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(?)

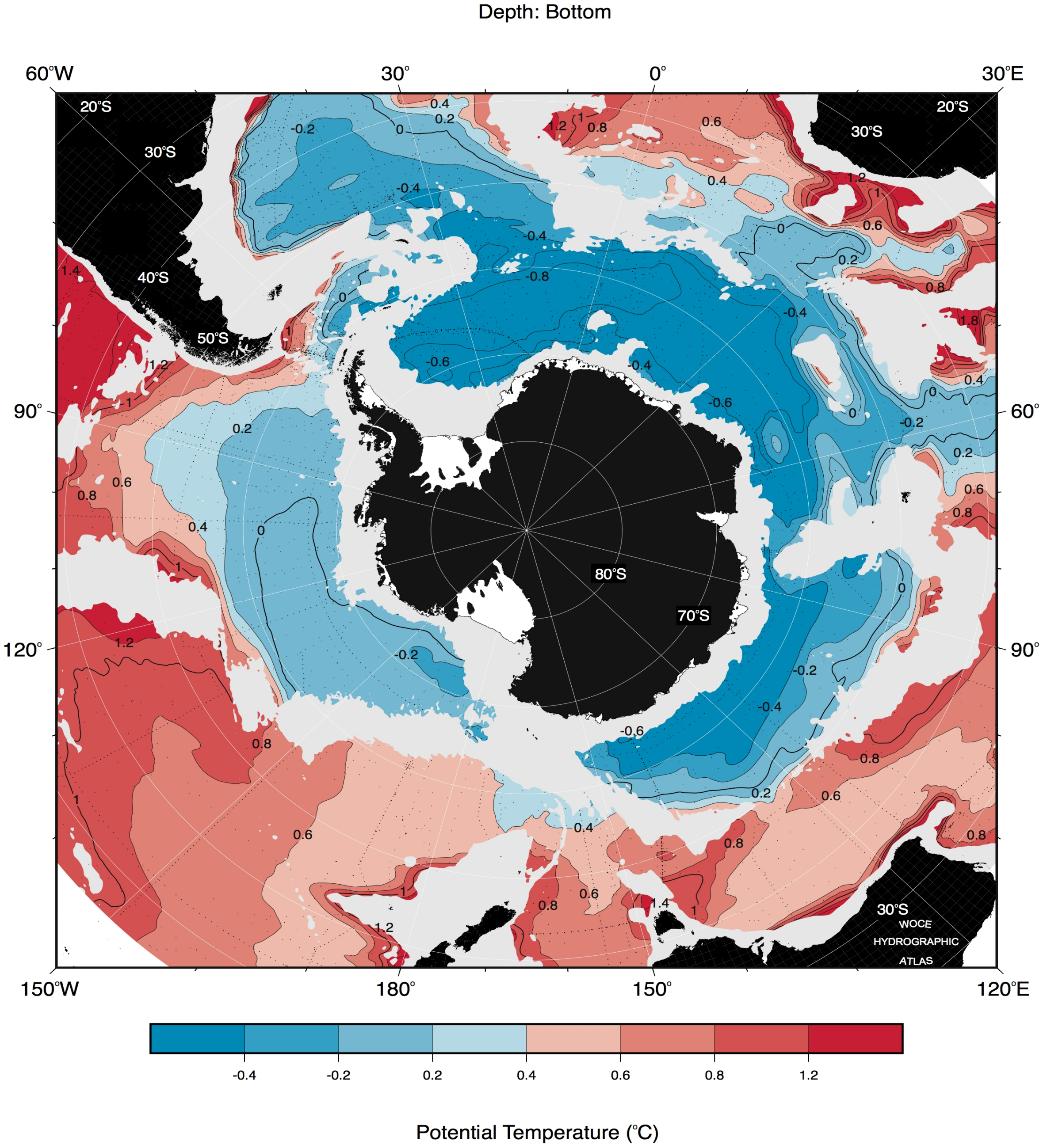
Bottom water production and export

- Bottom waters are formed around Antarctica's margins and spread into the global abyssal ocean

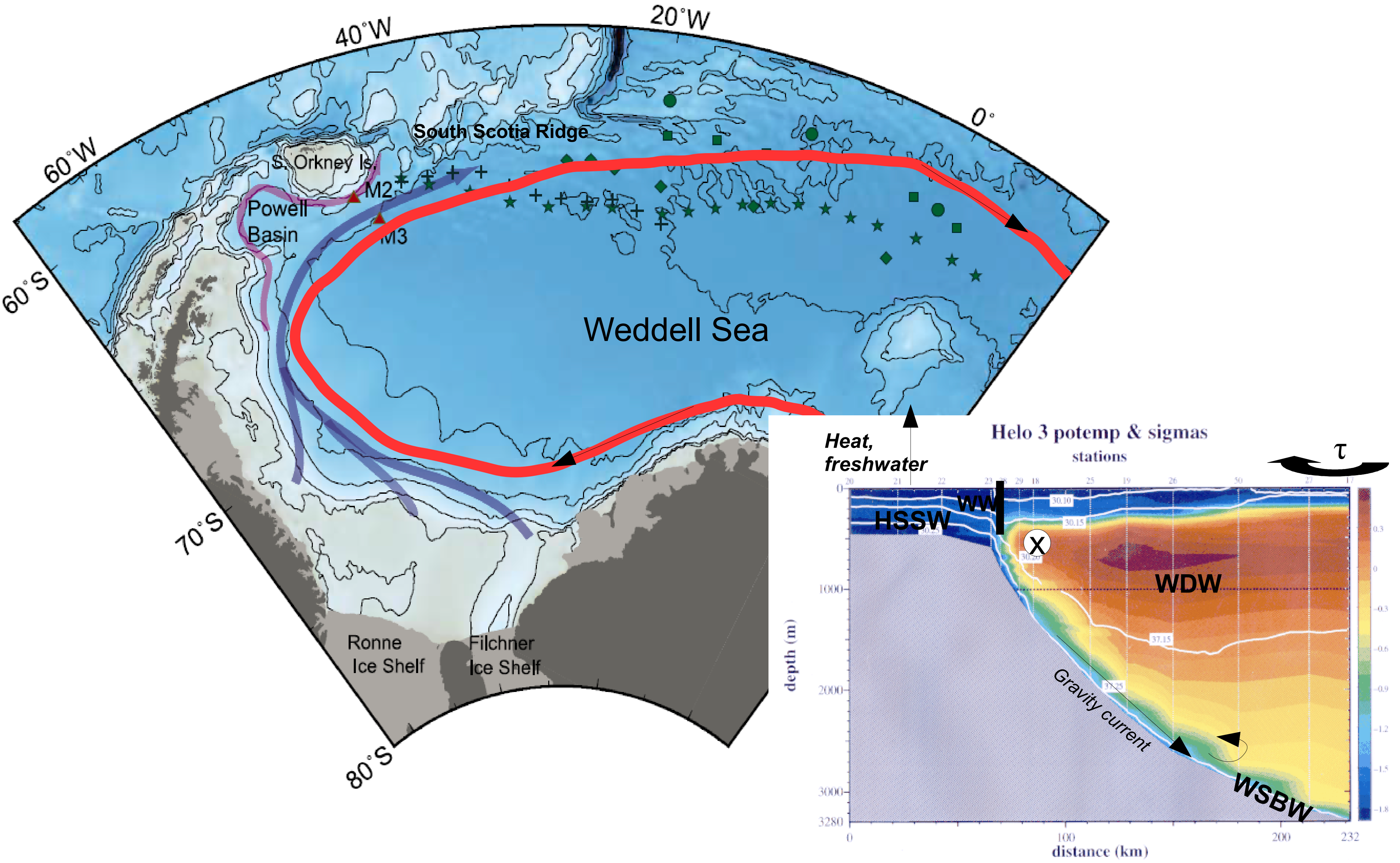
- Southern limb of the global overturning circulation

- Moderates global heat, carbon, and freshwater budgets

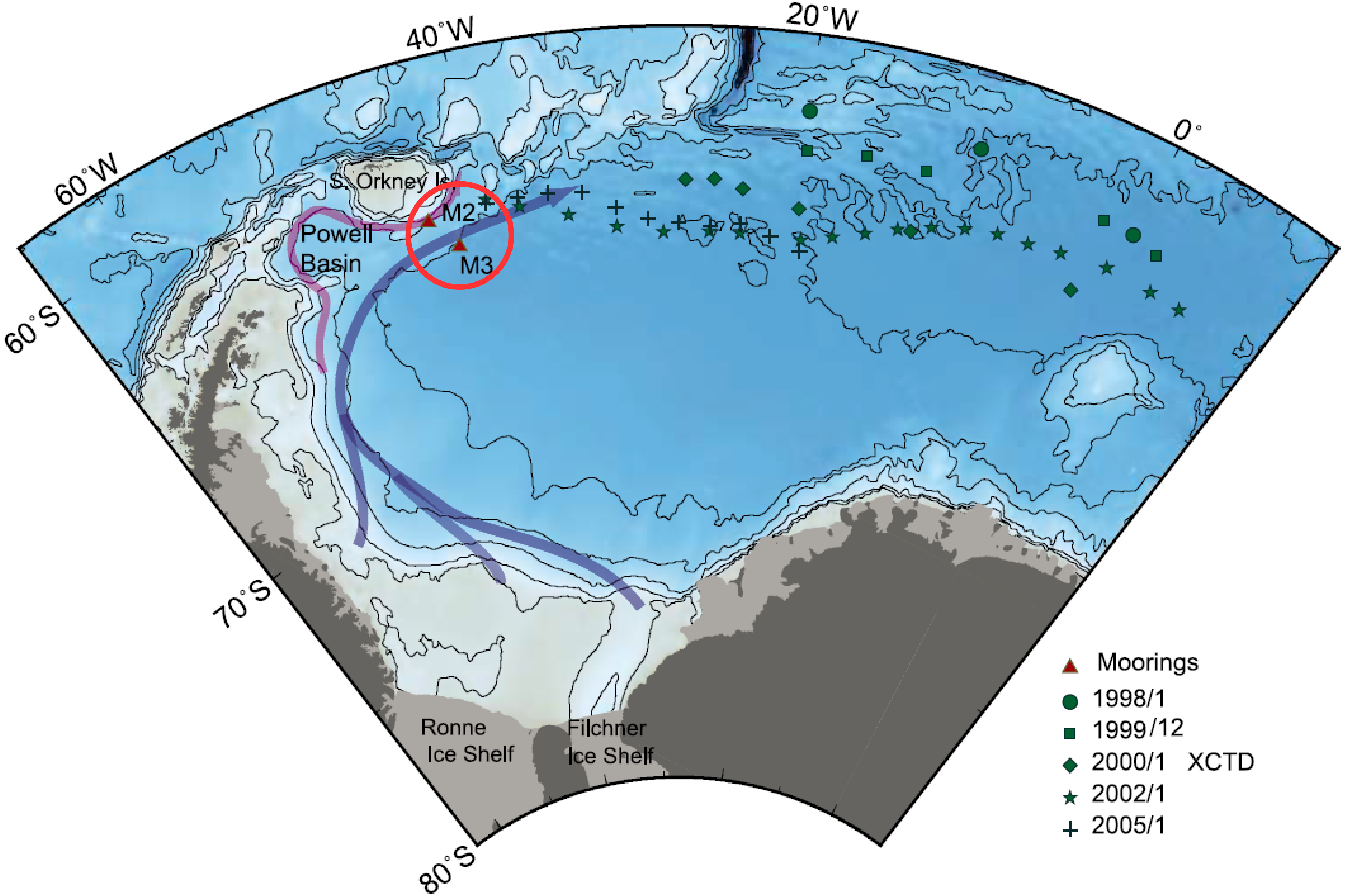
- Formal definition for this study: WSBW is bottom water with θ < -0.7ºC (restricted to Weddell basin)



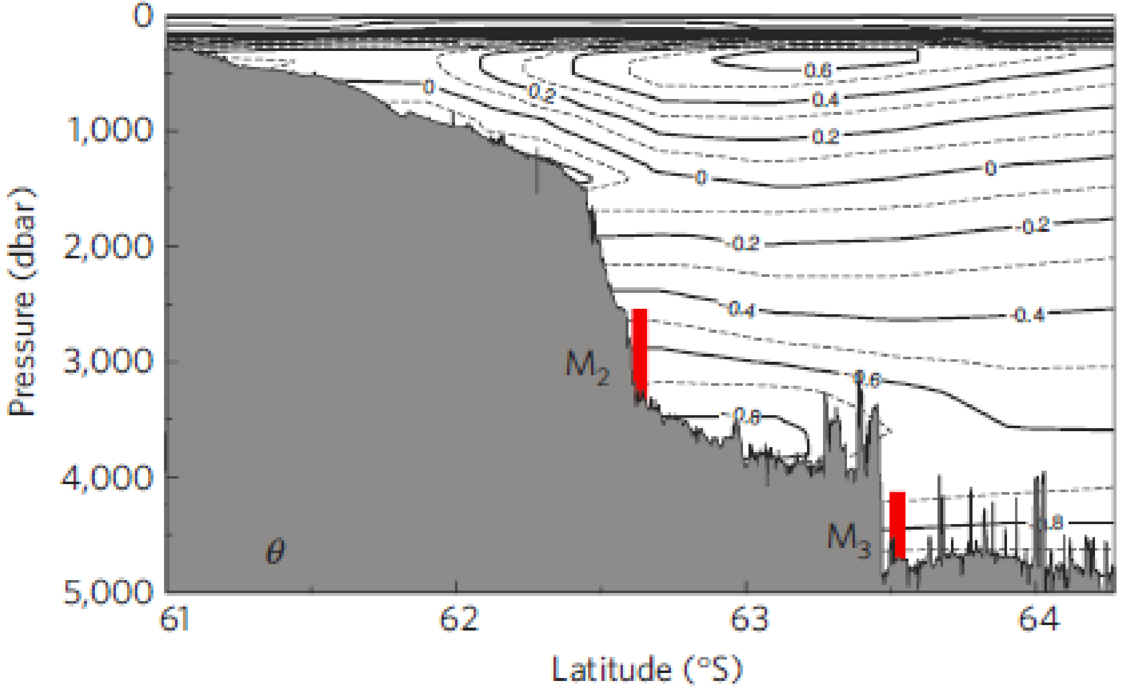
Bottom water production and export

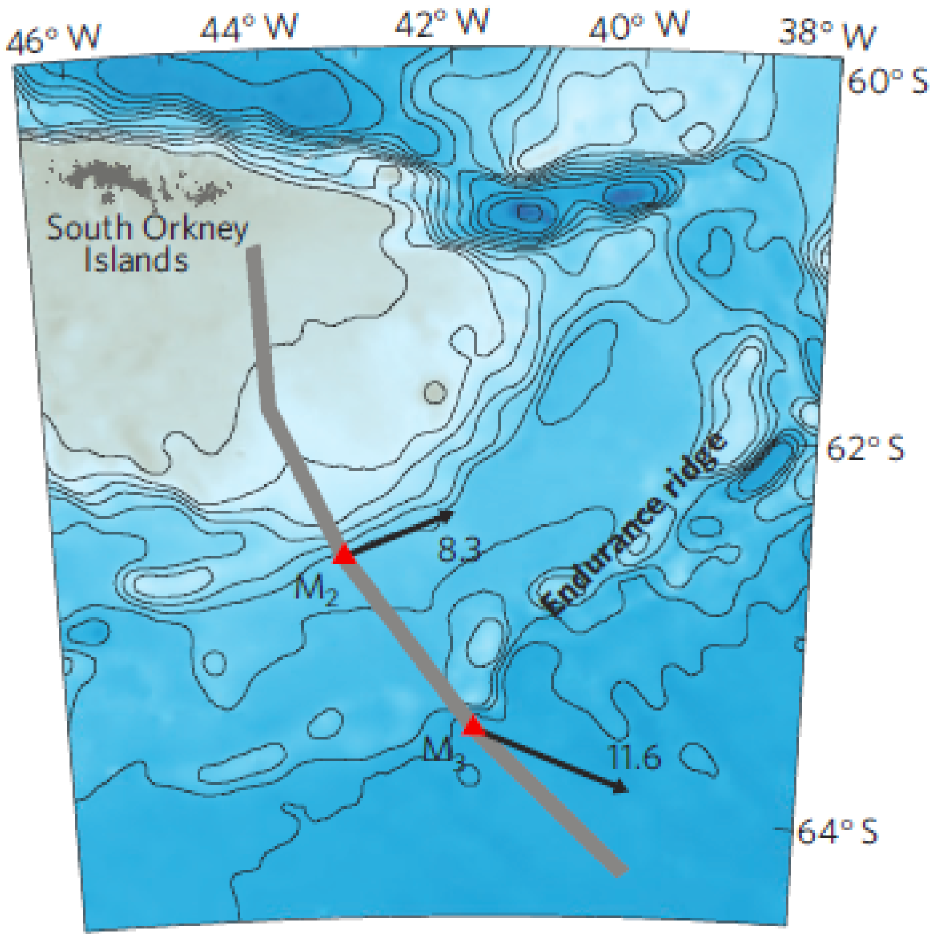


WSBW outflow moorings



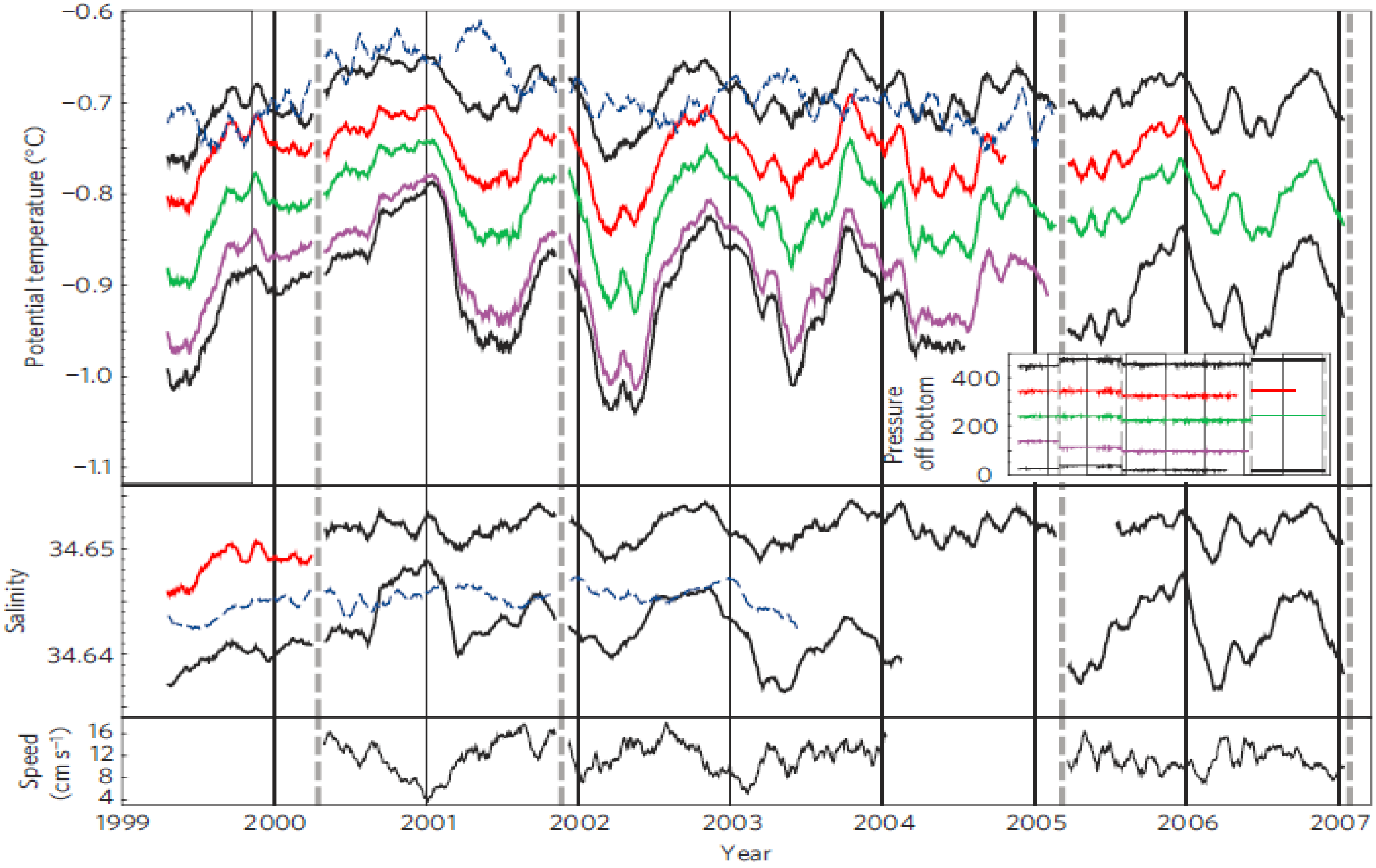
WSBW outflow moorings





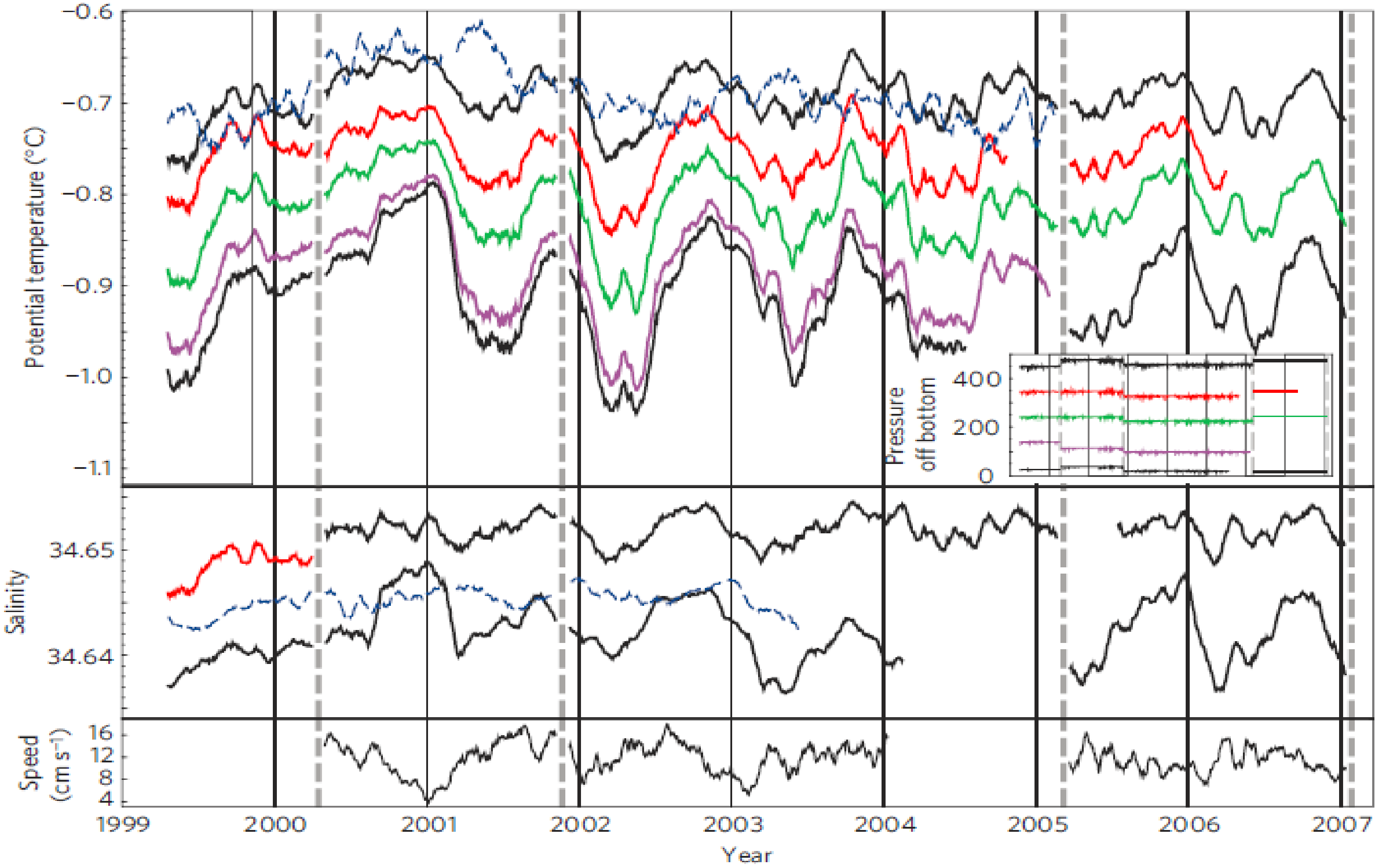
- Equipped with series of thermistors and current meters (we focus on deepest sensors, ~4500 m at M3)
- Positioned at steep escarpments to sample boundary current and minimize effects of gyre movement

Mooring data



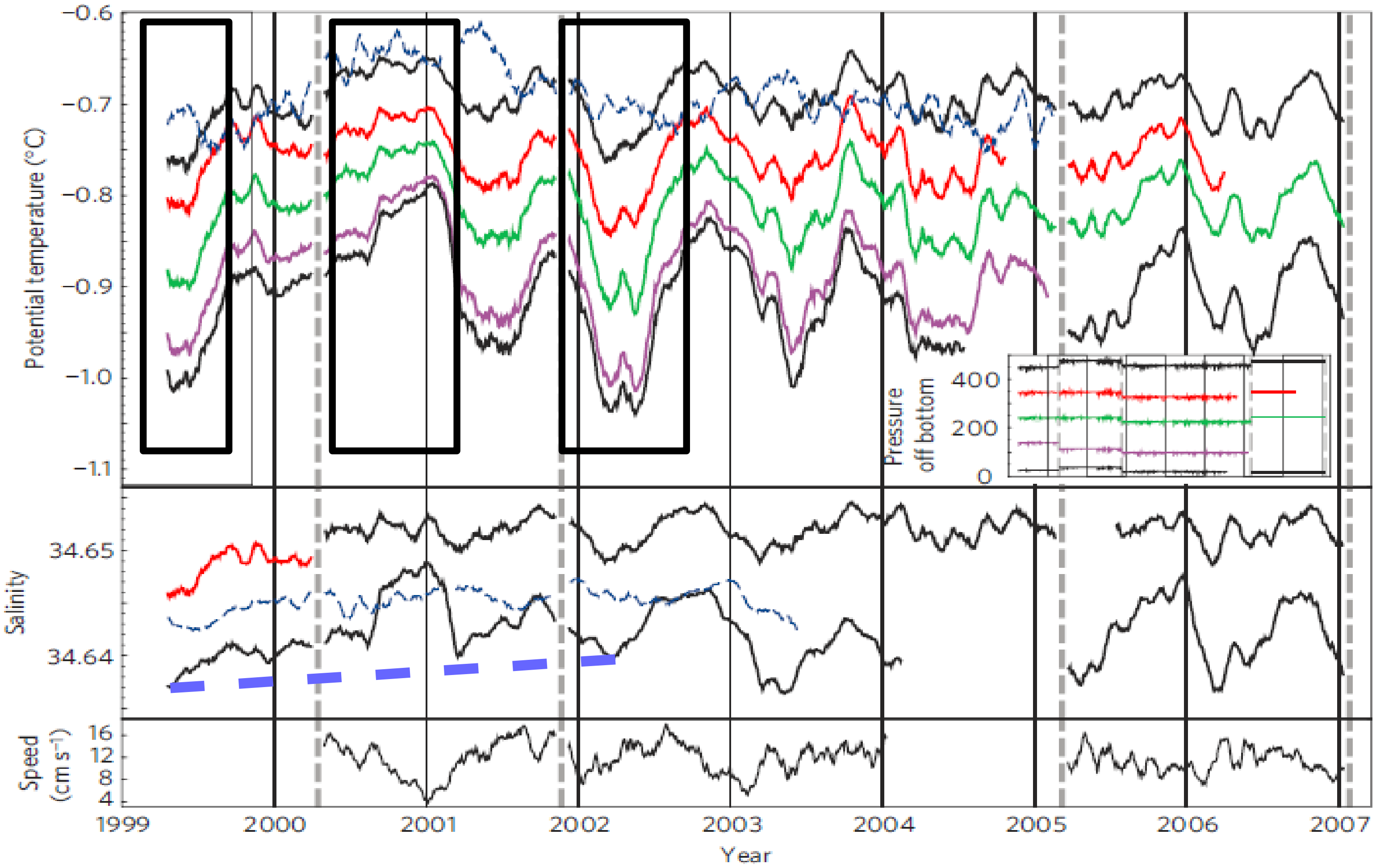
- 8 year record (longer now!) – first record long enough to record interannual variability

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



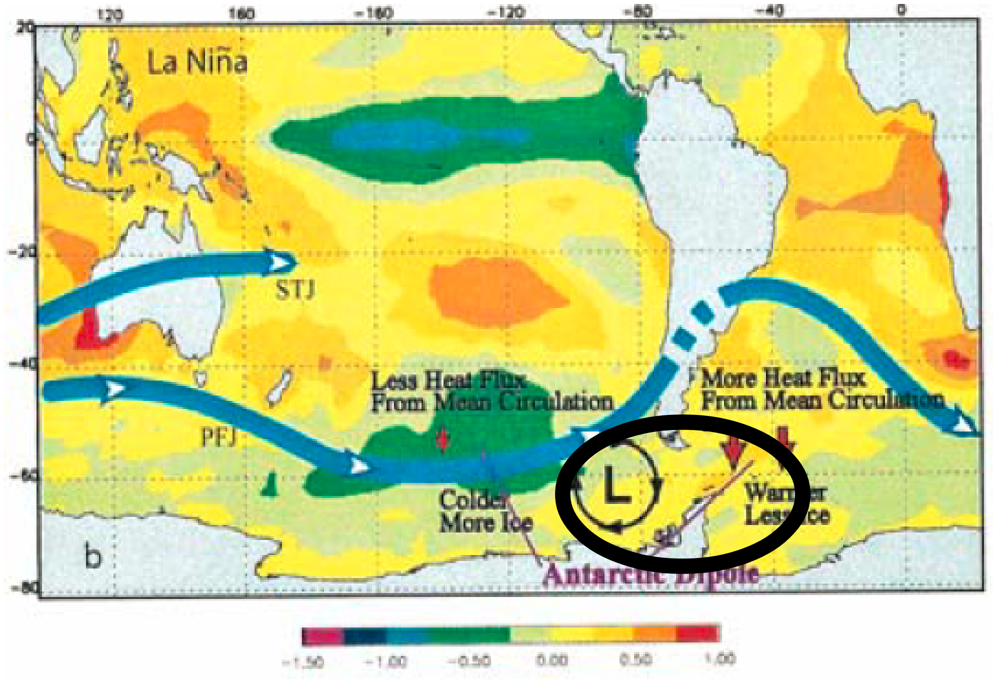
- But also distinct **interannual variability**:
  - Anomalously cold pulses in 1999, 2002.
  - No cold pulse in 2000
  - Increased salinification of cold pulse between 1999-2002

Large-scale climate forcing

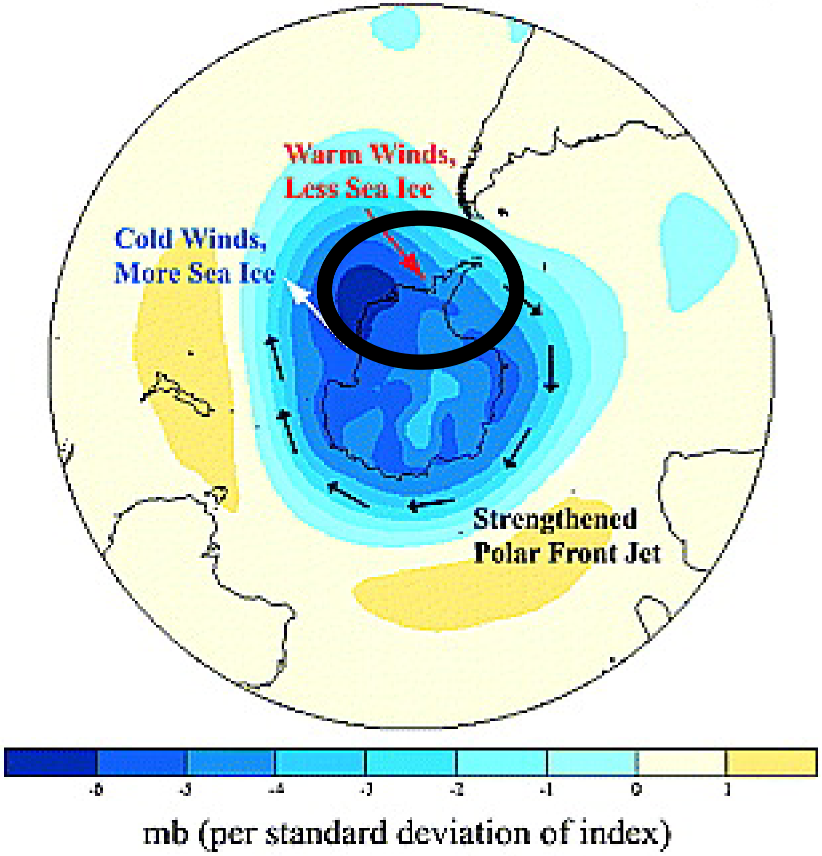
- Processes of formation and export are related to regional (Weddell) atmospheric forcing
- Regional atmospheric forcing is largely controlled by extra-polar climate variability
    - ENSO (e.g., *Yuan*, 2004; *Martinson and Iannuzzi*, 2003)
    - SAM (e.g., *Lefebvre and Goosse*, 2005)
    - But it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

Large-scale climate forcing

El-Niño – Southern Oscillation (ENSO)

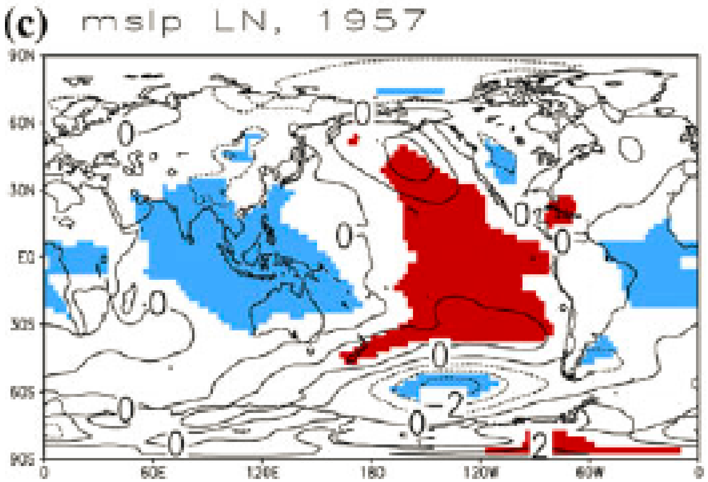


Southern Annular Mode (SAM)

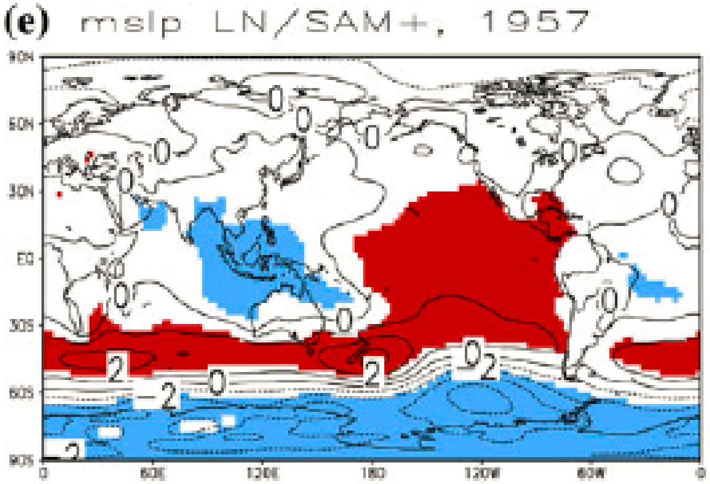


- Joint influence in Western Weddell via Amundsen SLP anomaly and dipole anomalies in wind/sea ice (EN/-SAM or LN/+SAM)
- Potential for **modulation** of impact

Large-scale climate forcing



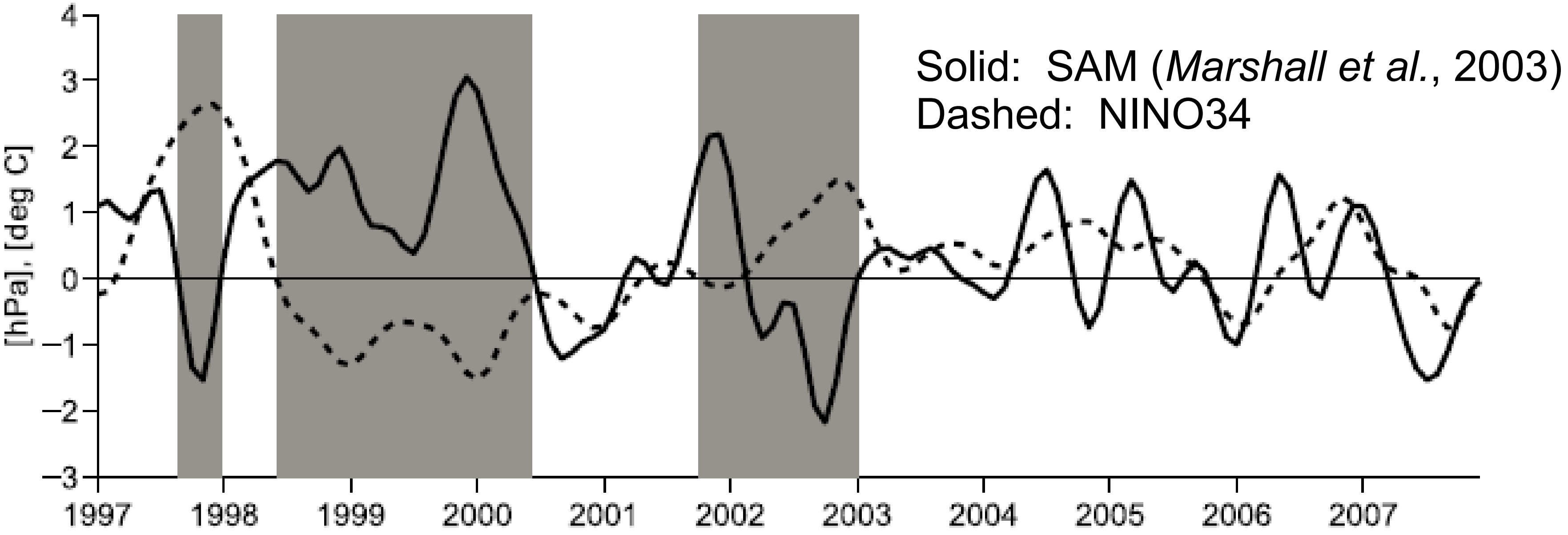
La Niña / neutral SAM SLPa composite



La Niña / +SAM SLPa composite

- 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).

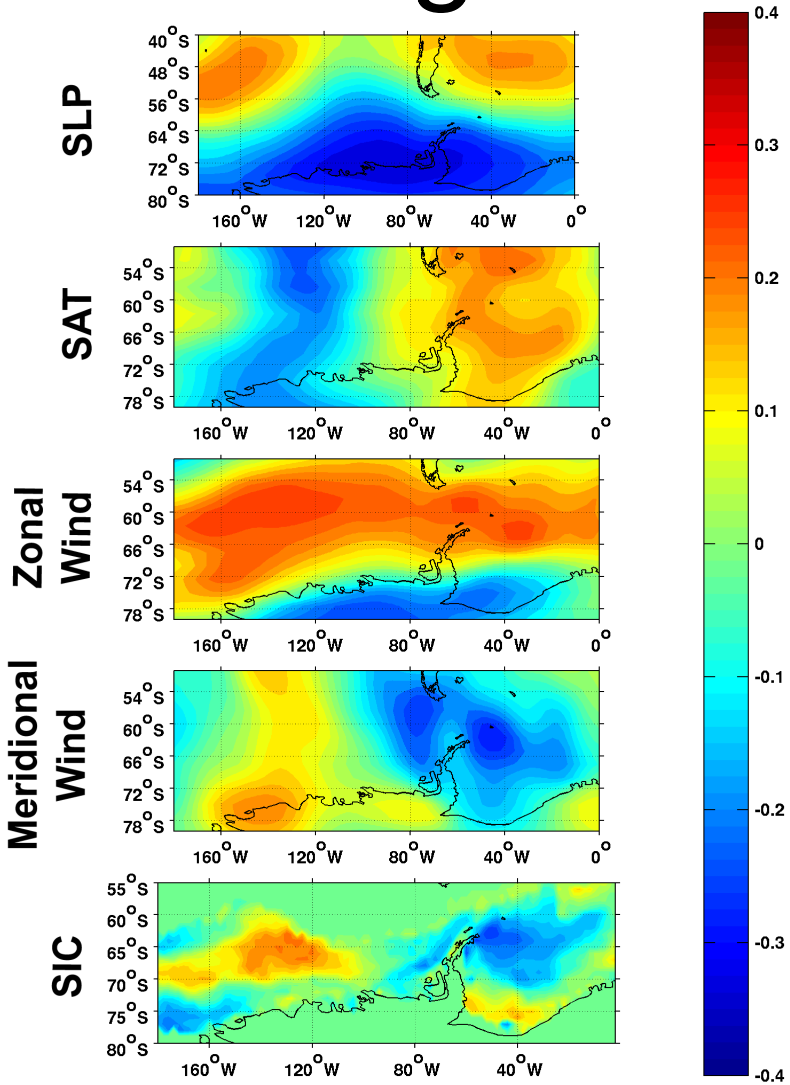
Large-scale climate forcing



Solid: SAM (*Marshall et al.*, 2003)
Dashed: NINO34

- The period of our hydrographic time series is dominated by favorable ENSO/SAM phase relationships.

Large-scale climate forcing

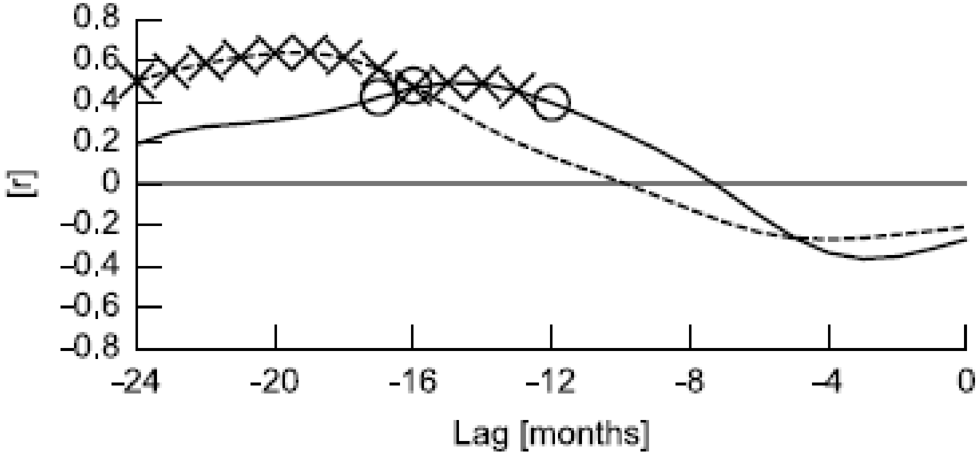


- MEOF analysis to capture coherent climate variability and obtain "most relevant" forcing index over the 1997-2007 period.
- EOF 1 (22% variance) shown
- Clearly represents simultaneous La Niña / +SAM variability

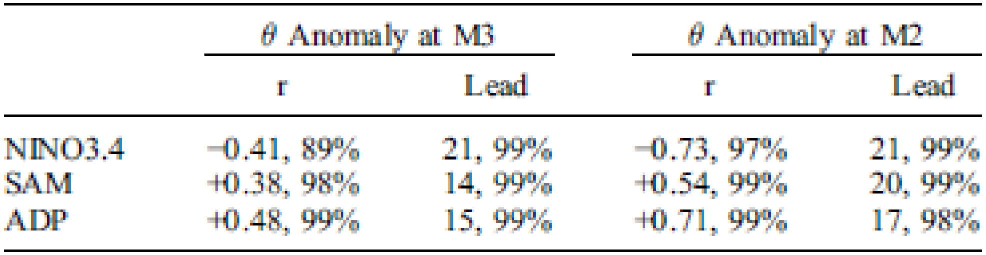
→ The period of our hydrographic time series is dominated by favorable ENSO/SAM phase relationships.

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)



	θ Anomaly at M3		θ Anomaly at M2	
	r	Lead	r	Lead
NINO3.4	−0.41, 89%	21, 99%	−0.73, 97%	21, 99%
SAM	+0.38, 98%	14, 99%	+0.54, 99%	20, 99%
ADP	+0.48, 99%	15, 99%	+0.71, 99%	17, 98%

Time scale(s) of forcing

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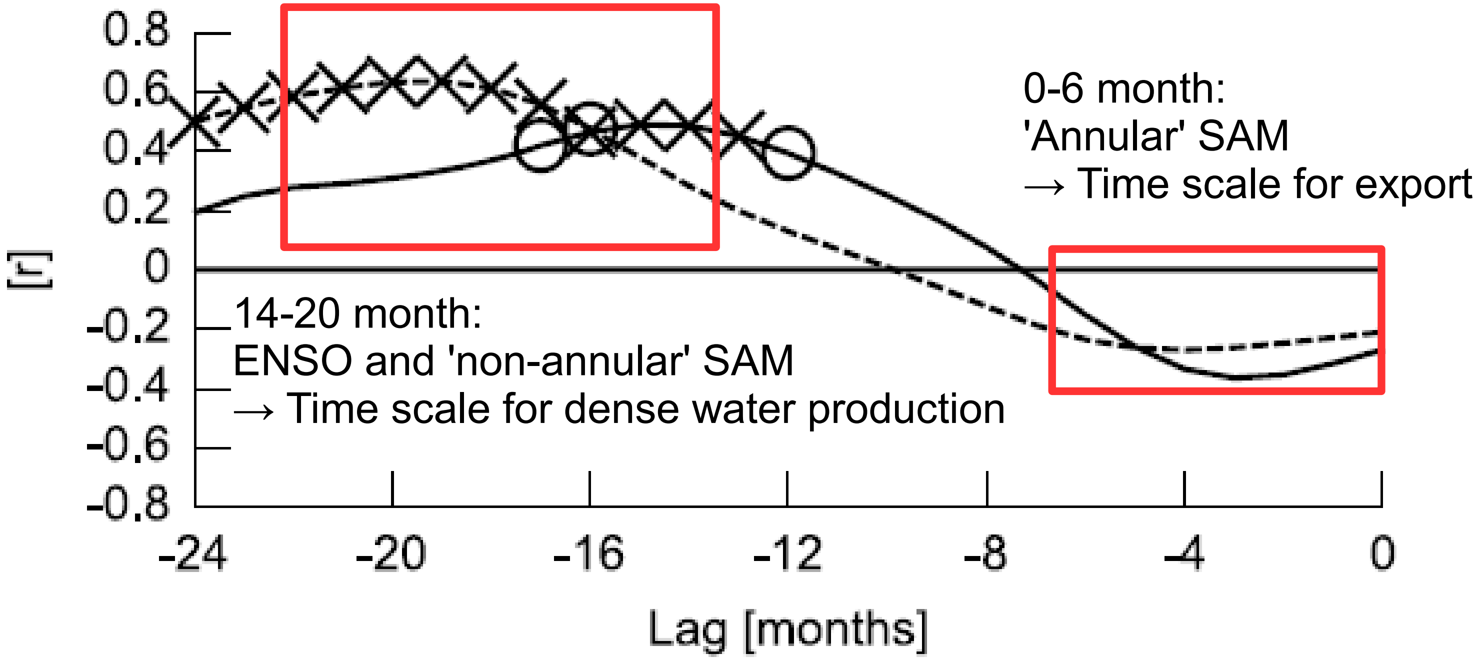
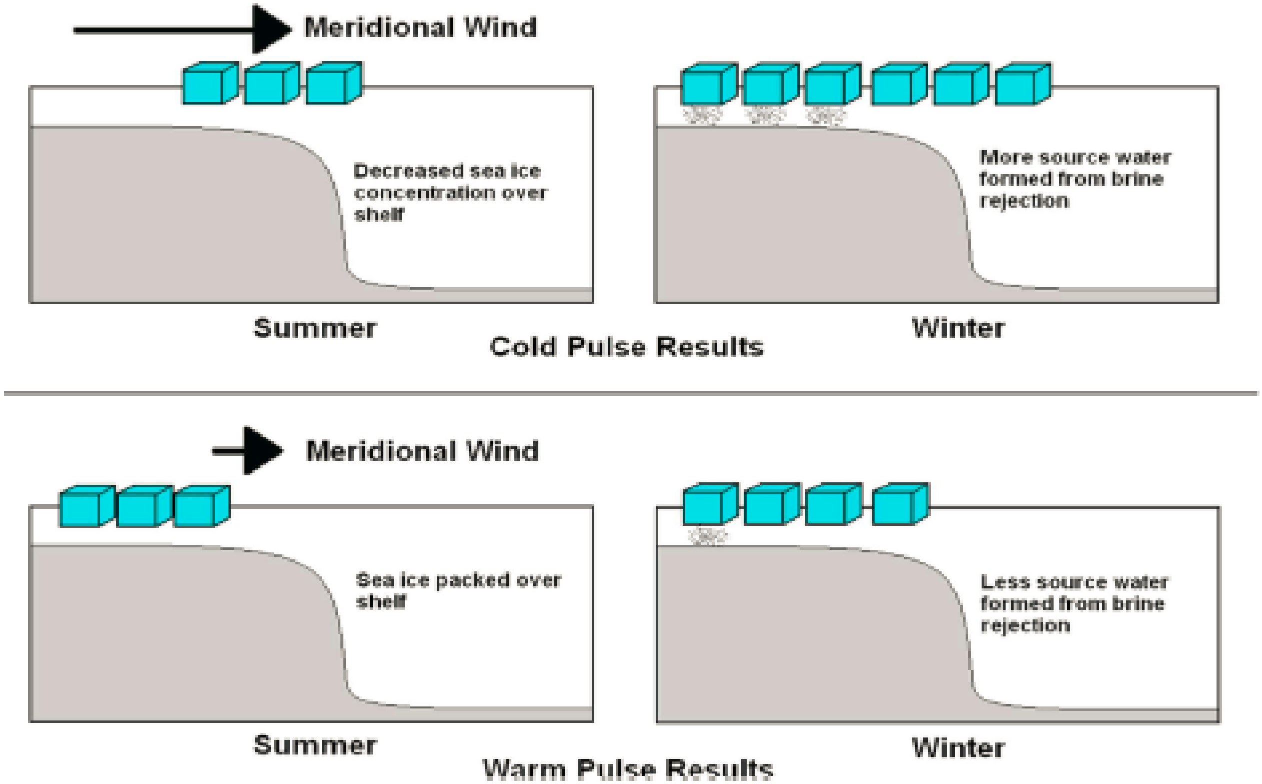


0-6 month:
'Annular' SAM
→ Time scale for export

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

Mechanism I: Production



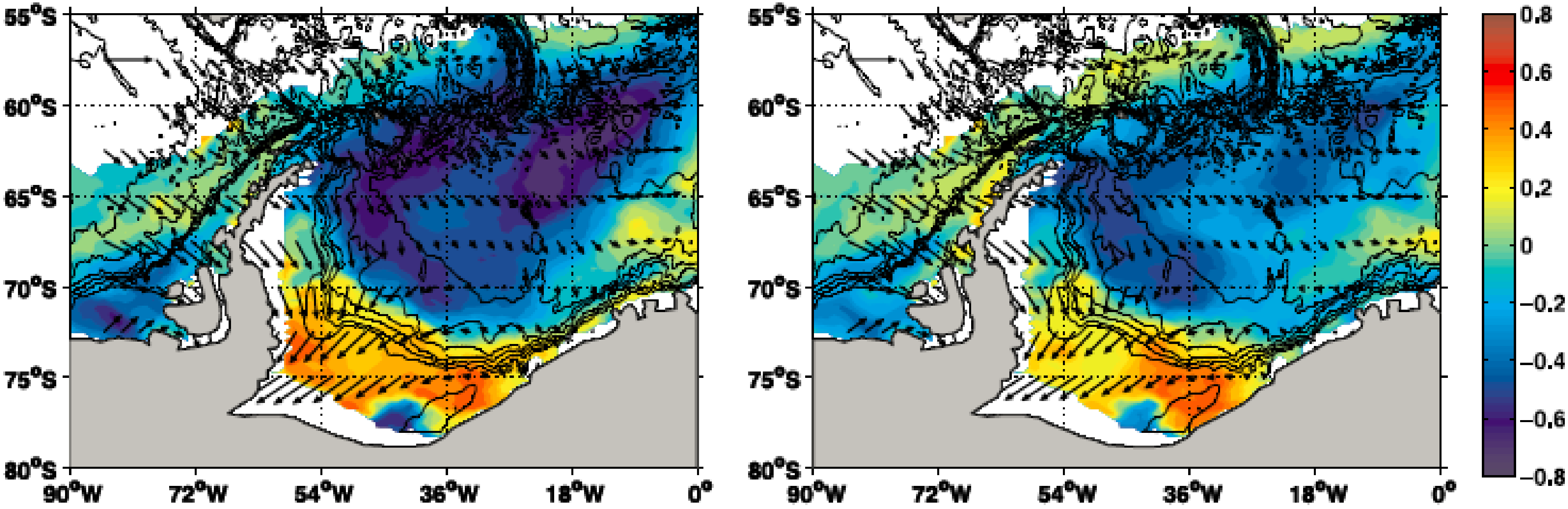
- Wind anomaly is associated with ENSO/SAM related dipole-pattern of anomalies.
- Controls summertime coastal polynya area and wintertime production of dense water.

Mechanism I: Production

Correlation coefficients

Color: WSBW temperature / Sea ice concentration

Vectors: WSBW temperature / wind



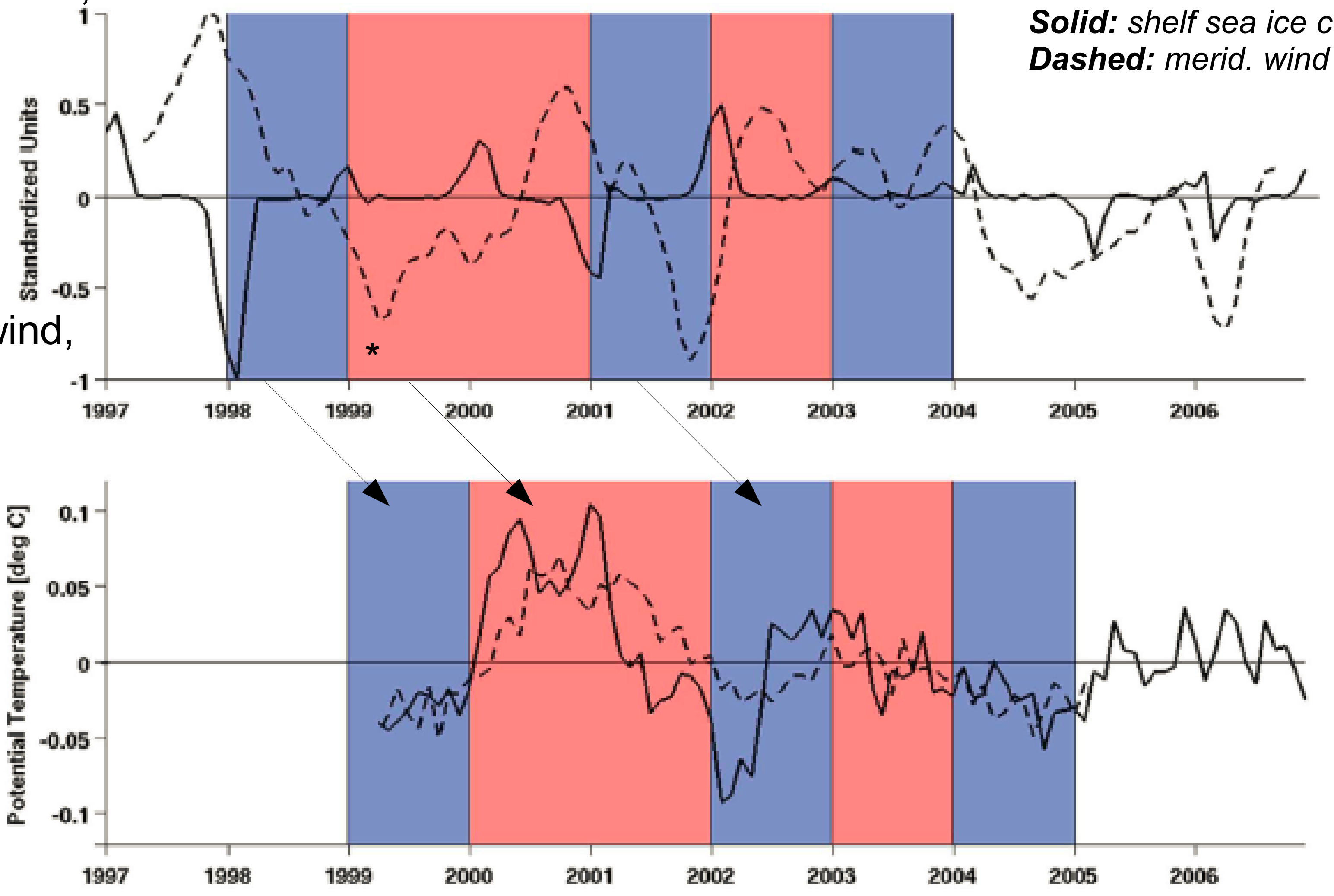
M2 temperature lags 17 months

M3 temperature lags 14 months

Mechanism I: Production

Stronger wind,
more ice

Weaker wind,
less ice



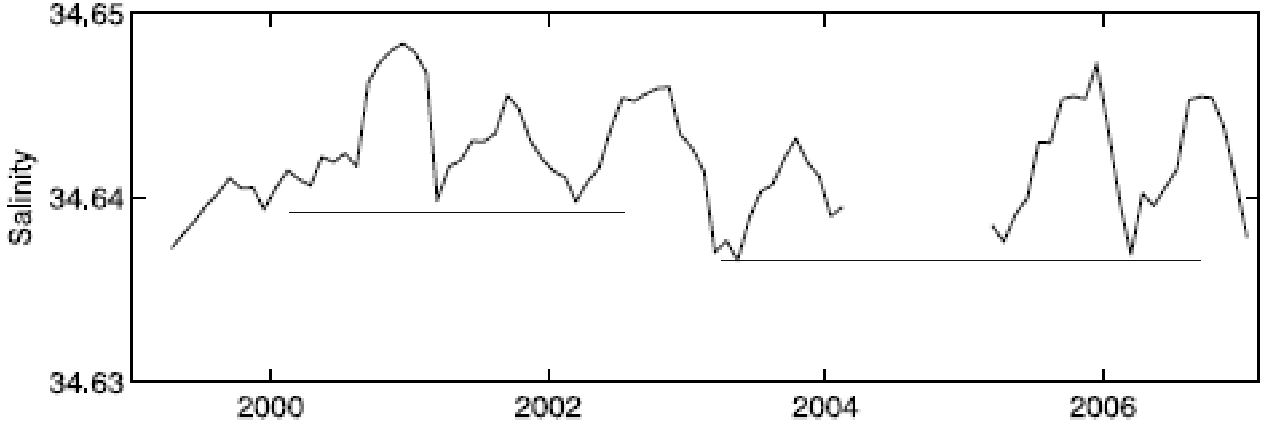
Solid: *shelf sea ice conc. anomaly*
Dashed: *merid. wind anomaly*

WSBW
θ-anom.

*If south**ward** wind persists, *no* HSSW is formed (*Timmerman et al.*, 2002)

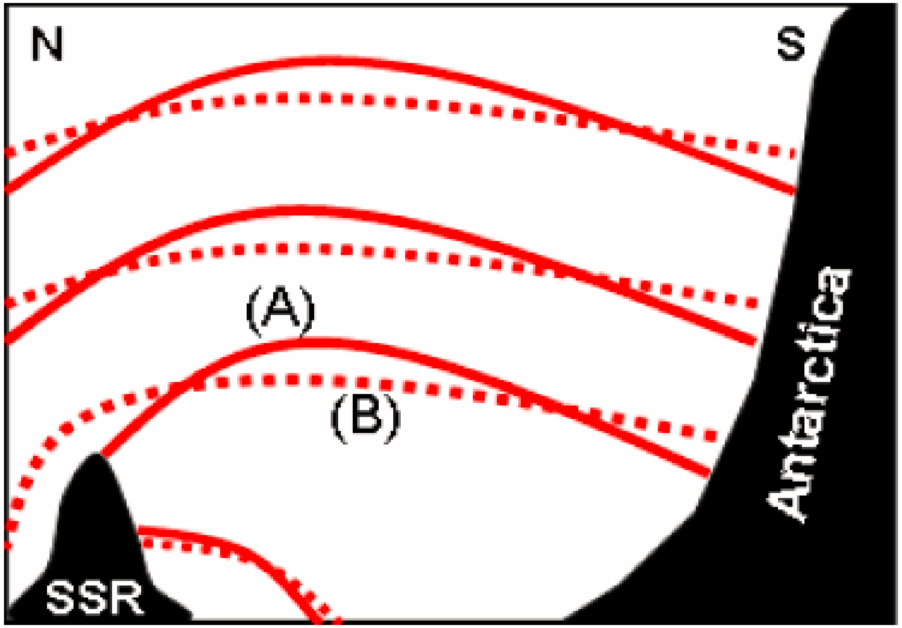
Mechanism I: Production

- In particular, the 1999-2002 period is dominated by the very strong 1997/1998 El-Niño.
- Ronne polynya extended 3 x 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

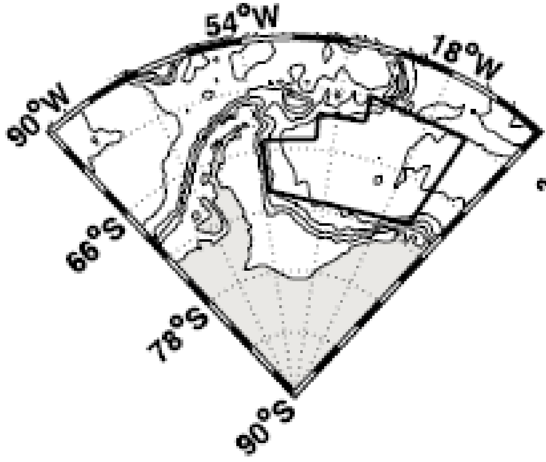
- WSBW temperature weakly correlated with SAM at 0-6 month lag.
- Stronger westerlies and increased cyclonic forcing may 'spin-up' the Weddell gyre.
- Baroclinicity: isopycnals slump at slope which may facilitate export.
- Also, enhanced cyclonic forcing increases cross-slope flux at zero lag (seen in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

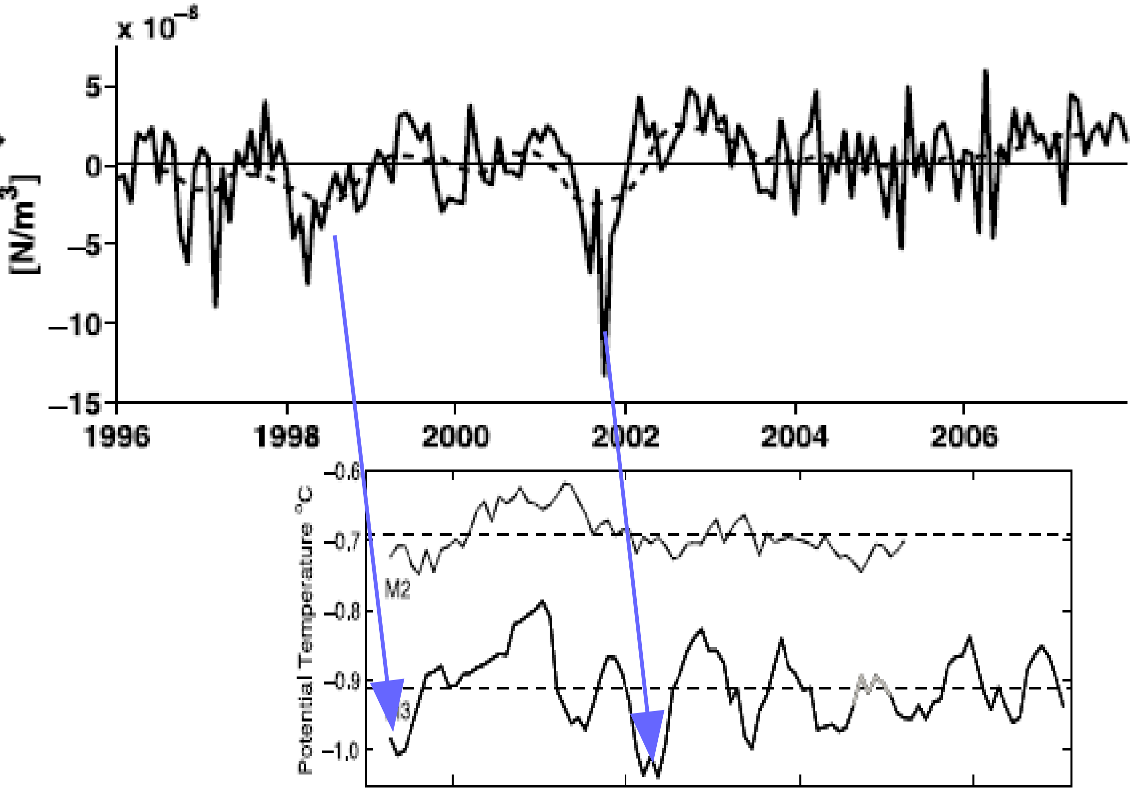


Meredith et al., 2008

Mechanism II: Export

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





- Cross-gyre XCTD sections suggest domed pycnocline 1/2002, flat pycnocline 1/2005.

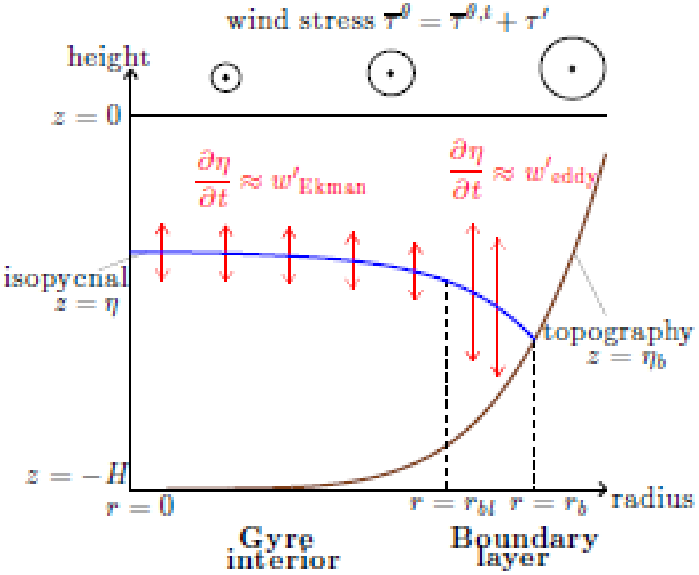
Mechanism II: Export

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

- One idea: *Meredith et al.*, 2011
  Appeal to response of bottom Ekman layer to barotropic changes in deep boundary current on sloping topography: $\tau = 0.5\, c_d^{-1}\, N^{-1}\, S^{-3/2} \sim 54$ days.

Mechanism II: Export

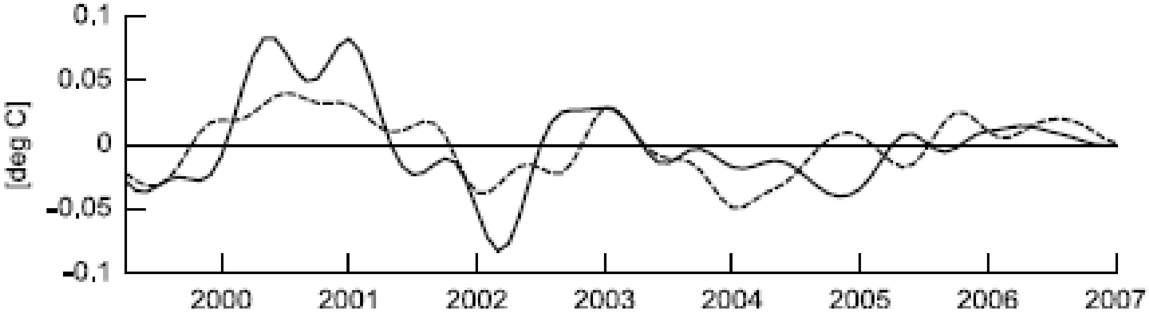
- Another (new) idea: *Su et al.*, 2014
  - Wind stress curl drives Ekman pumping in gyre interior.
  - Sloping isopycnals lead to baroclinic instability and rapidly responding mesoscale eddy buoyancy fluxes in the boundary.



- 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.



r = 0.66

  - ➔ Agreement is best over period of strongest climate forcing and favorable-phasing of ENSO/SAM.

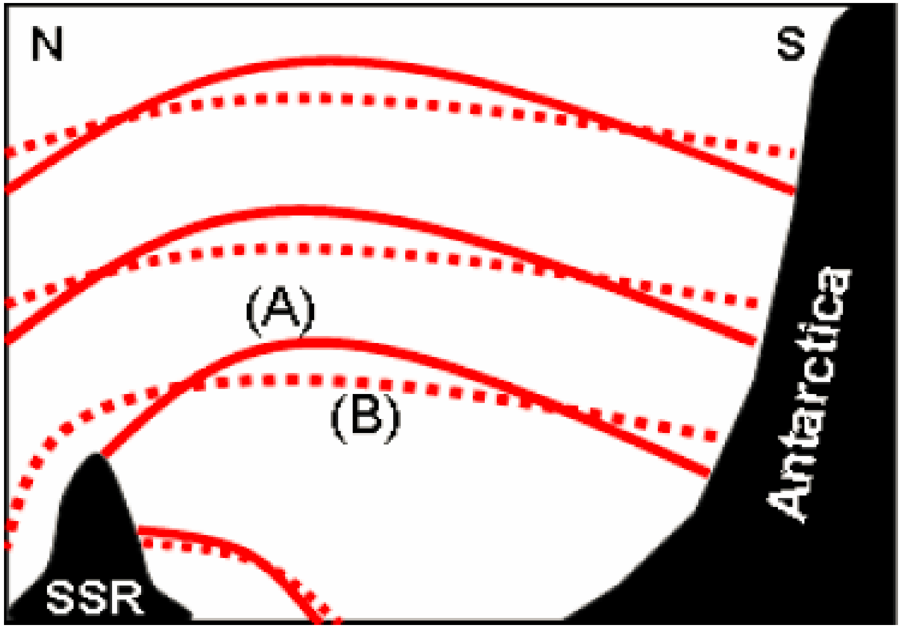
Potential relation to MOC

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

- Stronger gyre → less dense (warmer) classes of WSDW escape.

- Isopycnal excursions of 100 m (0.04 ºC) possible

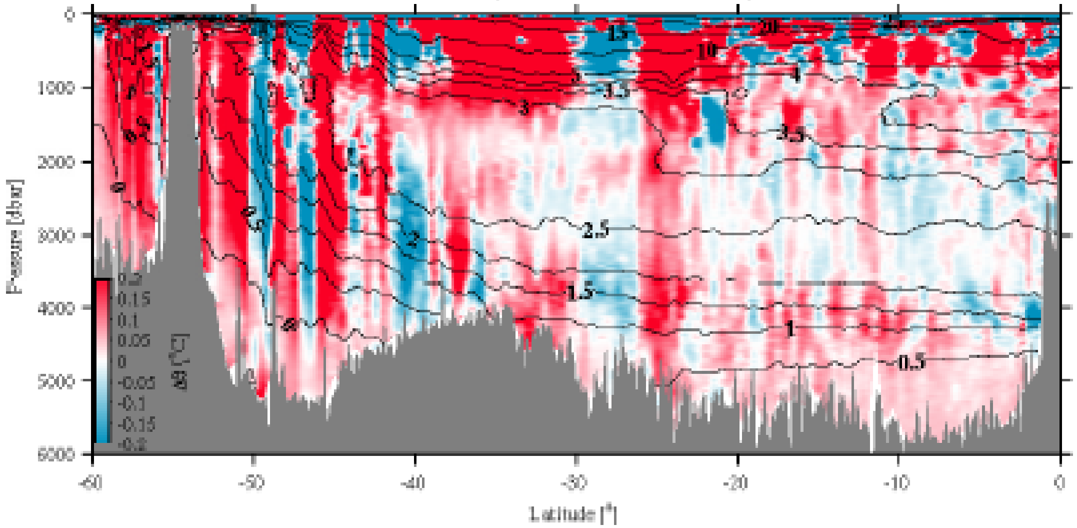
- Warming downstream?



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).



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.