SAM).

● SAM related wind-stress curl can spin up the Weddell gyre and facilitate export of cold water from the shelf, affecting the volume and timing of export on short (< 5 month) time scales.

● Superposition of many time scales (teleconnection, advection, shelf residence, baroclinic adjustment) can lead to interesting and complicated responses in WSBW properties and transport.