6-2014

Multiplatform, multidisciplinary investigations of the impacts of Modified Circumpolar Deep Water in the Ross Sea, Antarctica

Walker O. Smith Jr.
Virginia Institute of Marine Science

KT Goetz

DE Kaufman
Virginia Institute of Marine Science

BY Queste

V Asper

See next page for additional authors

Recommended Citation

Smith, Walker O. Jr.; Goetz, KT; Kaufman, DE; Queste, BY; Asper, V; Costa, DP; Dinniman, MS; Friedrichs, MAM; and al, et, Multiplatform, multidisciplinary investigations of the impacts of Modified Circumpolar Deep Water in the Ross Sea, Antarctica (2014). *Oceanography*, 27(2 SI), 180-185.
10.5670/oceanog.2014.36

Authors

Walker O. Smith Jr., KT Goetz, DE Kaufman, BY Queste, V Asper, DP Costa, MS Dinniman, MAM Friedrichs, and et al

Launch of a Slocum glider from RVIB *Nathaniel B. Palmer* in January 2011 during the SEAFARERS field study. This glider launch was done in open water away from sea ice. ©*Chris Linder/chrislinder.com*

Multiplatform, Multidisciplinary Investigations of the Impacts of Modified Circumpolar Deep Water in the Ross Sea, Antarctica

BY WALKER O. SMITH JR., KIMBERLY T. GOETZ, DANIEL E. KAUFMAN, BASTIEN Y. QUESTE, VERNON ASPER, DANIEL P. COSTA, MICHAEL S. DINNIMAN, MARJORIE A.M. FRIEDRICHS, EILEEN E. HOFMANN, KAREN J. HEYWOOD, JOHN M. KLINCK, JOSH T. KOHUT, AND CRAIG M. LEE

ABSTRACT. In 2010–2011, three projects combined to characterize the temporal and spatial distributions of Modified Circumpolar Deep Water (MCDW) in the Ross Sea using icebreaker-based sampling, gliders, instrumented seals, and hindcasts from a numerical circulation model. The fieldwork clearly identified MCDW throughout the Ross Sea, and the data were used to determine its influence on potential heat and nutrient inputs and biotic distributions. Furthermore, the numerical simulations confirm its apparent trajectory and location. Substantial small-scale variability in oceanographic and biological distributions suggests that such variability may play an important role in biogeochemical cycles. Data from the three projects provide a view of hydrographic variability in the Ross Sea that is impossible to obtain using traditional sampling. Multiplatform investigations are promising approaches to future polar experiments where logistical considerations are of paramount importance.

INTRODUCTION

The limited availability of logistical resources constrains investigations of polar oceanography, biogeochemistry, and ecology. For example, research vessels with icebreaking capability are in great demand for scientific missions in both the Arctic and Antarctic. Even with icebreaker capability, ships often cannot access certain regions due to heavy ice conditions, further limiting the ability to sample the ocean adequately to resolve the spatial and temporal variability associated with most biological processes (e.g., phytoplankton blooms). This constraint is further compounded by the small spatial scales of mesoscale variability in polar regions, which make alternate sampling approaches attractive. Satellite observations provide guidance for where and when to undertake field efforts (e.g., Fennel et al., 2011; Mahadeven et al., 2012), but cloud and ice distributions can restrict their utility. Here, we describe multiplatform sampling conducted in the Ross Sea (Figure 1), Antarctica, that investigated the distribution of a water mass (Modified Circumpolar Deep Water, or MCDW) on the continental shelf and its biological impacts.

Peloquin and Smith (2007) suggest that MCDW stimulates surface primary production, but the cause of such stimulation is unclear. One potential mechanism might be introduction of the micronutrient iron from deeper water or, alternatively, resuspension of iron from sediment as it flows through the region's troughs and mixes with surface waters. Given the different density characteristics of MCDW and surface waters, a second mechanism might be enhancement of the irradiance environment by an increase in vertical stratification. Because both light and iron play important roles in regulating phytoplankton growth and production (Smith et al., 2012), the input of MCDW might have far-reaching impacts on the oceanography, biogeochemistry, and ecology of the Ross Sea.

THE ROSS SEA

The Ross Sea is a well-studied, but logistically challenging, region of the Southern Ocean that is covered by sea ice for much of the year. Minimum sea ice coverage occurs in early February when the Ross Sea often, but not always, opens to the Pacific Ocean (Smith et al., 2012). Although the Ross Sea polynya begins its expansion in November, access to this area requires a well-powered icebreaker. Ice re-forms rapidly in late February, and the region is completely ice covered by the end of March. Substantial interannual variations in the magnitude of this pattern occur, and local influences (e.g., massive iceberg calving from the Ross Ice Shelf) can be significant. Oceanographic processes in the Ross Sea provide important contributions to the larger global circulation, such as the formation of dense High Salinity Shelf Water and flow of this dense bottom water off the shelf (Orsi and Wiederwohl, 2009; Smith et al., 2012, 2014a). The Ross Sea is home to a large fraction of the world's Emperor (*Aptenodytes forsteri*) and Adélie (*Pygoscelis adeliae)* penguins, and it supports substantial standing stocks of crabeater (*Lobodon carcinophagus*) and Weddell (*Leptonychotes weddellii*) seals, cetaceans (orcas and minkes), and pelagic birds. There is marked temporal and spatial variation in phytoplankton growth, with extreme gradients along the north-south axis. These variations occur over scales of days (or less) and a few kilometers.

Walker O. Smith Jr. *(wos@vims.edu) is Professor, Virginia Institute of Marine Science, College of William & Mary, Gloucester Pt., VA, USA.* **Kimberly T. Goetz** *is a graduate student in the Department of Ecology & Evolutionary Biology, University of California, Santa Cruz, CA, USA.* **Daniel E. Kaufman** *is a graduate student at Virginia Institute of Marine Science, College of William & Mary, Gloucester Pt., VA, USA.* **Bastien Y. Queste** *is a graduate student in the Centre for Ocean and Atmospheric Sciences, School of Environmental Sciences, University of East Anglia, Norwich, UK.* **Vernon Asper** *is Professor, Department of Marine Sciences, University of Southern Mississippi, Stennis Space Center, MS, USA.* **Daniel P. Costa** *is Professor, Department of Ecology & Evolutionary Biology, University of California, Santa Cruz, CA, USA.* **Michael S. Dinniman** *is Research Scientist, Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, VA, USA.* **Marjorie A.M. Friedrichs** *is Research Associate Professor, Virginia Institute of Marine Science, College of William & Mary, Gloucester Pt., VA, USA.* **Eileen E. Hofmann** *is Professor, Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, VA, USA.* **Karen J. Heywood** *is Professor, Centre for Ocean and Atmospheric Sciences, School of Environmental Sciences, University of East Anglia, Norwich, UK.* **John M. Klinck** *is Professor, Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, VA, USA.* **Josh T. Kohut** *is Associate Professor, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, USA.* **Craig M. Lee** *is Professor, Applied Physics Laboratory, University of Washington, Seattle, WA, USA.*

MULTIPLATFORM INVESTIGATION

In 2010–2011, three projects implemented field efforts, incorporating a range of approaches and technologies to investigate the appearance of MCDW and its impacts on the ecology and biogeochemistry of the Ross Sea at space and time scales not previously possible. MCDW is delineated by temperatures warmer than –1.7°C, salinities greater than 34.7, and oxygen saturations < 75%, all resulting from its more northerly origin and relatively old age (Orsi and Wiederwohl, 2009). The SEAFARERS (Slocum Enhanced Adaptive Fe Algal REsearch in the Ross Sea) project investigated the importance of MCDW intrusions onto the shelf as a potential micronutrient (Fe) source for phytoplankton growth (Kohut et al., 2012), and it included investigations of circulation, chemistry, sediments, and plankton. SEAFARERS used ship-based sampling, short-term moorings, and gliders (Figure 1 and opening-spread photo) to resolve the flow in troughs that provide direct connections between the northern Ross Sea shelf and the open ocean. The second project, GOVARS (Glider Observations of Variability in the Ross Sea), deployed two gliders in the southern Ross Sea, with the objective of quantifying spatial and temporal variability in hydrographic and fluorescence (a measure of chlorophyll) distributions at spatial scales never before assessed. The third project deployed satellite data relay loggers that included attaching conductivity-temperature-depth (CTD) sensors to Weddell seals (Figures 1 and 2) to collect hydrographic and seal-behavior information during dives. The hydrographic distributions obtained from these three field programs provided input to and were compared with simulated distributions obtained from a numerical model for the Ross Sea (Dinniman et al., 2011).

The platforms used in the three field studies have been used elsewhere, but never in the Ross Sea, which presented unique challenges. The gliders used in both GOVARS and SEAFARERS were launched from the fast ice attached to Ross Island, rather than in open water, due to the absence of a ship early in the season. The first GOVARS glider was deployed into McMurdo Sound from sea ice, while the second GOVARS glider and a SEAFARERS glider were launched from the fast ice east of Cape Crozier (Figure 1). Additional, shorter glider deployments were conducted later in the year from RVIB *Nathaniel B. Palmer*. Such deployments carried a significant amount of risk, in that gliders can easily

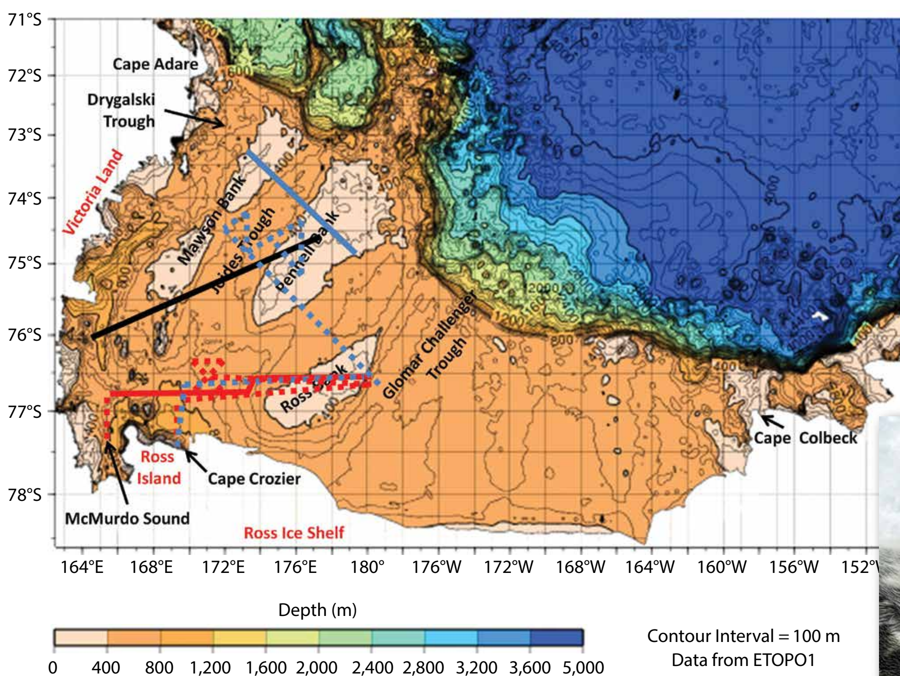

Figure 1. Locations of regions sampled with both traditional ship-based sampling and gliders during the Slocum Enhanced Adaptive Fe Algal REsearch in the Ross Sea (SEAFARERS) project (solid blue line) in January 2011 and by gliders during the Glider Observations of Variability in the Ross Sea (GOVARS) program (solid red line) from November 2010 to January 2011. Temperature measurements obtained from sensors deployed on Weddell seals between March and June 2011 were used to construct an across-shelf temperature distribution (black line). The Ross Sea circulation model was used to simulate temperature and salinity distributions along the same transect as sampled during SEAFARERS. Vertical distributions of hydrographic properties obtained from SEAFARERS, GOVARS, and the Ross Sea circulation model are shown in Figures 3, 4, and 5, respectively. Dashed lines indicate additional glider tracks sampled by each program but not included as part of the data discussion in this analysis.

Figure 2. A Weddell seal on the ice in the Ross Sea with an attached conductivity-temperature-depth (CTD)/satellite data relay logger. The logger is attached by gluing it to the animal's fur, which is not harmful to the animal, and it is shed when the animal molts during the austral summer. *Photo by Daniel Costa*

be trapped and/or damaged by ice. Marine mammals (e.g., elephant and crabeater seals; Hückstadt et al., 2012) have been used extensively to sample temperature and salinity during their dives in the area of the West Antarctic Peninsula (Costa et al., 2008), but never before in the Ross Sea.

IMPACTS OF MCDW

All three programs jointly observed the intrusion, distribution, and modification of MCDW as it moved across the continental shelf, and they confirmed that it substantially altered heat input to the shelf and modified distributions of higher trophic level animals. The SEAFARERS project found that MCDW intrusions occurred along the eastern slope of the Joides Trough (Kohut et al., 2012; Figure 3a–f), as predicted by circulation simulations (Figure 3g,h). The water mass at this northerly latitude was relatively unmodified from the CDW source water, and for the most part it remained distinct from surface waters. MCDW was also detected by the GOVARS project in the southern Ross Sea (between 175°E and 180°; Figure 4), although it was highly modified from the CDW source water (Figure 4). It was also clearly found ~ 45 km north of the GOVARS transect line (data not shown). The composite seal section also unmistakably showed the presence of MCDW in the water column (Figure 5), and the water mass was largely confined to mid-water depths. Individual seals often concentrated their dives within MCDW. All of these observations confirmed the modeled trajectory of the water mass from north to south, as well as the spatial restriction of MCDW. The results also show the extent of modification of the water mass as it traverses the continental shelf and mixes with surface waters.

In addition, some results were unexpected. For example, when we compared the ship-based vertical distributions in the northern Ross Sea to those collected by gliders, the glider observations indicated substantially more spatial (vertical and horizontal) variability (e.g., Figures 3d–f and 4). Similar variability was observed in the GOVARS data, where mixed layers varied between 10 and 76 m water depth (mean = 22 m; recent work of authors Kaufman, Friedrichs, Smith, Heywood, and Queste), compared to ship-based means from 5 to 46 m water depth during summer (mean = 24 m; Smith et al., 2000). Additionally, substantial penetrations of chlorophyll were noted to occur over small spatial scales (Figure 4). While such features have occasionally been observed by shipboard sampling (e.g., DiTullio et al., 2001), the ubiquity of deep chlorophyll

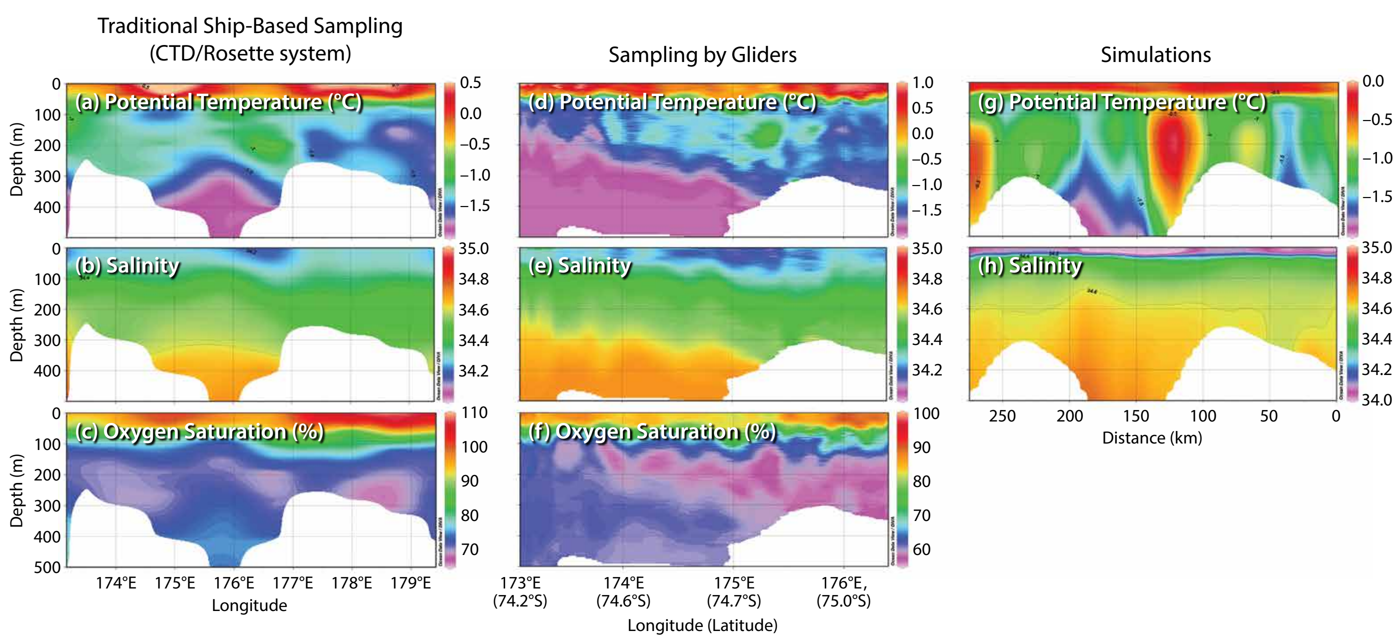

Figure 3. (left panel) Vertical distributions of (a) potential temperature in °C, (b) salinity, and (c) dissolved oxygen concentrations (percent saturation) along a transect in the northern Ross Sea (blue line in Figure 1) obtained using traditional ship-based sampling (CTD rosette system) during the SEAFARERS study. Circumpolar Water was clearly identified at ~ 200 m water depth on the flank of the Joides Trough based on its temperature and oxygen characteristics. (middle panel) Vertical distributions of (d) potential temperature in °C, (e) salinity, and (f) oxygen concentration (percent saturation) sampled by gliders during the SEAFARERS study. (right panel) Simulated distributions of (g) temperature and (h) salinity for late January 2011 along the section sampled during the SEAFARERS study (blue line in Figure 1). MCDW was detected at the same location by the ship-based survey. White area indicates the seafloor in all panels.

penetrations along the southern transect was surprising, and suggests that submesoscale processes and their impacts need to be more clearly defined in regions such as the Ross Sea.

It was also observed that seals often frequented the sites of MCDW penetration in troughs (Goetz et al., 2012). It is likely that this represents the presence of certain food items in the water mass, specifically *Euphausia superba*, Antarctic krill, which occur in waters off the shelf and whose subadult stages appear to be associated with intrusions (Piñones et al., 2013). Thus, the use of satellite tags allows identification of seal-foraging locations and their oceanographic characteristics.

COST CONSIDERATIONS AND TECHNOLOGICAL LIMITATIONS

Collecting data using gliders and marine mammals is relatively inexpensive. Gliders are initially costly (about $120,000 each), and there is a substantial risk of loss; however, the SEAFARERS and GOVARS projects deployed four gliders on seven missions without loss, and data were collected continuously from mid-November through mid-February. For comparison, ship costs for a similar period would exceed $5 million. Similarly, satellite data relay loggers for deployment on seals cost about $7,000 each and are expendable. Instrumenting 15 seals and collecting data over four months, especially in sea ice conditions and locations that are inaccessible to ship-based sampling, represents considerable cost savings and substantial scientific benefit. For example, during 2010–2011, 19 seals were instrumented, enabling us to collect over 7,000 CTD profiles between February and October. The in situ hydrographic distributions obtained from gliders and seals provide valuable calibration and evaluation data for the Ross Sea circulation model and allow physical qualities such as heat budgets to be computed. The combination of these measured and simulated data sets allows improvement of the Ross Sea circulation model and permits projections of the impacts of climate change (Smith et al., 2014b).

These emerging technologies have limitations. Gliders need open water to obtain both accurate GPS locations and new programs/instructions via satellite, and require acoustic infrastructure to enable sampling in ice covered waters. While marine mammals sample nonrandomly, they dive predominantly in regions with high mesoscale structure (fronts, eddies, and continental edge/slope; Bost et al., 2009). Nevertheless, they cannot be directed to specific locations. Furthermore, data collection is limited by size constraints on sensor packages that can be reliably affixed. Regardless, with the improved and miniaturized sensors that are available

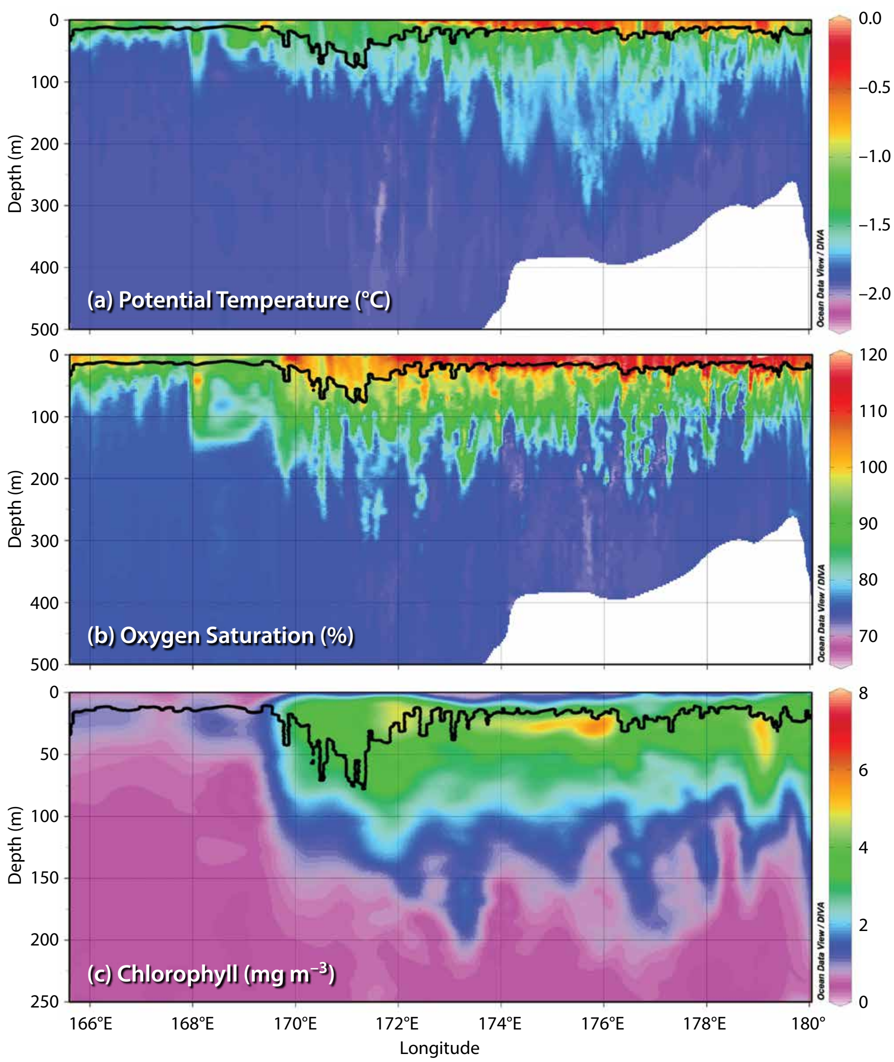

Figure 4. Vertical distributions of (a) temperature, (b) oxygen concentrations (percent saturation), and (c) derived chlorophyll obtained from the GOVARS glider deployed in the southern Ross Sea (red line in Figure 1). Sampling occurred from December 10, 2010, through January 2, 2011. White area indicates the seafloor, and the black line is the depth of the mixed layer (recent work of authors Kaufman, Friedrichs, Smith, Heywood, and Queste).

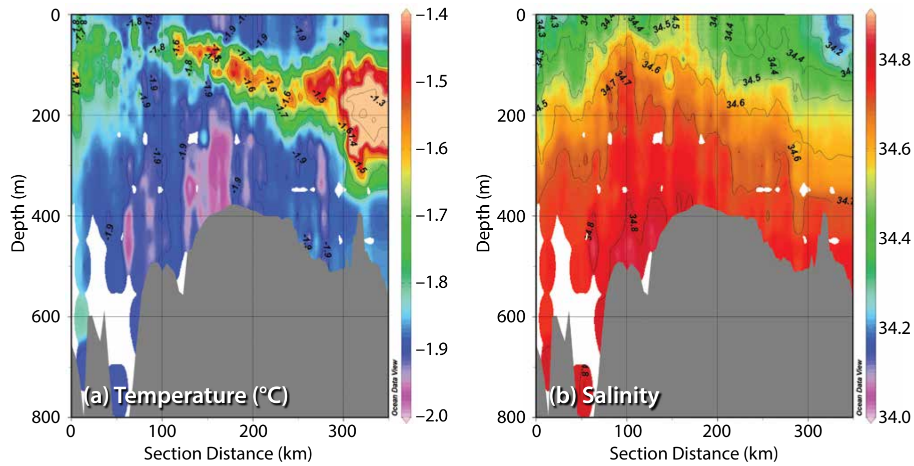

Figure 5. Vertical distributions of (a) temperature and (b) salinity constructed from a composite of Weddell seal dives (n = 19) between March and June 2011 (black line in Figure 1). The presence of MCDW between 50 and 300 m water depth is indicated by temperatures above −1.6°C and salinities greater than 34.7. Gray shading indicates the seafloor.

and in development, placing these on alternate platforms will be even more appealing in the future as a cost-effective, integrative means to sample challenging environments.

SUMMARY AND FUTURE

Results from three independent but complementary programs allowed characterization of the spatial and temporal distribution of MCDW intrusions onto the Ross Sea continental shelf by using traditional and alternative sampling approaches. The ability to combine the data sets with a Ross Sea circulation model to obtain distributions of water column structure over an annual time scale is a strength of these programs. This type of coordinated, collaborative research using a range of sampling technologies will allow better understanding of the influence of oceanographic events and their impacts on regional oceanography, productivity, and biogeochemical cycles, as well as insights into changes in the Ross Sea that are expected to occur in the future. They also can be applied to pan-Southern Ocean programs (such as the Southern Ocean Observing System) that endeavor to collect data continuously over the entire region. Such information will be invaluable as further modifications of Southern Ocean biogeochemistry occur.

REFERENCES

Bost, C.A., C. Cotté, F. Bailleul, Y. Cherel, J.B. Charrassin, C. Guinet, D.G. Ainley, and H. Weimerskirch. 2009. The importance of oceanographic fronts to marine birds and mammals of the southern oceans. *Journal of Marine Systems* 78:363–376, http://dx.doi.org/10.1016/j.jmarsys.2008.11.022.

Costa, D.P., J.M. Klinck, E.E. Hofmann, M.S. Dinniman, and J.M. Burns. 2008. Upper ocean variability in west Antarctic Peninsula continental shelf waters as measured using instrumented seals. *Deep Sea Research Part II* 55:323–337, http://dx.doi.org/10.1016/j.dsr2.2007.11.003.

Dinniman, M.S., J.M. Klinck, and W.O. Smith Jr. 2011. A model study of Circumpolar Deep Water on the West Antarctic Peninsula and Ross Sea continental shelves. *Deep Sea Research Part II* 58:1,508–1,523, http://dx.doi.org/10.1016/j.dsr2.2010.11.013.

DiTullio, G.R., J.M. Grebmeier, K.R. Arrigo, M.P. Lizotte, D.H. Robinson, A. Leventer, J.P. Barry, M.L. VanWoert, and R.B. Dunbar. 2000. Rapid and early export of *Phaeocystis antarctica* blooms in the Ross Sea, Antarctica. *Nature* 404:595–598, http://dx.doi.org/10.1038/35007061.

Fennel, K., I. Cetinić, E. D'Asaro, C. Lee, and M.J. Perry. 2011. Autonomous data describe North Atlantic spring bloom. *Eos Transactions, American Geophysical Union* 92(5):465, http://dx.doi.org/10.1029/2011EO500002.

Goetz, K., P. Robinson, M. Shero, J. Burns, and D. Costa. O' seal, where art thou? Overwinter movement, habitat, and navigation of Weddell seals in the Ross Sea. Paper presented at the Scientific Committee on Antarctic Research (SCAR) Open Science Conference, Portland, Oregon, July 16–19, 2012.

Hückstadt, L.A., J.M. Burns, P.L. Koch, B.I. McDonald, D.E. Crocker, and D.P. Costa. 2012. Diet of a specialist in a changing environment: The crabeater seal along the western Antarctic Peninsula. *Marine Ecology Progress Series* 455:287–301, http://dx.doi.org/10.3354/meps09601.

Kohut, J.T., E. Hunter, and B. Huber. 2012. Small-scale variability of the cross shelf flow over the outer shelf of the Ross Sea. *Journal of Geophysical Research* 118:1,863–1,876, http://dx.doi.org/10.1002/jgrc.20090.

Mahadevan, A., E. D'Asaro, C. Lee, and M.J. Perry. 2012. Eddy-driven stratification initiates North Atlantic spring phytoplankton blooms. *Science* 337:54–58, http://dx.doi.org/10.1126/science.1218740.

Orsi, A.H., and C.L.Wiederwohl. 2009. A recount of Ross Sea waters. *Deep Sea Research Part II* 56:778–795, http://dx.doi.org/10.1016/j.dsr2.2008.10.033.

Peloquin, J.A., and W.O. Smith Jr. 2007. Phytoplankton blooms in the Ross Sea, Antarctica: Interannual variability in magnitude, temporal patterns, and composition. *Journal of Geophysical Research* 112, C08013, http://dx.doi.org/10.1029/2006JC003816.

Piñones, A., E.E. Hofmann, K.L. Daly, M.S. Dinniman, and J.M. Klinck. 2013. Modeling the remote and local connectivity of Antarctic krill (*Euphausia superba*) populations along the western Antarctic Peninsula. *Marine Ecology Progress Series* 481:69–92, http://dx.doi.org/10.3354/meps10256.

Smith, W.O. Jr., D.G. Ainley, K.R. Arrigo, and M.S. Dinniman. 2014a. The oceanography and ecology of the Ross Sea. *Annual Review of Marine Science* 6:469–487, http://dx.doi.org/10.1146/annurev-marine-010213-135114.

Smith, W.O. Jr., M.S. Dinniman, E.E. Hoffman, and J. Klinck. 2014b. The effects of changing winds and temperatures on the oceanography of the Ross Sea in the 21st century. *Geophysical Research Letters* 41:1,624–1,631, http://dx.doi.org/10.1002/2014GL059311.

Smith, W.O. Jr., J. Marra, M.R. Hiscock, and R.T. Barber. 2000. The seasonal cycle of phytoplankton biomass and primary productivity in the Ross Sea, Antarctica. *Deep Sea Research Part II* 47:3,119–3,140, http://dx.doi.org/10.1016/S0967-0645(00)00061-8.

Smith, W.O. Jr., P.N. Sedwick, K.R. Arrigo, D.G. Ainley, and A.H. Orsi. 2012. The Ross Sea in a sea of change. *Oceanography* 25(3):90–103, http://dx.doi.org/10.5670/oceanog.2012.80.