"Sea Level and Ocean Heat Content Variations Analyzed with the Latest ECCO State Estimate"

Ichiro Fukumori (Jet Propulsion Laboratory, California Institute of Technology)
Rui M. Ponte (Atmospheric and Environmental Research)
Chris Piecuch (Woods Hole Oceanographic Institution)
Patrick Heimbach (University of Texas at Austin)

Outline

1. Brief description of ECCO ocean state estimation
2. Recent examples analyzing ocean heat content and sea level variations using ECCO products;
   a) Decadal changes in the subpolar North Atlantic
   b) Intraseasonal-to-interannual changes on the Antarctic continental shelf

ECCO Version 4 Release 3

"Estimating the Circulation and Climate of the Ocean"

Aims at making the best possible estimate of ocean circulation by combining nearly all available global ocean data sets with a state-of-the-art ocean circulation model.

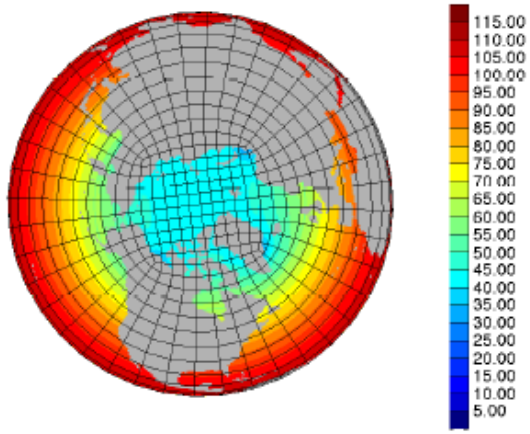
Variable	Observations
Sea level	TOPEX/Poseidon (1993-2005), Jason-1&2 (2002-2015), CryoSat-2 (2011-2015), SARAL/AltiKa (2013-2015)
Temperature profiles	Argo floats (1995-2015), XBTs (1992-2008), CTDs (1992-2011)
Salinity profiles	Argo floats (1997-2015), CTDs (1992-2011), SEaOS (2004-2010)
Sea surface temperature	AVHRR (1992-2013), AMSR-E (2002-2010)
Sea surface salinity	Aquarius (2011-2013)
Sea-ice concentration	SSM/I DMSP-F11, 13, & 17 (1992-2015)
Ocean bottom pressure	GRACE (2002-2014)
Mean dynamic topography	DTU13 (1992-2012)

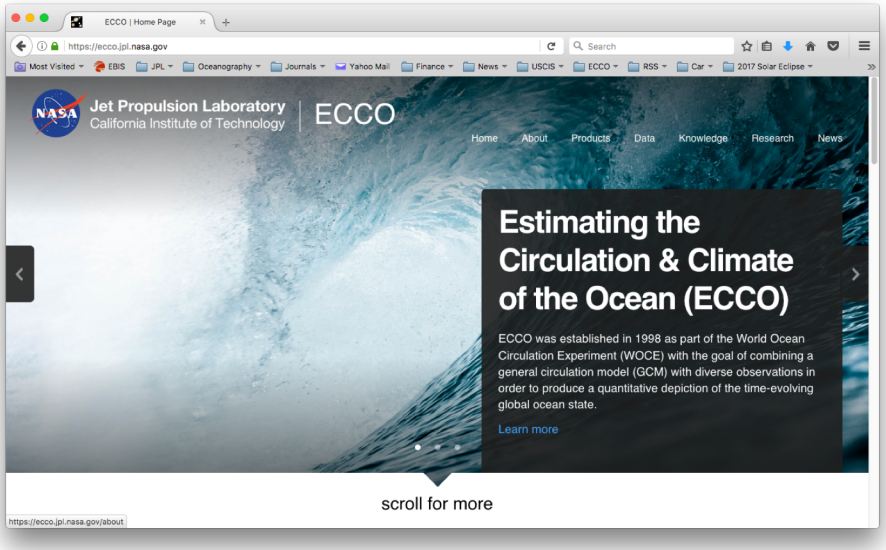
http://ecco-group.org

ECCO Version 4 Release 3

The *Version 4* estimate is ECCO's first truly global multi-decadal ocean state estimate. *Release 3* improves upon the estimate and extends it to 2015 (and soon to 2017).

Characteristics	ECCO Version 4 Release 3
model	MITgcm
grid system	latitude-longitude-cap
resolution	0.3˚~1˚, 50 levels
sea-ice model	prognostic
period	1992-2015
external forcing	bulk parameterization, geothermal heating
correlation	mean & anomaly error, grid inhomogeneity
controls	initial condition, external forcing, mixing parameters
estimation	adjoint method

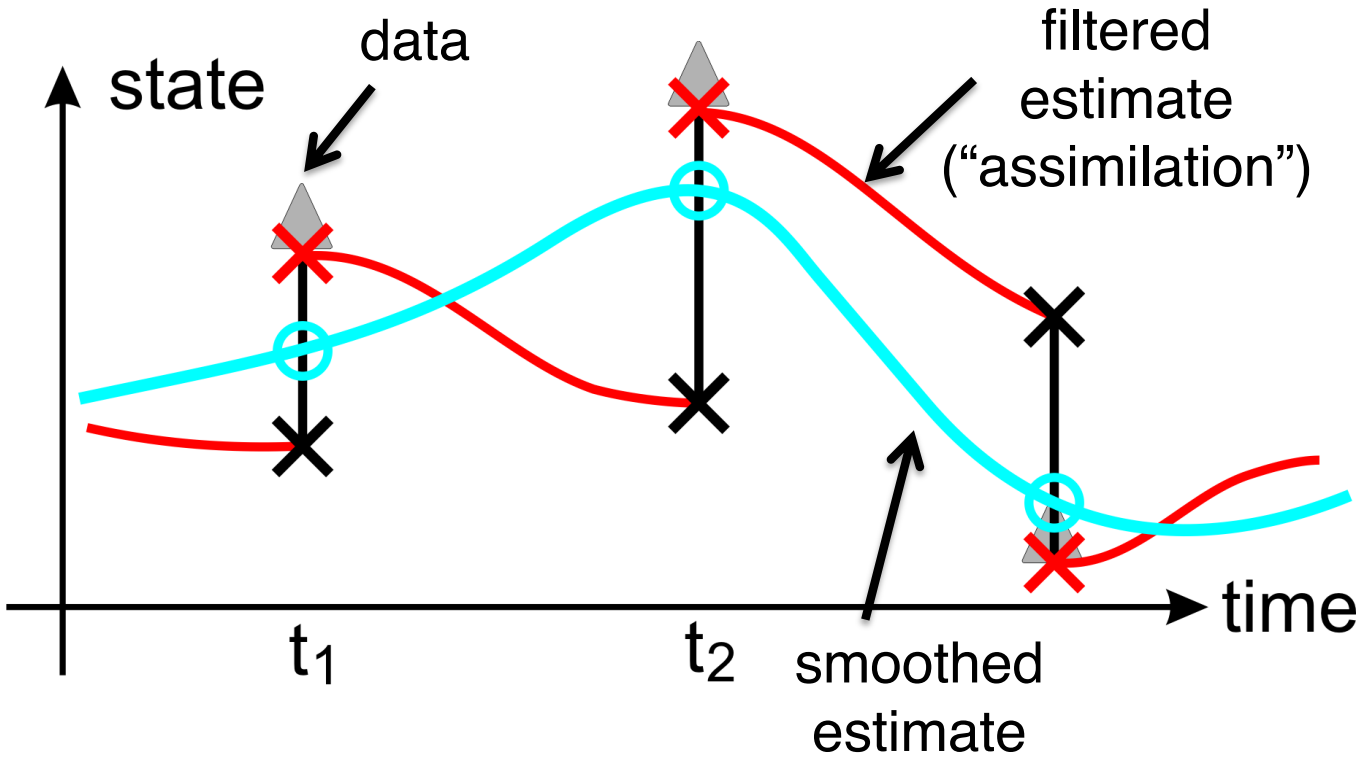




ecco-group.org (also ecco.jpl.nasa.gov)

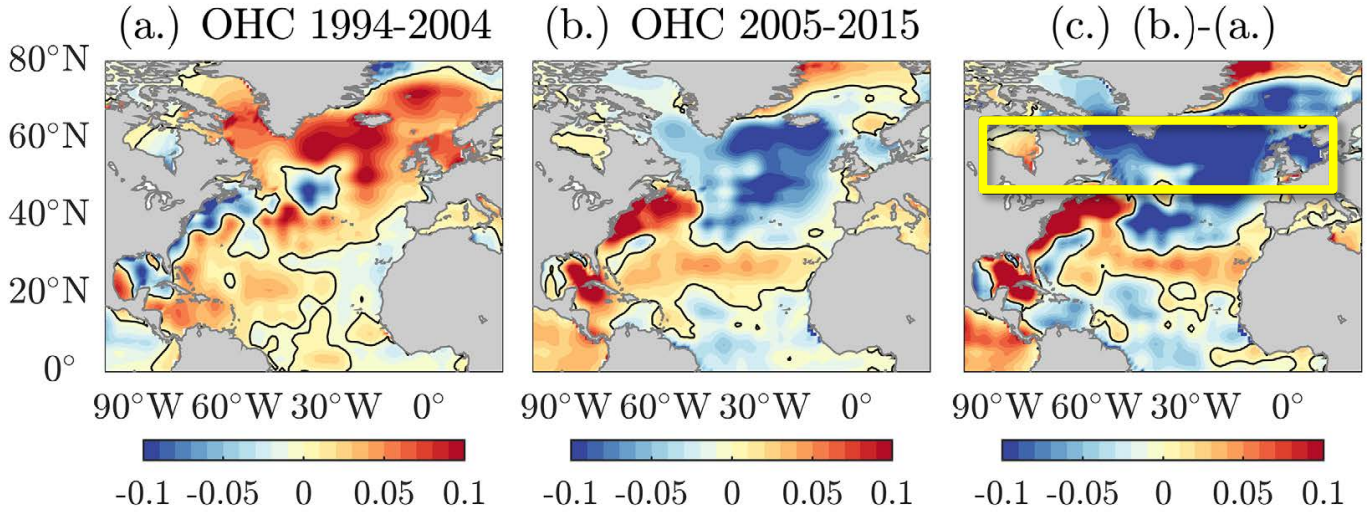
ECCO State Estimate

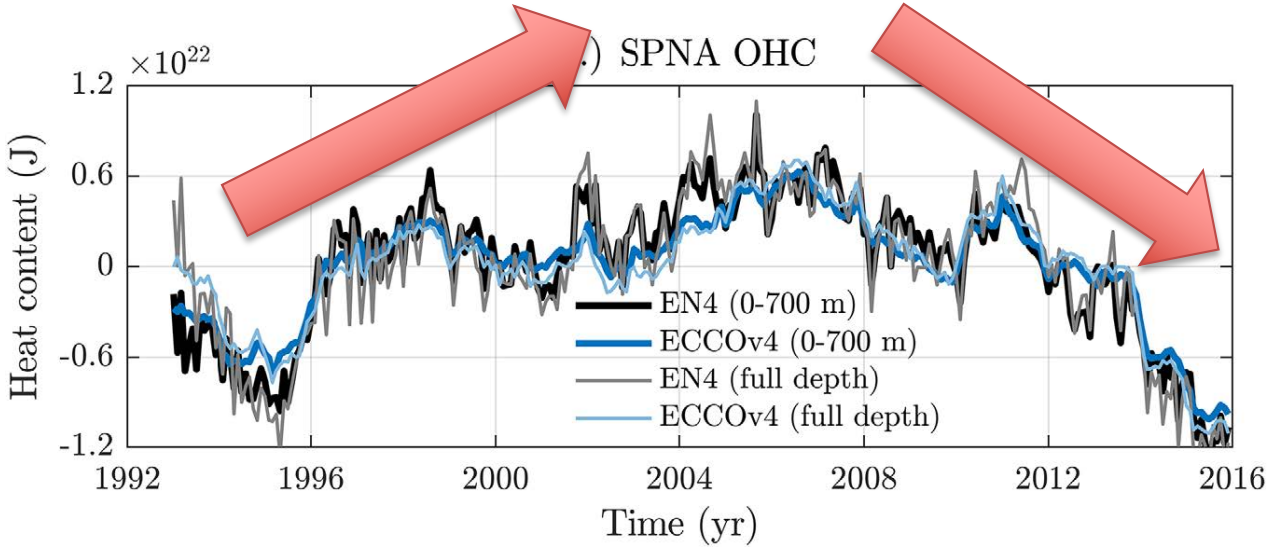
ECCO analyses are so-called *smoothed* as opposed to *filtered* estimates and are characterized by their physical consistency; e.g., budgets are closed by explicit physical processes, permitting studies of attribution and causation of the oceanic state.



Decadal North Atlantic Ocean Heat Content Change

Trend (°C/yr) of Ocean Heat Content (OHC) (Met Office Hadley Center EN4.2.0)

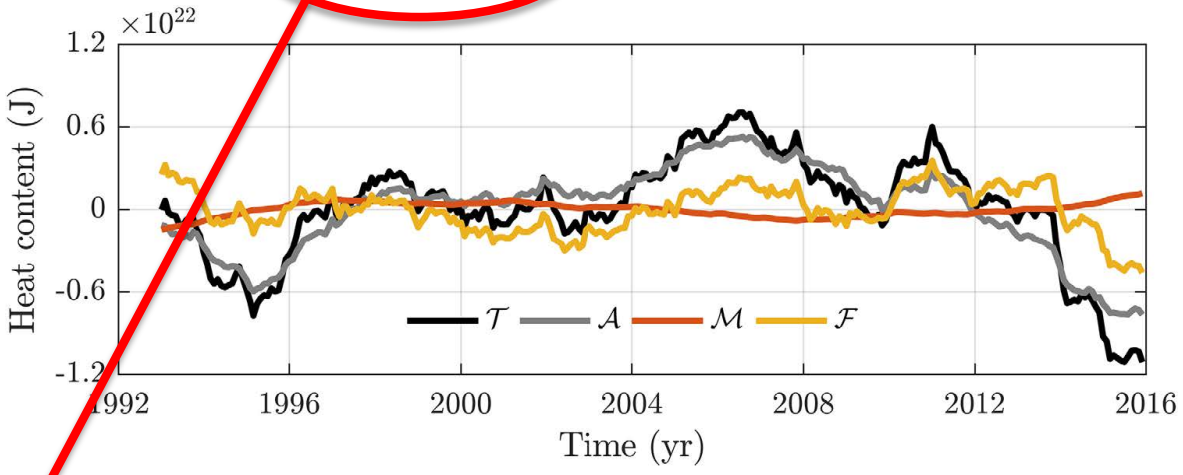




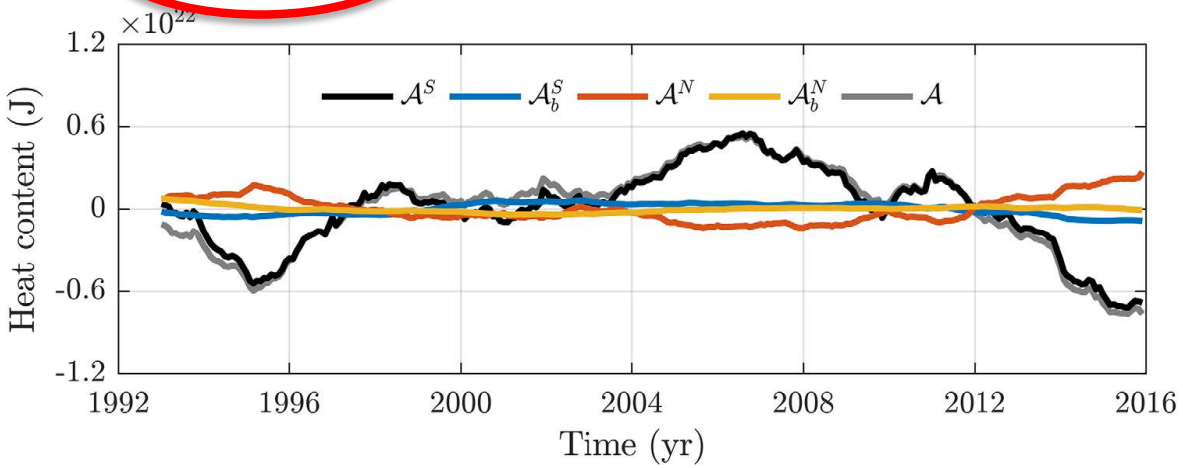
(Piecuch et al., 2017, *J. Geophys. Res.*, ***122****(9), 7181-7197*)

Decadal North Atlantic Ocean Heat Content Change

OHC (T) = Advection (A) + Mixing (M) + Forcing (F)

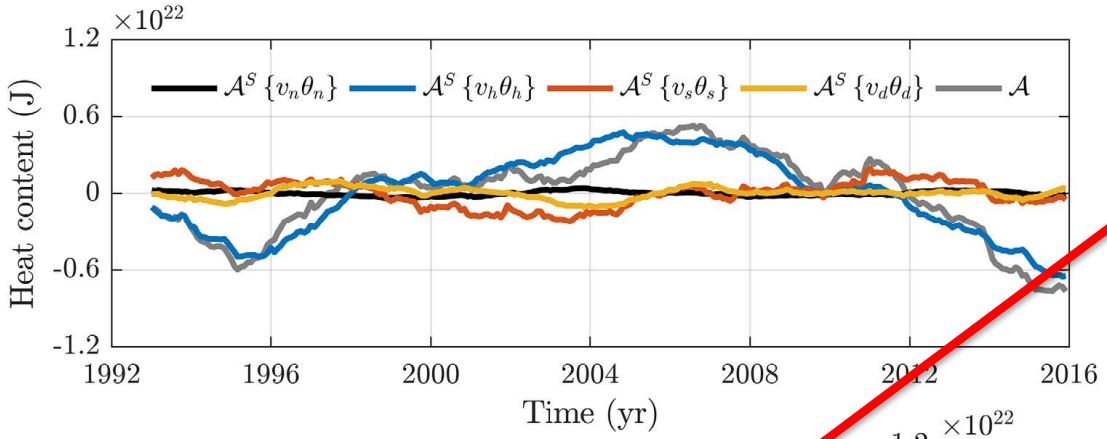


Advection (A) = Eulerian South + Bolus South + Eulerian North + Bolus North



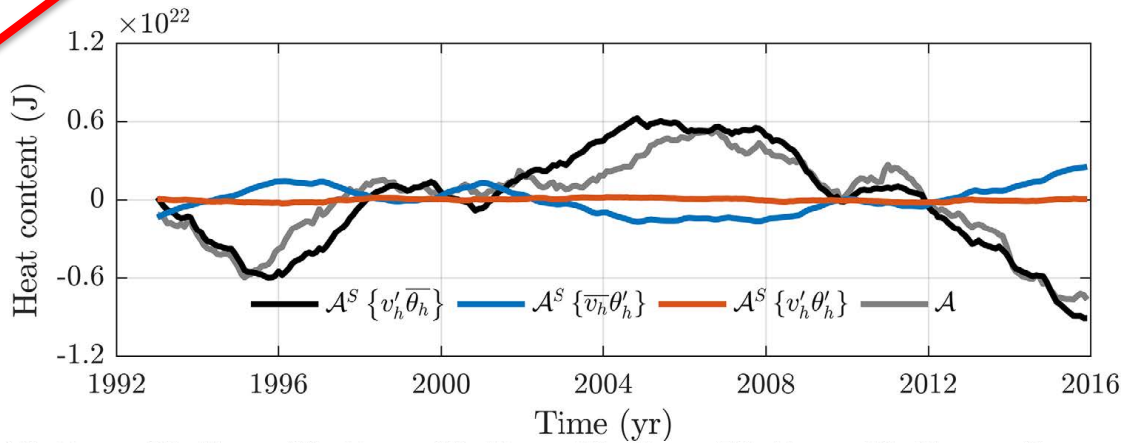
(Piecuch et al., 2017, *J. Geophys. Res.*, ***122****(9), 7181-7197*)

Decadal North Atlantic Ocean Heat Content Change

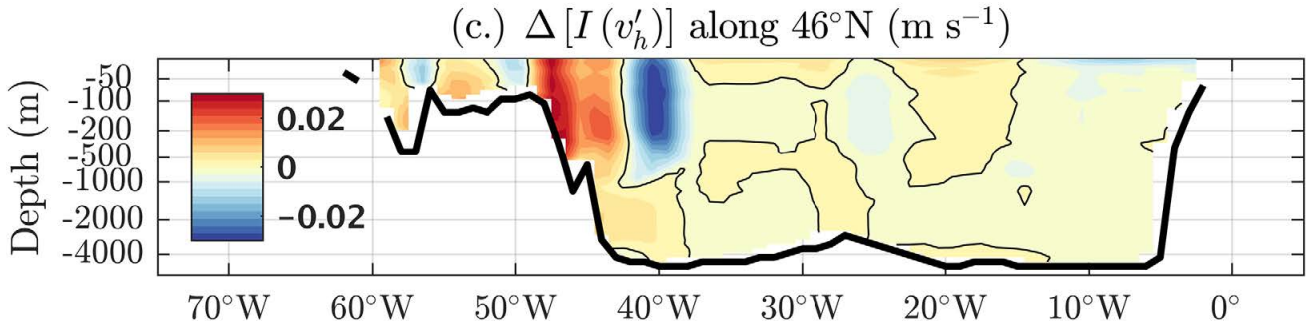


Eulerian South = Net Volume Transport +
Horizontal Gyre Transport +
Shallow Overturning +
Intermediate & Deep Overturning

Horizontal Gyre Transport =
$v'\overline{T}$ + $\overline{v}\,T'$ + $v'T'$



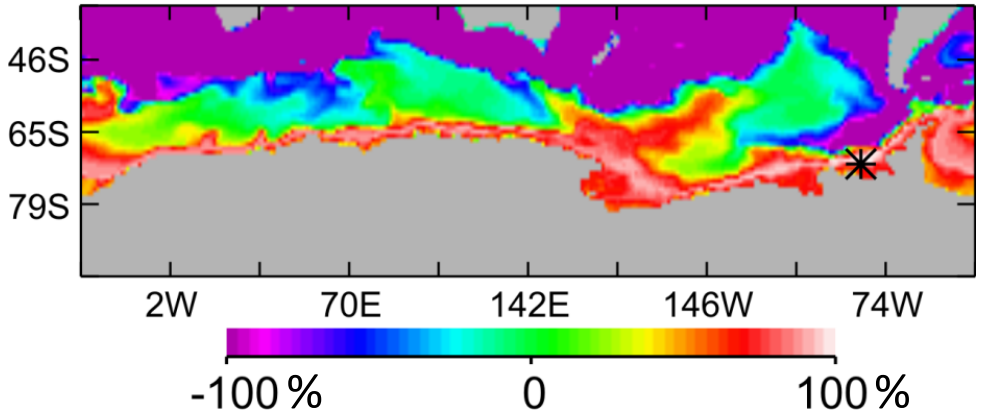
Decadal trend reversal in v



(Piecuch et al., 2017, *J. Geophys. Res.*, ***122****(9), 7181-7197*)

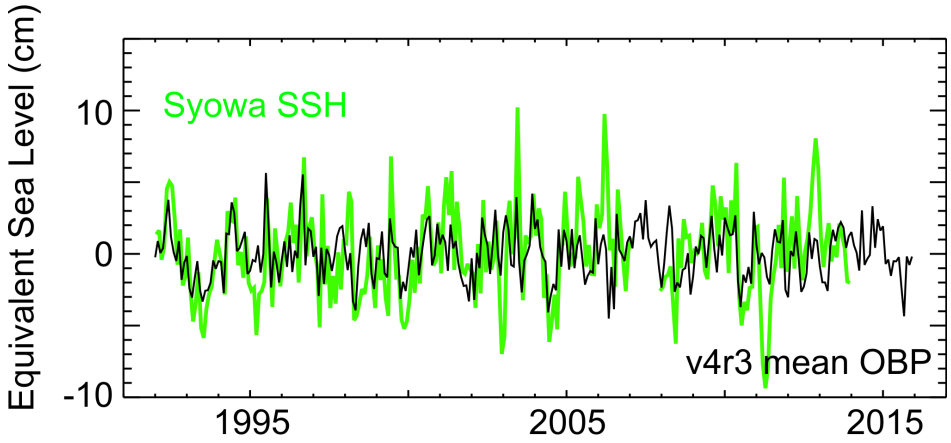
Coherent Circumpolar Antarctic Variation

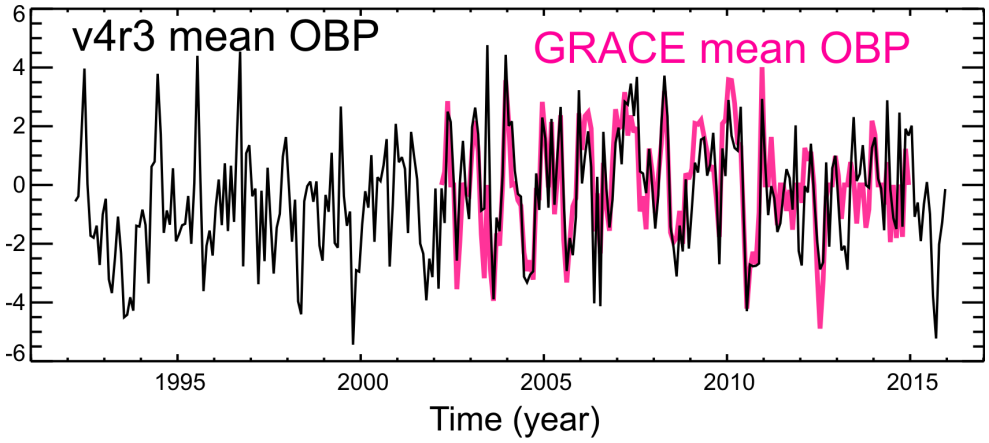
Sea level & ocean bottom pressure fluctuate coherently around Antarctic across the continental shelf.



OBP variance at each location explained by that at asterisk.

$$1 - \frac{\mathrm{var}\{P_i - P_*\}}{\mathrm{var}\{P_i\}}$$





Cause of Antarctic Variation (forcing)

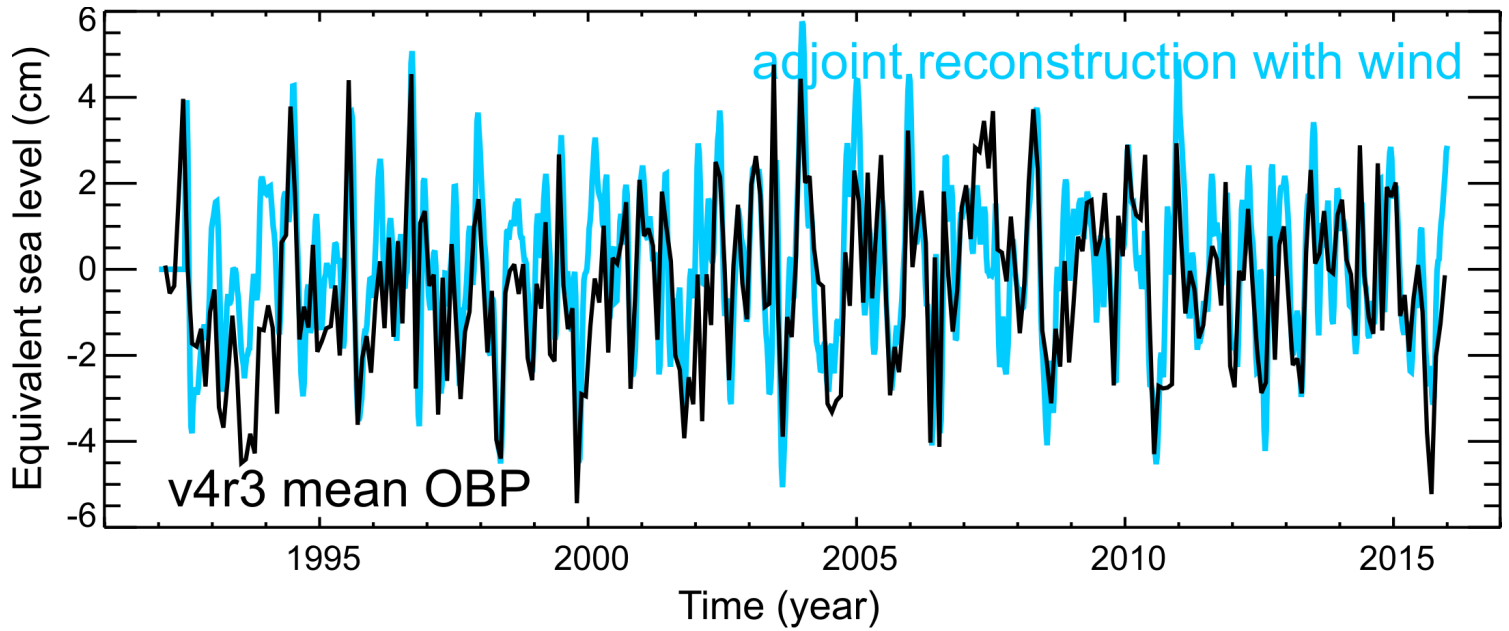
The model's adjoint provides an effective means to identify forcing responsible for the variations.

Mean OBP at time t

$$J(t) \approx \sum_i \sum_{\mathbf{x}} \sum_{\Delta t} \frac{\partial J}{\partial \phi_i(\mathbf{x}, \Delta t)} \delta\phi_i(\mathbf{x}, t - \Delta t)$$

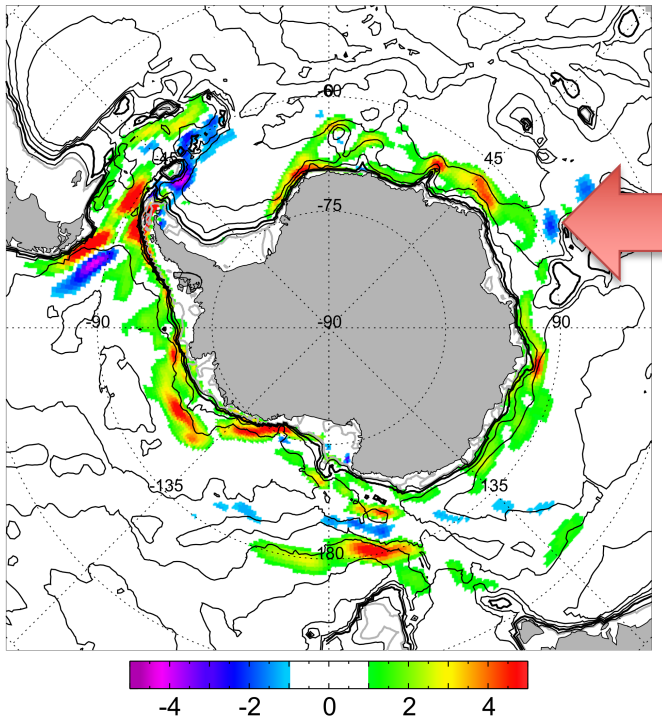
forcing i at location **x** & time t-Δt

adjoint gradient



Cause of Antarctic Variation (location)

Winds along the continental slope are responsible for the variation.



Variance explained by winds at different locations;

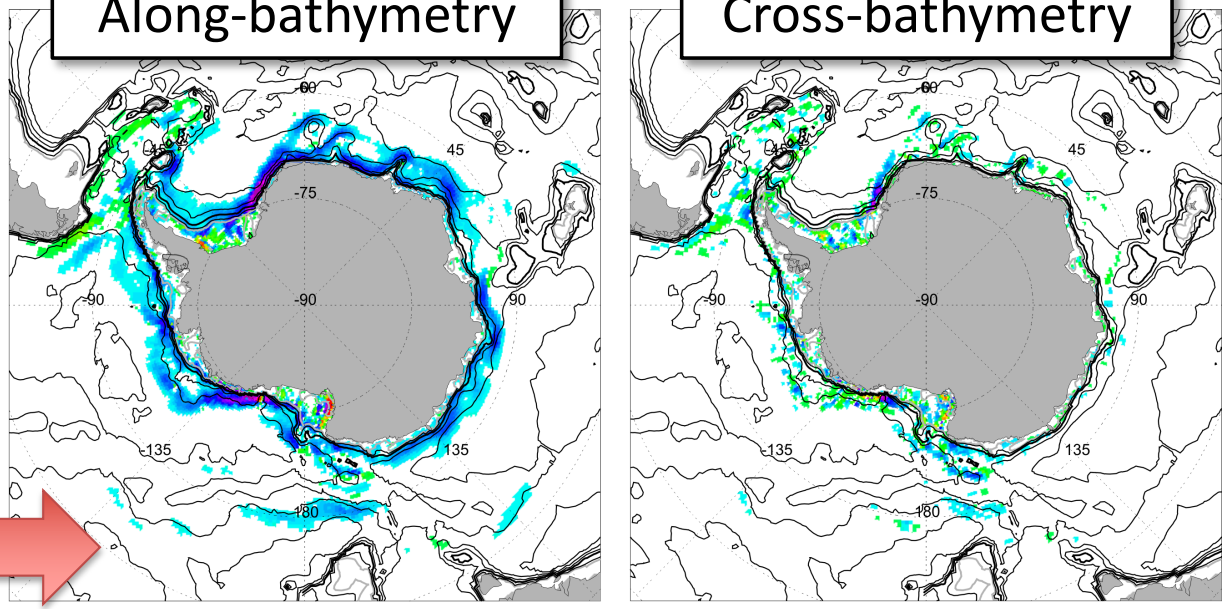
$$1 - \frac{\mathrm{var}\left\{ J_{wind} - \sum_{i=\mathrm{wind}} \sum_{\Delta t} \frac{\partial J}{\partial \phi_i(\mathbf{x}, \Delta t)} \delta\phi_i(\mathbf{x}, t - \Delta t) \right\}}{\mathrm{var}\{ J_{wind} \}}$$

Sensitivity to wind;

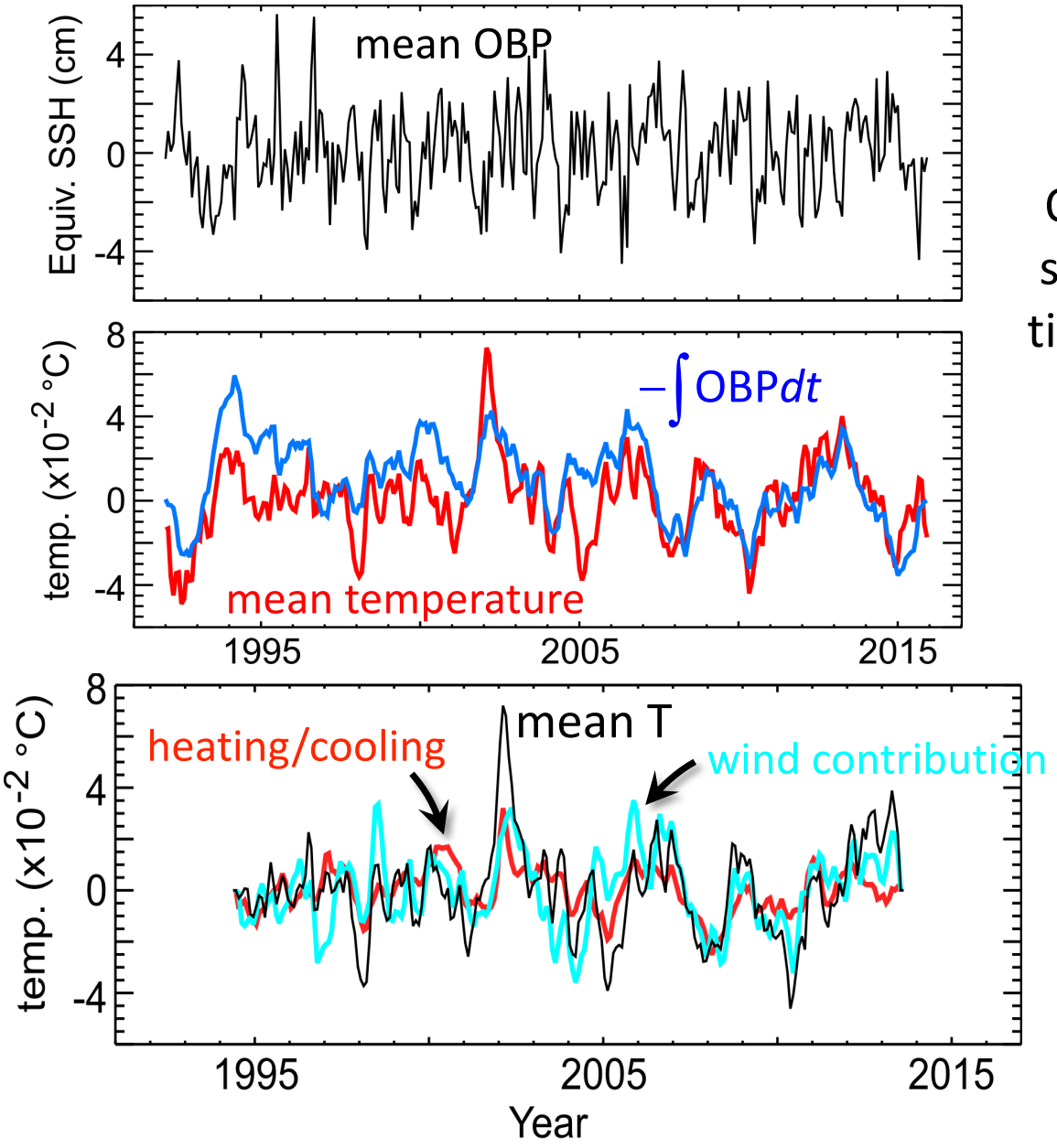
$$\frac{\partial J}{\partial \phi_{wind}(\mathbf{x}, \text{4-weeks})}$$

Along-bathymetry

Cross-bathymetry



OBP vs Ocean Heat Content



Ocean heat content change on the shelf is (negatively) correlated with time-integrated OBP, suggestive of a shelf-offshore exchange.

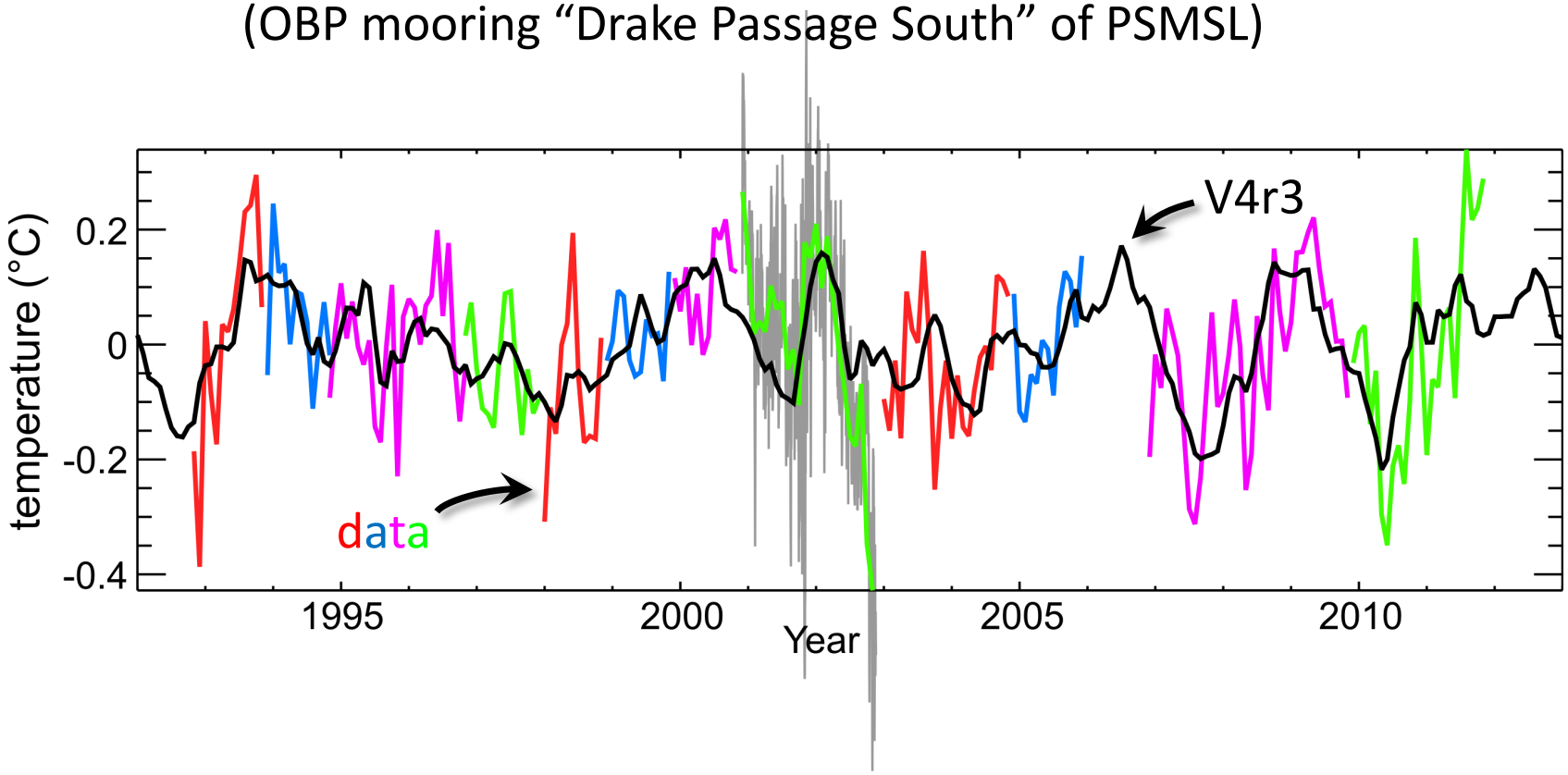
However, quantitative accounting shows heating & wind-driven circulation contributing nearly equally to mean T on the shelf.

$$J(t) \approx \sum_i \sum_{\mathbf{x}} \sum_{\Delta t} \frac{\partial J}{\partial \phi_i(\mathbf{x}, \Delta t)} \delta\phi_i(\mathbf{x}, t - \Delta t)$$

Ocean Heat Content Change (Validation)

ECCO V4r3's temperature variations are consistent with available but scarce long-term in situ observations.

1000m Temperature @ southern end of Drake Passage
(OBP mooring "Drake Passage South" of PSMSL)



Summary

1. ECCO estimates (http://www.ecco-group.org) provide ***complete and consistent descriptions*** of the ocean ***beyond what is measured***, useful for analyzing ***causal mechanisms*** of observed variations,
    a) In addition to the state (e.g., temperature, velocity), ***fluxes*** are available to facilitate budget analyses,
    b) The model's ***adjoint*** provides a means to quantify effects of different forcing and changes to the state,

2. Recent decadal ***subpolar North Atlantic Ocean heat content change*** is a result of wind-driven variations of midlatitude horizontal gyre circulation,

3. Intraseasonal-to-Interannual ***variations on the Antarctic shelf***;
    a) Near-uniform circumpolar ***sea level variations*** are driven by along-bathymetry winds along the continental slope,
    b) ***Temperature variations*** are correlated with (time-integrated) circumpolar sea level change but are driven by both wind and surface heat fluxes,
    c) ECCO estimates provide effective means to assess climate variations, including those in regions with scarce long-term observations.

ECCO Summer School 2019

When: May 19-31, 2019

Where: Friday Harbor Laboratories, WA

What: Introduce products, tools, and mathematics of ocean state estimation to early career scientists.

Aim: Nurture the next generation of oceanographers and climate scientists in ocean state estimation so that they may utilize the products most effectively and further advance the subject.

Look for forthcoming announcements and/or contact any of the ECCO principals for detail.