Final Report for: Pulling the Meridional Overturning Circulation From the South - DE-SC0005100

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Executive Summary:

This project concerned the Atlantic Meridional Overturning Circulation (AMOC), its stability, variability and sensitivity to atmospheric forcing, both mechanical (wind-stress) and thermodynamical (heat and freshwater surface fluxes). The focus of the study is the interhemispheric cell in the largely *adiabatic* regime, where the flow is characterized by a descending branch in the high latitudes of the North Atlantic and the upwelling branch in the Antarctic Circumpolar Current (ACC) region of the Southern Ocean. These two end points are connected by shared isopycnals along which the flow takes place.

The approach is to systematically study the amplitude and frequency of the AMOC's response to localized buoyancy with an ocean-only model in both coarse and high-resolution configurations, analyzed with innovative diagnostics, focused on the "residual overturning circulation" (ROC), which is the proper measure of the transport of heat and other tracers.

Accomplishments:

1) Coarse and high resolution computations where succesfully compared to illustrate the sensitivity of the strength of the residual circulation to wind-stress in the ACC and buoyancy perturbations in the North Atlantic. A conceptual model was developed illustrating that the upper bound of the residual transport is set by the wind-stress in the ACC (cf. publication 1 and figure 1).

2) We have shown that the residual circulation can be accurately estimated in eddy-resolving general circulations models using a Statistical Transformed Eulerian Mean (STEM) evaluation of the eddy-fluxes of temperature and salinity. This technique can be readily applied using diagnostics that are routinely saved in GCM's (cf. publication 2).

3) We have shown that freshwater feedbacks in the adiabatic AMOC increase the range of surface buoyancy values that are shared between the ACC region and the high latitudes of the Northern Hemisphere leading to a strengthening of the AMOC, compared to that obtained with thermal forcing only.

4) We have shown that freshwater feedbacks in the adiabatic AMOC can lead to multiple equilibria where the residual overturning is either reinforced or shut down. Self-sustained multidecadal oscillations are observed with amplitudes which increase as the critical forcing for AMOC shutdown is approached. These oscillations mediate the transition between AMOC "on" and "off" states (cf. publication 7 and figure 2).

5) We have established that the presence of zonally varying topography in the ACC region increases the poleward heat transport by eddies leading to a shoaling of the stratification and a decrease of the zonal transport on the ACC. In addition, the sensitivity of the stratification and zonal transport

of the ACC to the wind-stress forcing is greatly reduced by zonally varying topography.

6) We have analyzed the energetics of semi-enclosed seas with vertical exchange flow at the strait, and found a simple relation between the flux of (potential) energy into (or out of) the strait and the surface buoyancy flux. This relation allows to estimate the energy input due surface buoyancy forcing relative to the wind-work. We have found that the energy flux at the strait is into the basin for antiestuarine basins (such as the Mediterranean and the Red Seas) and out of the basin for estuarine basins (such as the Black and Baltic Seas). Using reanalysis products for the abovementioned four semi-enclosed seas, we find that, the energy flux at the strait due to surface buoyancy flux can be smaller, larger or of the same order as the wind-work. This allows a further classification of semi-enclosed seas as being primarily powered by wind or by buoyancy, or by both.

7) We have discovered that, in a configuration of the global ocean where the Atlantic sector differs from the Indo-Pacific sector *only* on basin width, with forcing and geometry otherwhise zonally symmetric, sinking is preferred in the narrow basin, i.e. the Atlantic sector. The preference for narrow-basin sinking is due to a combination of a deeper wind-driven circulation and a weaker meridional overturning velocity in a wider basin. The first property derives from a well-known result of theories the wind-driven circulation applied to advection of a tracer. The second property is due to the independence of the meridional overturning circulation on the width of the basin, a result proven in our latest submitted paper.

Publications:

Wolfe, C. L. and P. Cessi, 2011. The adiabatic pole-to-pole overturning circulation, *J. Phys. Oceanogr.*, **41**, 1795-1810.

Wolfe, C.L., Approximations to the ocean's residual overturning circulation in arbitrary tracer coordinates, 2014. *Ocean Modelling*, **75**, 20-35.

Young, W.R., C.L. Wolfe, and W.H. Munk, Generation of ripples by shear-flow instability, 2014. *J. Fluid Mech.*, **739**, 276-307.

Cessi, P., N. Pinardi and V. Lyubarstev, 2014. Energetics of semi-enclosed basins with two-layer flows at the strait, *J. Phys. Oceanogr.*, **44**, 967-979.

Abernathey, R. and P. Cessi, 2014. Topographic enhancement of eddy efficiency in baroclinic equilibration, *J. Phys. Oceanogr.*, **44**, 2107-2126.

Wolfe, C. L. and P. Cessi, 2014. Salt Feedback in the Adiabatic Overturning Circulation. *J. Phys. Oceanogr.*, **44**, 1175-1194.

Wolfe, C. L. and P. Cessi, 2015. Multiple regimes and low-frequency variability in the quasi-adiabatic overturning circulation, *J. Phys. Oceanogr.*, **44**, 1690-1708.

Jones, C. S. and P. Cessi, 2015. Interbasin transport of the meridional overturning circulation, submitted to *J. Phys. Oceanogr.*.

Meetings presentations:

18th Conference on Atmospheric and Oceanic Fluid Dynamics, AMS conference, Spokane, WA "A simple model of the adiabatic pole-to-pole overturning circulation" P. Cessi and C.L. Wolfe, 2011

18th Conference on Atmospheric and Oceanic Fluid Dynamics, AMS conference, Spokane, WA "Modeling the ocean's adiabatic pole-to-pole overturning circulation" C.L. Wolfe and P. Cessi, 2011

Past Present and Future Change in the Atlantic Meridional Overturning Circulation, International Science Meeting, Bristol, UK "The adiabatic pole-to-pole overturning circulation" P. Cessi and C.L. Wolfe, 2011

DOE Integrated Climate Modeling Science team meeting, Washington, DC, "Multiple Thermohaline Equilibria in the Adiabatic Regime" C.L. Wolfe and P. Cessi, 2011

DOE Integrated Climate Modeling Science team meeting, Washington, DC, 2011 "The adiabatic pole-to-pole overturning circulation" P. Cessi and C.L. Wolfe, 2011

2012 Ocean Sciences Meeting, Salt Lake City, UT "Multidecadal oscillations and multiple equilibria in the adiabatic regime" Wolfe, C. L. and Cessi, P.

2012 Ocean Sciences Meeting, Salt Lake City, UT "The adiabatic pole-to-pole overturning circulation" P. Cessi and C.L. Wolfe.

2012 Conference in Mathematical Geophysics, IUGG, Edinburgh, UK "Thermohaline feedbacks and multiple equilibria in the adiabatic regime". P. Cessi and C.L. Wolfe.

2012 AGU Fall meeting, San Francisco, CA. "The Energy Balance of the Antarctic Circumpolar Current". R. P. Abernathey and P. Cessi

2013 Workshop on Southern Ocean circulation, MIT, Cambridge, MA: "Equilibration of circumopolar currents with and without topography" Abernathey, R. and P. Cessi;

2013 19th Conference on Atmospheric and Oceanic Fluid Dynamics, AMS conference, Newport, RI: "Equilibration of circumopolar currents with and without topography" Abernathey, R. and P. Cessi; "The Role of Salt in the Ocean's Adiabatic Overturning Circulation" Wolfe, C.L. and P. Cessi; "Adiabatic Eastern boundary currents" Cessi, P. and C.L. Wolfe.

2013: U.S. AMOC/U.K. RAPID International Science Meeting: AMOC Variability: Dynamics and Impacts, Baltimore, MD. "The Role of Salt in the Ocean's Adiabatic Overturning Circulation" Wolfe C.L. and P. Cessi.

2013: IAPSO/IUGG Joint Assembly, Gothenburg, Sweden: "Adiabatic Eastern boundary currents" Cessi, P. and C.L. Wolfe.

2014: Ocean Sciences Meeting, Honolulu, HI "Salt Feedback in the adiabatic overturning circulation" Wolfe, C. L. and Cessi, P.; "Multiple equilibria and low-frequency variability in the quasi-adiabatic overturning circulation"C.L. Wolfe and P. Cessi.

2014: DOEs Integrated Climate Modeling Principal Investigator Meeting, Potomac, MD. " Salt feedbacks, multiple regimes and low-frequency variability in the adiabatic overturning circulation", Cessi P.

2015: 20th Conference on Atmospheric and Oceanic Fluid Dynamics, AMS conference, Minneapolis, MN: "Do multiple states of the quasi-adiabatic meridional overturning circulation exist?" P. Cessi and C. L. Wolfe; "Low-frequency variability of the quasi-adiabatic overturning circulation" Wolfe, C.L. and P. Cessi; "Size Matters: Why is there overturning in the Atlantic but not in the Pacific?" Jones, C. S. and P. Cessi.

2015: IUGG General Assembly, Prague, Czech Republic: "Multiple regimes and low-frequency variability in the quasi-adiabatic overturning circulation" Cessi, P. and C.L. Wolfe and "Energetics of semi-enclosed basins with two-layer flows at the strait" Cessi, Pinardi, Lyubartsev.

2015: U.S. AMOC/U.K. RAPID International Science Meeting, Bristol, UK. "Size matters: another reason why the Atlantic is saltier than the Pacific" Jones C. S. and P. Cessi.

2015: The Atlantic Meridional Overturning Circulation in a Global Perspective, Stockholm, Sweden, "Size matters: another reason why the Atlantic is saltier than the Pacific." Cessi P. and C.S. Jones.

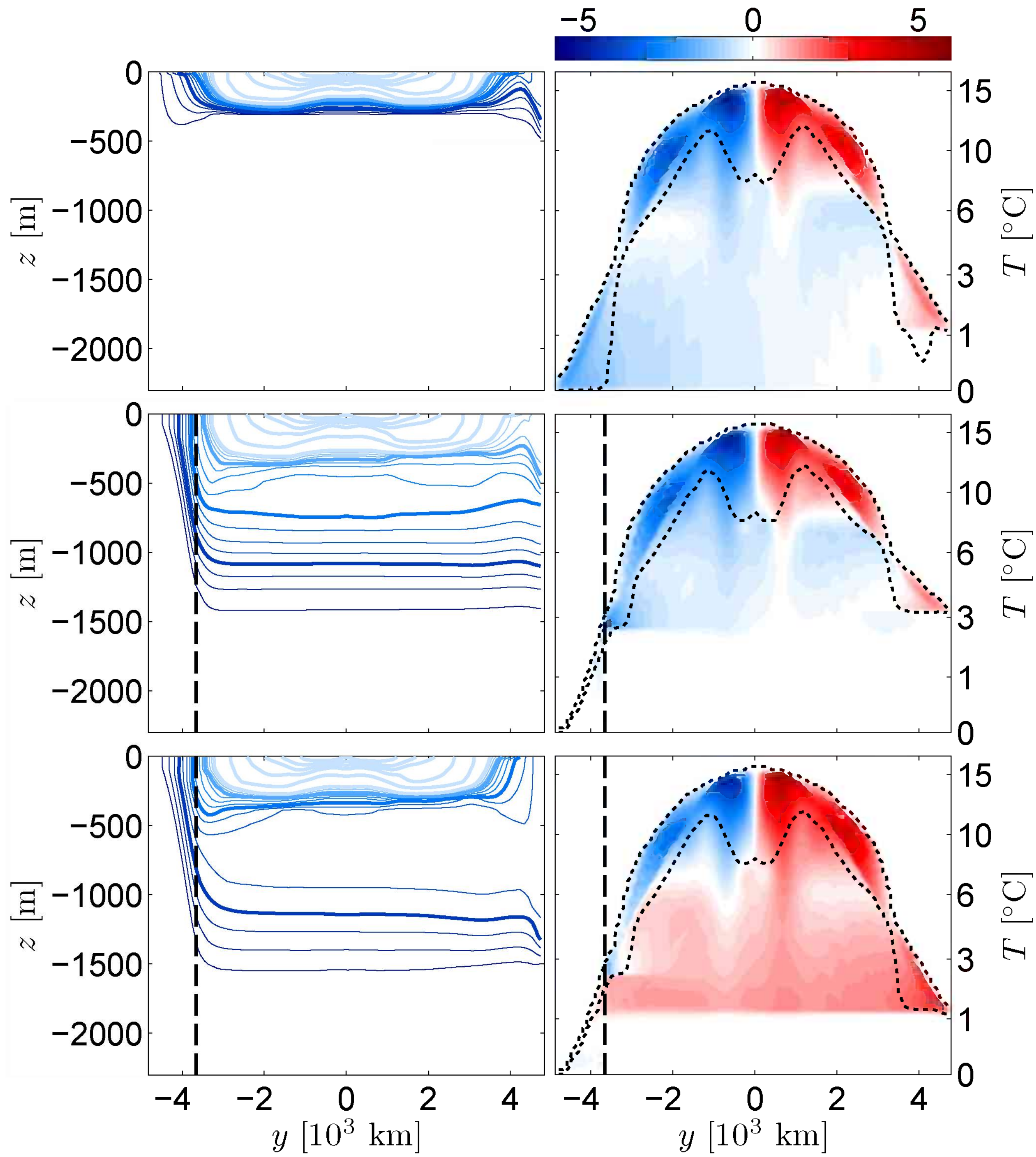

Figure 1: The zonally averaged temperature (left) and residual overturning (right) in three configurations: fully closed basin (top), reentrant ACC region in the southernmost eight of the domain but no isopycnals outcropping in both the ACC region and the Northern Hemisphere (middle), shared isopycnals outcropping in both the ACC region and the Northern Hemisphere (bottom). Notice the lack of stratification and AMOC in the top panel, and the lack of AMOC in the middle panel. Contour intervals for the left panels are in 1 °C (thick lines) and 0.25 °C (thin lines). Contour intervals for the right panels are 0.2 Sverdrup.

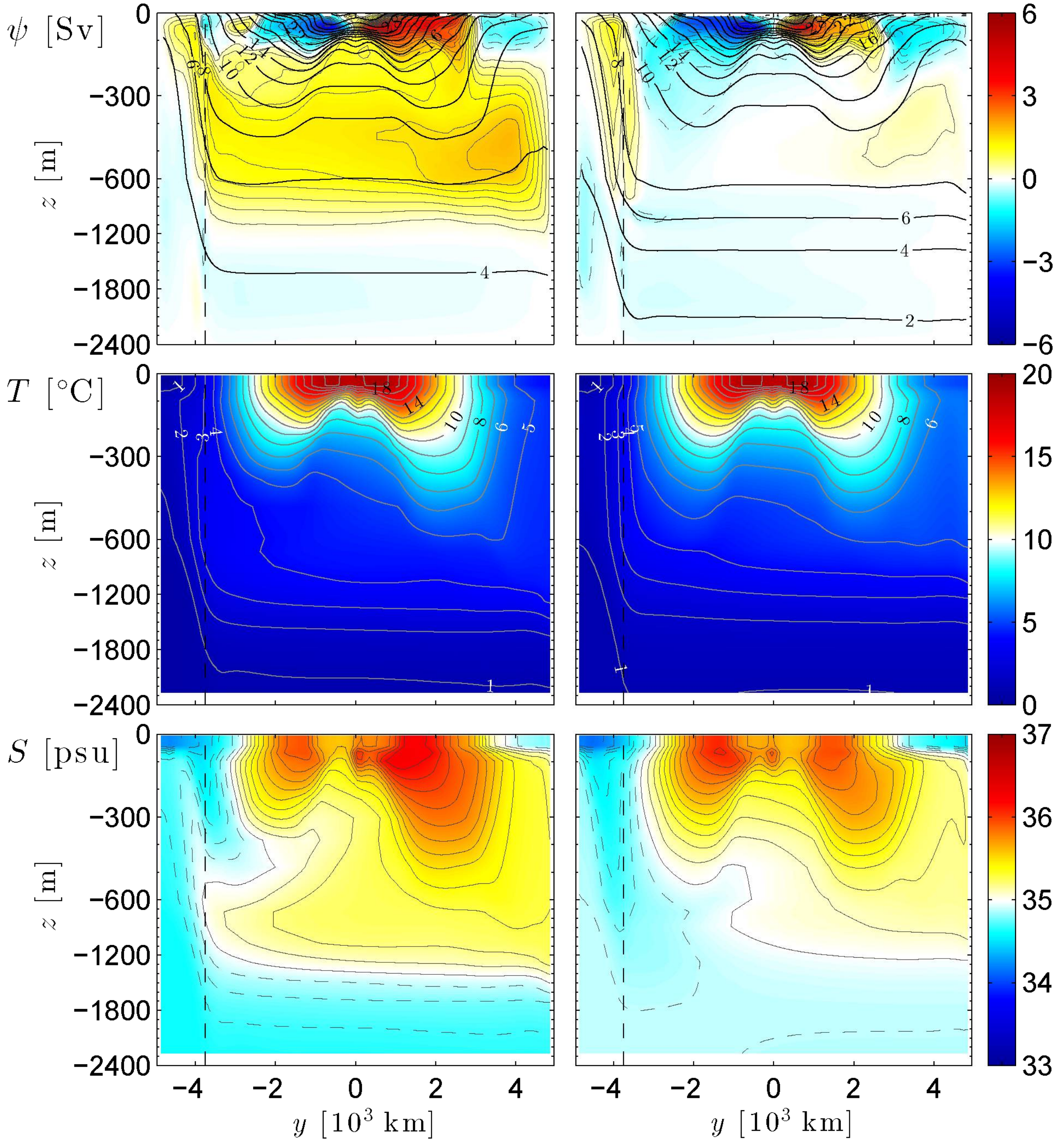

Figure 2: The upper panels give the residual streamfunction, middle panels the zonally averaged temperature, and the lower panels the zonally averaged salinity. The left panels are for the "on" state and the right panels are for the "off" state. Both states have the same fresh water flux symmetric around the equator, but the temperature flux differ slightly: the "on" state has $\Delta T = 4\,°\mathrm{C}$ while the "off" state has $\Delta T = 5\,°\mathrm{C}$, where ΔT is the pole-to-pole temperature difference. The equator-to-pole temperature difference (from the south pole to the equator) is $20\,°\mathrm{C}$. The diffusivity below the mixed layer is $3 \times 10^{-6}\,\mathrm{m^2\,s^{-1}}$. The thick contours in the upper panels give contours of the effective buoyancy field in units of $10^{-3}\,\mathrm{m\,s^{-2}}$; the thin contours are for the ROC and the contour interval is 0.5 Sv. The vertical dashed line denotes the northern edge of the reentrant channel. The contour intervals in the middle and bottom panels are $1\,°\mathrm{C}$ and 0.1 psu, respectively.