

Dense Outflows and Deep Convection in the Antarctic Zone of the Southern Ocean

Robin D. Muench
Earth & Space Research
2101 Fourth Avenue, Suite 1310
Seattle, WA 98121 USA
phone: (206) 363-7528 fax: (206) 726-0524 email: rmuench@esr.org

Grant Number: N00014-08-1-0548

<http://www.esr.org>

<http://www.ldeo.columbia.edu/res/div/ocp/projects/anslope.shtml>

LONG-TERM GOALS

This project has sought to better define the dynamics of those processes, including mixing, tides, current-topography interactions and nonlinear equation of state phenomena that impact vertical transports of heat and mass in the Southern Ocean. These transports are crucial to the formation of Antarctic Bottom Water (AABW), a primary global ocean water type, and are integral to the Southern Ocean branch of the meridional overturning circulation (MOC). Increased understanding of these features will improve their representation in large-scale models and enhance our ability to predict climate-related changes in the MOC.

OBJECTIVES

Specific objectives have been to:

- Quantify and dynamically assess the impacts of tidal currents, submesoscale bottom topography, and nonlinearities in the seawater equation of state on pathways, transport and mixing of dense outflows in the Southern Ocean, with emphasis on the Ross Sea contribution to AABW.
- Assess turbulent mixing responses at small and microscales to externally imposed conditions of varying vertical shear and stability, with an emphasis on the role of the seawater equation of state and with potential relevance to deep ocean convection.

APPROACH

This project has relied on analyses of field data that were acquired from the Southern Ocean. Data were obtained from the Ross Sea region during 2003 to 2005 under the auspices of the international AnSlope (Antarctic Slope) project, and from the eastern Weddell Sea as part of MaudNESS (Maud Rise Nonlinear Equation of State Study). Data include seawater temperature, salinity and currents, and scalar and shear microstructure. The study has relied on established methods including classical water mass, spectral, tidal and microstructure analyses. Findings from the field data analyses have been compared where possible with results from laboratory, analytical and numerical modeling work.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2009		2. REPORT TYPE Annual		3. DATES COVERED 00-00-2009 to 00-00-2009	
4. TITLE AND SUBTITLE Dense Outflows And Deep Convection In The Antarctic Zone Of The Southern Ocean				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Earth & Space Research, 2101 Fourth Avenue, Suite 1310, Seattle, WA, 98121				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
14. ABSTRACT This project has sought to better define the dynamics of those processes, including mixing, tides, current-topography interactions and nonlinear equation of state phenomena that impact vertical transports of heat and mass in the Southern Ocean. These transports are crucial to the formation of Antarctic Bottom Water (AABW), a primary global ocean water type, and are integral to the Southern Ocean branch of the meridional overturning circulation (MOC). Increased understanding of these features will improve their representation in large-scale models and enhance our ability to predict climate-related changes in the MOC.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			
			Same as Report (SAR)	7	

WORK COMPLETED

Three refereed manuscripts have been published [*Gordon et al.*, 2009; *Padman et al.*, 2009; *Muench et al.*, 2009a] that describe and discuss the physical characteristics and dynamics of the dense outflow from the NW Ross Sea and assess the impact of strong regional tidal currents and shear-driven mixing on the outflow. A fourth manuscript has been submitted that presents results of a study on the interactions between dense outflows and corrugated seafloor topography, with emphasis on the Ross Sea case [*Muench et al.*, 2009b]. These latter results were presented, in addition, at the June 2009 ONR physical oceanography workshop in Chicago. New results from studies of interactions among weak current shear and processes related to the seawater equation of state in the very weakly stratified upper ocean of the Maud Rise region of the Weddell Sea were presented at the July 2009 IAPSO (International Association for Physical Sciences of the Ocean) Assembly in Montreal. Finally, initial steps were taken in helping to organize the newly-formed SCOR (Scientific Council on Ocean Research) Affiliated Group on Ocean Mixing [<http://www.scor-int.org/OceanMixingProject.htm>].

RESULTS

Overview

This project has continued its focus on two Southern Ocean regions that have been identified as having either active or potentially active roles in deep and bottom water formation. First, it has contributed to quantifying and dynamically understanding the dense outflow exiting the NW Ross Sea shelf, from where it flows down-slope and contributes to the AABW. Second, it has carried out preliminary analyses of data that detail upper ocean conditions in the Maud Rise region of the eastern Weddell Sea, a known recent past site for deep convection.

Impacts of downslope corrugations on a dense outflow: the NW Ross Sea

Efforts to evaluate the impacts of axially down-slope oriented seafloor corrugations on dense outflows have continued. Seafloor mapping carried out in the NW Ross Sea in conjunction with the AnSlope project [*Gordon et al.*, 2009] revealed a continuous field of down-slope trending corrugations, with vertical trough to crest amplitudes of 10-20 m and along-slope wavelengths of 1-2 km, underlying the dense outflow on the continental slope. Previous work [e.g., *Wåhlin*, 2004; *Özgökmen and Fischer*, 2008] has shown that such corrugations can channel dense bottom flows and thereby enhance down-slope transport. Application of analytical and numerical models to the NW Ross Sea outflow, using field data recently acquired during the AnSlope project, showed that corrugation trough-to-trough wavelengths were optimal for enhancing down-slope transport [*Muench et al.*, 2009b]. Estimated transport enhancement over a 25-km long slope, using regional appropriate oceanographic and seafloor corrugation values, yield a ~13% increase in down-slope transport over the smooth seafloor case. Down-slope transport increases with corrugation height, as well as varying with along-slope wavelength, and presence of deeper corrugations elsewhere on the Antarctic margins suggests that this process may have significant impacts in other regions having dense outflows (Figure 1). Their presence in the NW Ross Sea may help explain why the observed dense outflow has an unusually large angle ($> 30^\circ$ as compared to the more typical $10-15^\circ$) down-slope from isobaths [*Gordon et al.*, 2009].

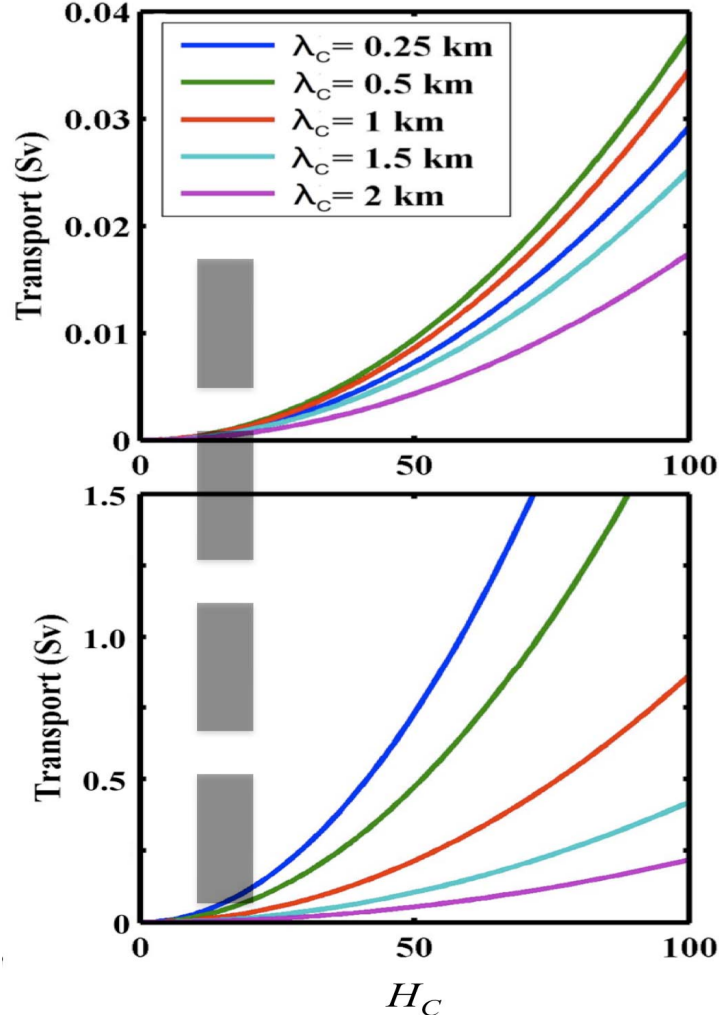


Figure 1. Downslope transport due to dense outflow interaction with seafloor corrugations, using oceanographic conditions appropriate to the NW Ross Sea, as a function of corrugation vertical amplitude H_C in km and along-slope wavelength λ_C in m: (upper) transports for a single corrugation; and, (lower) for a 25-km long corrugated slope approximating the dimensions of the NW Ross Sea outflow site [Muench et al., 2009b]. Broad dashed line approximates H_C for the NW Ross Sea.

Impacts of seawater equation of state effects on upper ocean vertical heat transport: the eastern Weddell Sea

The Maud Rise region in the eastern Weddell Sea combines extremely weak vertical stratification with local current-topography interactions to yield anomalously high upward heat fluxes that limit winter ice formation and predispose the region to deep convection [de Steur et al., 2007]. Potential mechanisms for these heat fluxes include pycnocline erosion, upwelling associated with the topographic interactions, shear-driven turbulence, and the equation of state related processes double-diffusion, cabelling, and thermobaricity. Microstructure T and shear data were obtained, in conjunction with CTD-derived T and S and ADCP current profiles, from the Maud Rise region during the 2005 MaudNESS field program.

Analysis of the MaudNESS data allow a preliminary assessment of upper ocean processes that contribute to high heat fluxes. Cases in which fluxes were dominated by entrainment across the pycnocline, shear-driven turbulence, double-diffusion, and combinations of these, were examined. An example illustrating heat fluxes in the presence of both shear and double diffusive instability across the Pycnocline is shown in Figure 2. Flux is significant (15 W m^{-2}) across the pycnocline, where turbulence is associated with local shear rather than surface mixed layer turbulence (which is shown by a dissipation ε drop to zero near 75 m). Density ratio R_ρ is near 1, highly favorable for double diffusion, so that even small shear is sufficient to drive it unstable.

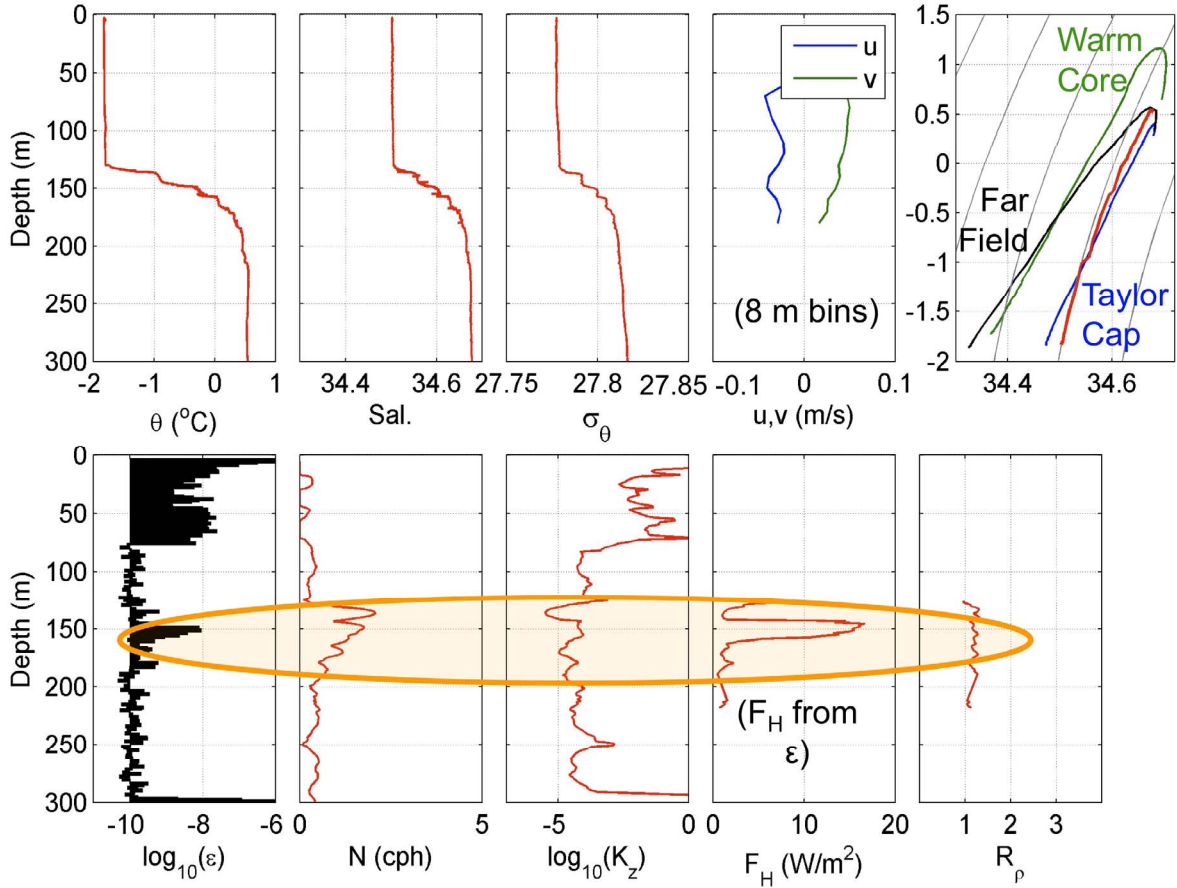


Figure 2. Vertical property profiles from a site on the SW flank of Maud Rise during August 2005 (See Figure 3 for location). Potential temperature θ , salinity Sal, potential density σ_θ , buoyancy frequency N and density ratio R_ρ were derived from a CTD cast. Current speeds u and v were measured using a vessel-mounted acoustic Doppler current profiler (ADCP). Dissipation ε was derived from shear microstructure. Diffusivity K_z and heat flux F_H were derived after Osborn (1980) assuming mixing efficiency $\Gamma=0.2$. The ellipse serves to highlight the thermocline features.

More than 400 sets of such vertical profiles, covering a broad variety of conditions, were obtained during MaudNESS. While rigorous analyses of these data is incomplete, a regional summary of vertical upper ocean heat flux values computed using a small subset of these data is presented in Figure

3. The largest heat fluxes coincide with the area having the lowest concentrations, both in percent coverage and with respect to thickness, of winter ice cover.

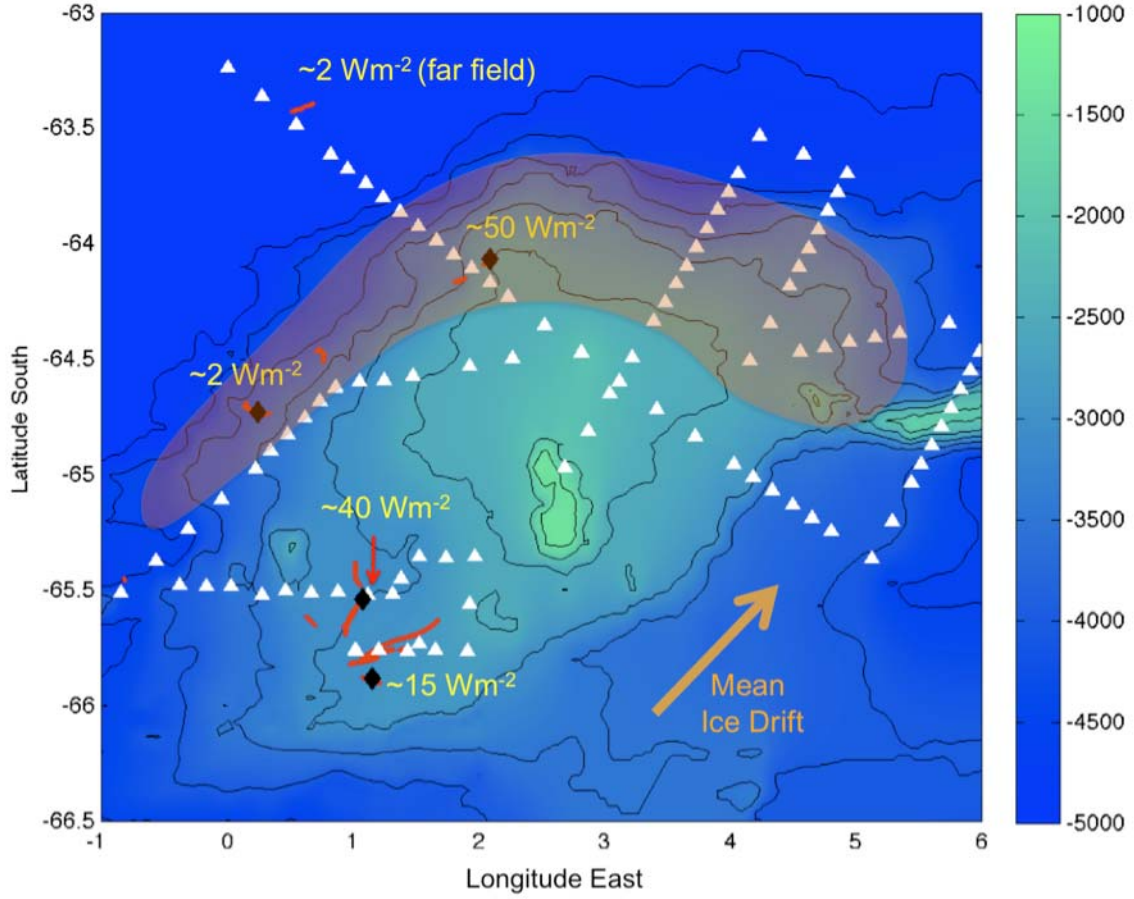


Figure 3. Maximum heat fluxes of $\sim 50 \text{ W m}^{-2}$ reflected pycnocline entrainment and coincided with the upstream and broadest portion of a perennial winter thin ice/open water region (shaded area). Minimum heat fluxes of $\sim 2 \text{ W m}^{-2}$ directly downstream to the SW reflected suppression of mixing by enhanced vertical density gradients which may reflect meltwater addition. The high heat flux ($\sim 40 \text{ W m}^{-2}$) on the SW flank of the Rise reflects strong instability to double diffusive staircase convection. A lower flux ($\sim 15 \text{ W m}^{-2}$) just to the south reflects both shear instability and double diffusion (see Figure 2).

Shear-driven pycnocline heat flux, representative of far-field conditions and generally active throughout the region, is generally small ($\sim 1\text{-}2 \text{ W m}^{-2}$). Upwelling of warm deep water over the northern flank of Maud Rise, however, facilitates pycnocline entrainment such that fluxes can locally exceed 50 W m^{-2} . However, entrainment fluxes can be large even when the pycnocline is deep, if R_ρ is small and double diffusion is actively occurring. Fluxes can be relatively large ($\sim 40 \text{ W m}^{-2}$) due to double diffusive convection in the non-entraining case for $R_\rho \approx 1$. Mean pycnocline R_ρ ranged from $\sim 1.0\text{-}1.5$, and the entire region is only marginally stable with respect to double diffusive convection. Given that the canonical mixing efficiency $\Gamma=0.2$ used in computing these fluxes [Osborn, 1980] represents the shear-driven mixing component but not the double diffusive component, it seems reasonable that values of $\Gamma > 0.2$ are appropriate in regions unstable to double diffusive convection.

IMPACT/APPLICATIONS

We have improved the quantitative and dynamical understanding of dense outflows, with an emphasis on Antarctic outflows as typified by that exiting the NW Ross Sea. We demonstrate for the first time the potential impacts of submesoscale seafloor corrugations on dense outflows that contribute to Antarctic Bottom Water. These results can be expected to influence the direction of future studies of dense outflows in general, and of Antarctic Bottom Water in particular. They will impact the physical oceanographic and, through impacts on the MOC, the climate research communities in that they provide a further motive for inclusion of sub-gridscale processes in the OGCMs (oceanic general circulation models) that are used in climate change research.

Equation of state processes such as double diffusion impact vertical heat fluxes and contribute to deep ocean convection that impacts deep and bottom water characteristics. Understanding these processes is essential to prediction of interactions among climatic and upper ocean changes, formation rate of AABW, and water mass modification through deep convection. Early results from the eastern Weddell Sea suggest that, under certain conditions, these processes sufficiently impact heat fluxes to warrant their incorporation into OGCMs.

RELATED PROJECTS

Research under this grant has been carried out in collaboration with the following projects:

- AnSlope (Antarctic Slope Project): A study of the impacts of shelf break dynamical processes on the transport of dense water from near-coastal formation region to the deep ocean floor [Gordon *et al.*, 2009].
- GCECPT (Gravity Current Entrainment Climate Process Team): A dedicated research group focused on dense overflow processes and potential interactions with climate [Legg *et al.*, 2008].
- MaudNESS (Maud Rise Nonlinear Equation of State Study): A process-oriented field and modeling study of mixing processes in a very weakly stratified upper ocean near Maud Rise in the Weddell Sea, with potential applications to deep convection [<http://www.oc.nps.edu/~stanton/thermo/Maudness/MaudnessMainHome.html>] .

REFERENCES

- de Steur, L., D.M. Holland, R.D. Muench, and M.G. McPhee, 2007: The warm-water "halo" around Maud Rise: Properties, dynamics and impact. *Deep-Sea Res.* 1, 54, doi:10.1016/j.dsr.2007.03.009.
- Gordon, A.L., A.H. Orsi, R.D. Muench, B.A. Huber, E. Zambianchi, and M. Visbeck, 2009: Western Ross Sea continental slope gravity currents. *Deep-Sea Res.* 2, 56, doi:10.1016/j.dsr2.2008.10.037.
- Legg, S., B. Briegler, Y. Chang, E. Chassignet, G. Danabasoglu, T. Ezer, A. Gordon, S. Griffies, R. Hallberg, L. Jackson, W. Large, T. Özgökmen, H. Peters, J. Price, U. Riemenschneider, W. Wu, X. Xu, and J. Yang, 2008: Improving oceanic overflow representation in climate models: the Gravity Current Entrainment Climate Process Team. *Bull. American Met. Soc.*, 90, 657-670.
- Muench, R.D., L. Padman, A.L. Gordon, and A. Orsi, 2009a: A dense water outflow from the Ross Sea, Antarctica: Mixing and the contribution of tides, in: *Proc. 39th International Liège Colloquium on*

Ocean Hydrodynamics, edited by J.-M. Beckers and H. Burchard, *J. Mar. Systems*, 31, doi:10.1016/j.jmarsys.2008.11.003.

Muench, R.D., A.K. Wåhlin, T.M. Özgökmen, R. Hallberg, and L. Padman, 2009b: Impacts of bottom corrugations on a dense Antarctic outflow: the NW Ross Sea. *Geophys. Res. Letters*, 37.

Osborn, T.R., 1980: Estimates of the local rate of vertical diffusion from dissipation measurements. *J. Phys. Oceanog.*, 10, 83-89.

Özgökmen, T.M., and P.F. Fischer, 2008: On the role of bottom roughness in overflows. *Ocean Modeling*, 20, 336-361.

Padman, L., S. Howard, A. Orsi, and R.D. Muench, 2009: Tides of the Northwestern Ross Sea and their impact on dense outflows of high salinity shelf water. *Deep-Sea Res.* 2, 56, doi:10.1016/j.dsr2.2008.10.026.

Wåhlin, A.K., 2004: Downward channeling of dense water in topographic corrugations. *Deep-Sea Res.* 1, 51, 577-590.

PUBLICATIONS

Gordon, A.L., A.H. Orsi, R.D. Muench, B.A. Huber, E. Zambianchi, and M. Visbeck, 2009: Western Ross Sea continental slope gravity currents. *Deep-Sea Res.* 2, 56, doi:10.1016/j.dsr2.2008.10.037 [published, refereed].

Muench, R.D., L. Padman, A.L. Gordon, and A. Orsi, 2009: A dense water outflow from the Ross Sea, Antarctica: Mixing and the contribution of tides, in: *Proc. 39th International Liège Colloquium on Ocean Hydrodynamics*, edited by J.-M. Beckers and H. Burchard, *J. Mar. Systems*, 31, doi:10.1016/j.jmarsys.2008.11.003 [published, refereed].

Muench, R.D., A.K. Wåhlin, T.M. Özgökmen, R. Hallberg, and L. Padman, 2009: Impacts of bottom corrugations on a dense Antarctic outflow: the NW Ross Sea. *Geophys. Res. Letters*, 37.

Padman, L., S. Howard, A. Orsi, and R.D. Muench, 2009: Tides of the Northwestern Ross Sea and their impact on dense outflows of high salinity shelf water. *Deep-Sea Res.* 2, 56, doi:10.1016/j.dsr2.2008.10.026 [published, refereed].