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Observations of the Antarctic Slope Undercurrent in the southeastern Weddell Sea

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[1] The Antarctic Slope Front presents a dynamical barrier between the cold Antarctic shelf waters in contact with ice shelves and the warmer subsurface waters offshore. Two hydrographic sections with full-depth current measurements were undertaken in January and February 2009 across the slope and shelf in the southeastern Weddell Sea. Southwestward surface-intensified currents of ~30 cm s^{-1}, and northeastward undercurrents of 6–9 cm s^{-1}, were in thermal-wind balance with the sloping isopycnals across the front, which migrated offshore by 30 km in the time interval between the two sections. A mid-depth undercurrent on February 23 was associated with a 130-m uplift of the main pycnocline, bringing Warm Deep Water closer to the shelf break. This vertical displacement, comparable to that caused by seasonal variations in wind speed, implies that undercurrents may affect the exchanges between coastal and deep waters near the Antarctic continental margins. **Citation:** Chavanne, C. P., K. J. Heywood, K. W. Nicholls, and I. Fer (2010), Observations of the Antarctic Slope Undercurrent in the southeastern Weddell Sea, *Geophys. Res. Lett.*, *37*, L13601, doi:10.1029/2010GL043603.

1. Introduction

[2] The cold waters on the Antarctic continental shelves are separated from the warmer subsurface waters offshore by the Antarctic Slope Front (ASF) [*Jacobs*, 1991], a pronounced deepening of isopycnals toward the coast, mainly attributed to coastal downwelling caused by the prevailing easterly winds [*Sverdrup*, 1954]. The ASF extends continuously from 120°W near the Amundsen Sea westward to 55°W at the tip of the Antarctic Peninsula [*Whitworth et al.*, 1998]. The ASF dynamics control the exchanges of heat, salt and freshwater across the continental shelf, and their transport around the continent by its associated westward surface-intensified flow, which we refer to here as the Antarctic Slope Current (ASC). The ASF therefore influences deep water formation [*Gill*, 1973], melting of ice shelves [*Smedsrud et al.*, 2006], and transport of nutrients and krill [*Pauly et al.*, 2000].

[3] In the southeastern Weddell Sea (Figure 1), the narrow continental shelf allows Warm Deep Water (WDW) to come into close proximity with ice shelves, and episodically flush sub-ice shelf cavities [*Nicholls et al.*, 2006]. As a result, regional modeling of basal melting is extremely sensitive to how well the narrow continental shelf topography and ASF dynamics are resolved [*Nicholls et al.*, 2008], making it difficult to predict the local freshwater budget. This in turn affects predictions of Antarctic Bottom Water formation downstream in the southwestern Weddell Sea [*Thoma et al.*, 2006]. We present observations of hydrography and currents from two sections obtained in 2009 from the continental shelf and slope in front of Riiser-Larsenisen (Figure 1), as part of the Synoptic Antarctic Shelf-Slope Interactions study (SASSI). They provide new insights into some aspects of ASF dynamics.

2. Observations

[4] Temperature, salinity and absolute current profiles were measured on each section (Figure 2). Lowered Acoustic Doppler Current Profiler (LADCP) currents were processed using Lamont Doherty Earth Observatory (LDEO) software version IX.5 [*Visbeck*, 2002]. To obtain a synoptic picture of the ASC, barotropic semi-diurnal tides were removed from the LADCP currents by least-squares fitting M_2 sines and cosines to the time-series of depth-averaged currents on each section (Figure 3). This assumes that the tidal amplitude and phase were constant along the sections, a reasonable first-order approximation for the dominant semi-diurnal barotropic tides according to CATS2008b (an update to the circum-Antarctic inverse barotropic tide model described by *Padman et al.* [2002]). The estimated semi-diurnal currents captured the observed depth-averaged variability better than CATS2008b predictions, with amplitudes of 5–7 cm s^{-1} for the along-slope component and less than 3 cm s^{-1} for the cross-slope component.

[5] Detided LADCP currents at 100 m depth are shown in Figure 1. On January 31, a surface-intensified southwestward jet of 33 cm s^{-1} was located at the offshore extremity of section 1, over the 1600 m isobath. It decreased to 6 cm s^{-1} within 11 km shoreward. Currents at station 5, ~5 km from the ice shelf edge, were weak (3 cm s^{-1}) and toward the ice shelf. On February 23, the surface jet had migrated offshore, with a peak velocity of 28 cm s^{-1}, located over the 3000 m isobath, and a width narrower than 28 km, embedded in a larger-scale but slower (~10 cm s^{-1}) southwestward flow. From these two snapshots, the ASC does not appear to be tied to topographic gradients, but rather displays a variable cross-slope position.

[6] The vertical sections of the along-slope velocity component (Figures 2c and 2g) reveal that the ASC is mostly confined above the main pycnocline, roughly represented by the 28.1 neutral density surface [*Whitworth et al.*, 1998], which separates the colder and fresher Antarctic Surface Water from the warmer and saltier WDW (Figure 2). Along

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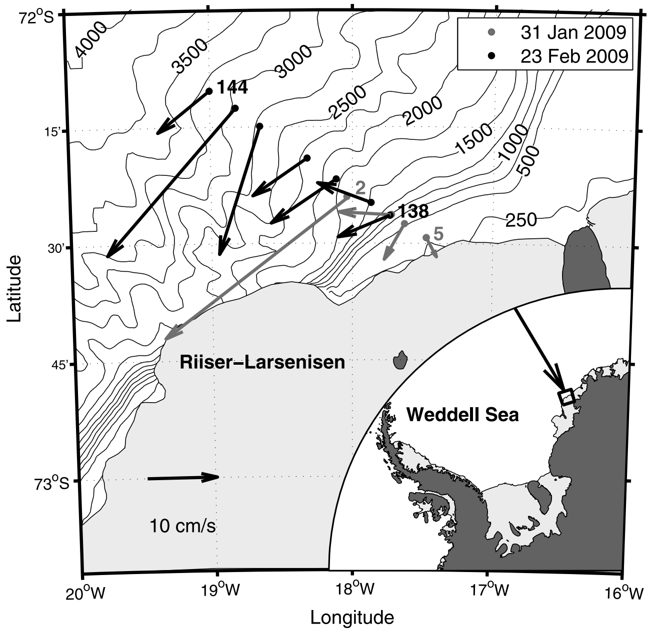

Figure 1. Location of the stations with detided LADCP currents at 100 m depth in front of Riiser-Larsenisen. The insert shows the location of the study area (small black rectangle indicated by the arrow) in the southeastern Weddell Sea. Stations 2–5 (section 1, gray) were undertaken on January 31 and stations 138–144 (section 2, black) on February 23, 2009. Ice is shaded light where floating and dark where grounded. Isobaths are shown every 250 m.

each section, the strongest vertical shear measured by the LADCPs is located where the pycnocline is steepest, consistent with thermal-wind balance. The offshore increase in density is associated with surface-intensified south-westward currents, that decrease or even reverse direction with increasing depth, yielding deep counter-currents, or undercurrents, such as the near-bottom north-eastward current that reached 9 cm s^{-1} at station 2 on January 31 (Figure 2c).

[7] Another north-eastward undercurrent was observed on February 23 at station 138 near the shelf break (Figure 2g), but it was located at mid-depth, reaching 6 cm s^{-1} at a depth of 525 m (Figure 4), while currents below 700 m returned to a south-westward flow direction. The vertical shear therefore changed sign below 525 m, with an associated reversal of the pycnocline slope consistent with thermal-wind balance: the 28.1 neutral density surface was lifted by 130 m between stations 139 and 138 (Figure 2). This could not have resulted from onshore bottom Ekman transport, since the along-slope currents above the bottom were south-westward (Figures 2g and 4), and should therefore yield offshore bottom Ekman transport. The observed onshore cross-slope currents near the bottom (Figure 2h) were therefore not due to bottom friction. Instead, they could be associated with the transient circulation allowing the currents and density field to adjust to geostrophic equilibrium. The geostrophic shear between stations 138 and 139 compares favorably with the average of the velocity profiles measured by the LADCPs at both stations (Figure 4), demonstrating that the undercurrent was in thermal-wind balance to first order.

3. Discussion

[8] A mid-depth undercurrent was observed with LADCPs along the Antarctic continental slope at 18°W on

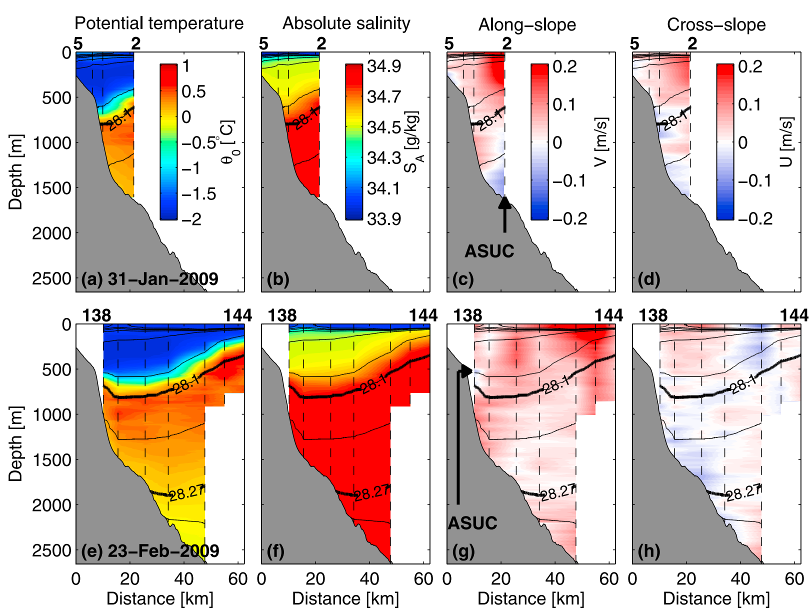

Figure 2. Vertical sections of (a, e) potential temperature, (b, f) absolute salinity (computed using the Gibbs Sea-Water software version 1.0 for MATLAB [*McDougall et al.*, 2009]), (c, g) along-slope (>0 toward the south-west) and (d, h) cross-slope (>0 offshore) detided current components measured by the LADCPs on (top) January 31 (section 1) and (bottom) February 23 (section 2), 2009. Neutral density contours are overlain on each plot. The 28.1 and 28.27 neutral densities enclosing WDW are shown by thick lines. The station positions are indicated by vertical dashed lines, and the first and last station of each section labeled on top of each plot. The Antarctic Slope Undercurrent (ASUC) cores are indicated in Figures 2c and 2g.

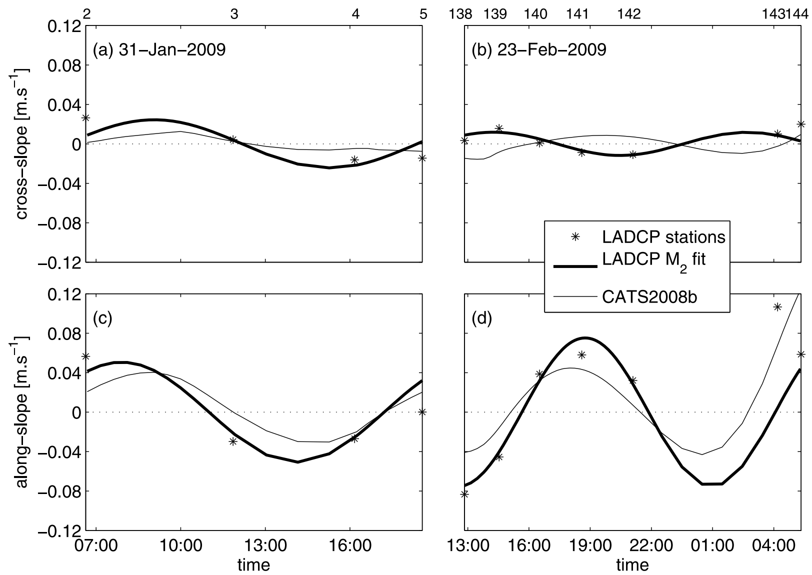

Figure 3. Time series of depth-averaged currents on (a, c) January 31 (section 1) and (b, d) February 23 (section 2), rotated into cross-slope (>0 offshore, Figures 3a and 3b) and along-slope (>0 toward the south-west, Figures 3c and 3d) components. LADCP currents at each station (labeled on top of Figures 3a and 3b) are represented by stars (the average over stations 2–5 for section 1 and 138–142 for section 2 have been removed). Semi-diurnal tides estimated by least-squares fit (thick lines) and barotropic tides (using 10 tidal constituents) predicted by CATS2008b (thin lines) are also shown.

February 23, 2009. Hydrographic observations showed the undercurrent was in thermal-wind balance with a 130-m uplift of the pycnocline, bringing WDW closer to the shelf break, and therefore reducing the efficiency of the ASF dynamical barrier. This vertical shift is comparable to that caused by temporal variations in wind speed [*Fahrbach et al.*, 1992; *Ohshima et al.*, 1996]. Undercurrents may therefore be an important component of the physical processes controlling the exchanges between coastal and deep waters near the Antarctic continental margins. Have similar undercurrents been observed elsewhere around Antarctica?

[9] *Heywood et al.* [1998] first noticed a north-eastward undercurrent at 17°W during an hydrographic section in March 1995. They reported a maximum velocity of 4.6 cm s^{-1} at 700 m depth, ~300 m above the bottom, and a shoreward uplift of isopycnals below the undercurrent core. They pointed out that a similar undercurrent was present at 20°W in the hydrographic observations of *Fahrbach et al.* [1994] in October 1986, with speeds exceeding 4 cm s^{-1} at depths between 1000 and 1500 m. Upward sloping isotherms are visible along the continental slope at 17°W between 700 m and 400 m depth in a hydrographic section in February 1997 [*Nøst*, 2004]. Recently, *Núñez-Riboni and Fahrbach* [2009] reported bottom-intensified eastward undercurrents of 5–10 cm s^{-1} in hydrographic sections in December 2000 and February 2005 at the prime meridian, in front of Fimbulisen. The February 2005 section displayed two separate undercurrent cores: one on the continental slope and one at the ice shelf edge. All these previous observations were deduced from geostrophy referenced to shipboard ADCP or moored current meters.

[10] In a regional numerical simulation, *Smedsrud et al.* [2006] reproduce an eastward undercurrent with speeds exceeding 6 cm s^{-1} at 500 m depth at 1°W, just above the 570-m deep sill below Fimbulisen. It is associated with an uplift of the pycnocline over the sill, enabling WDW to enter the sub-ice shelf cavity, and responsible for high basal melt rates at the grounding line of Jutulstraumen ice stream in their model. *Smedsrud et al.* [2006] and *Núñez-Riboni*

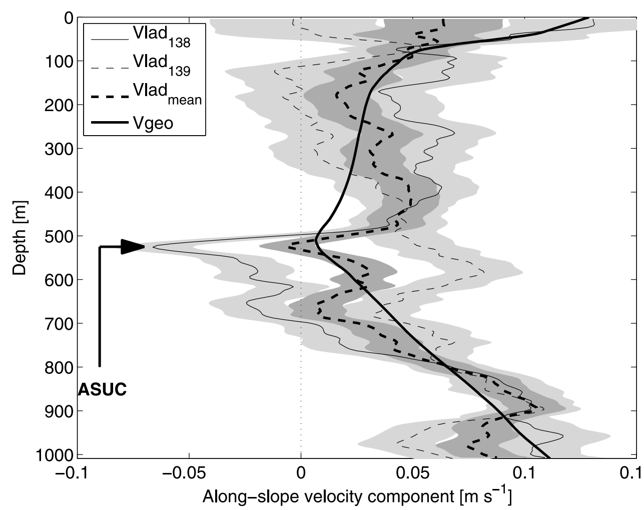

Figure 4. Vertical profiles of the along-slope current component (>0 toward the south-west) near the shelf break on February 23, 2009. Detided currents from the LADCPs at station 138 (thin solid line) and 139 (thin dashed line) are averaged together (thick dashed line), and compared with geostrophic currents (thick solid line) between stations 138 and 139 (with the barotropic component adjusted to that of the average LADCP currents). Shadings give the one standard deviation uncertainty for the LADCP currents (light, given by the inversion at each station; dark, obtained by propagation of errors for the mean).

and Fahrbach [2009] assign the presence of the undercurrent below Fimbulisen to the elevated sea level at the ice-shelf edge resulting from the blocked onshore wind-driven Ekman transport [*Clarke*, 1978]. However, the resulting eastward current below the ice shelf should be surface intensified, as is its westward counterpart seaward of the ice shelf (the ASC). Therefore, this mechanism cannot explain the bottom-intensified undercurrent. Similarly, *Núñez-Riboni and Fahrbach* [2009] suggest that the undercurrent they observed on the continental slope could be driven by the intensification of wind momentum transfer to the ocean by sea-ice [*Fennel and Johannessen*, 1998]. Again, the resulting currents should be surface-intensified, contrary to the observed undercurrents.

[11] A plausible forcing mechanism for these undercurrents is provided by theoretical and numerical studies of the eastern boundary circulation of the major ocean basins, where other undercurrents have long been observed, such as the California Undercurrent [*Wooster and Jones*, 1970]. They share similar characteristics with the undercurrents observed around Antarctica - located at mid-depth over the continental slope below oppositely-flowing surface-intensified currents, confined within 10–20 km from topography, and a few 100 m in height - except that they occur in coastal upwelling areas. *McCreary* [1981], using a linear analytical model with a vertical side wall, showed that the along-slope currents are set up by the propagation of Kelvin waves from localized along-shore wind patches, and that the depth and thickness of the undercurrent are determined by the number of vertical Kelvin modes reaching a given area. In a non-linear numerical model with a sloping continental rise and shelf, *Suginohara* [1982] showed that the coastal circulation was mainly set up by the propagation of the first two coastal-trapped wave modes, with the undercurrent characteristics determined by the second mode structure. *Middleton and Cirano* [1999] simulated a coastal downwelling system and found that its early evolution (first 10–20 days) could be qualitatively described by linear coastal-trapped wave dynamics, with undercurrents developing as for the upwelling systems.

[12] These along-shore currents are in thermal-wind balance with the cross-shore density gradients, consistent with our observations. We therefore hypothesize that Antarctic Slope Undercurrents are associated with the propagation of coastal-trapped waves, which have been observed in the Weddell Sea [*Middleton et al.*, 1982], and might therefore be common features of the circulation along Antarctic continental slopes. Confirmation of this hypothesis requires a more complete set of observations, but we note that the few available observations in the southeastern Weddell Sea are consistent with a westward deepening of the undercurrent, as noted by *Smedsrud et al.* [2006], i.e., in the direction of propagation of coastal-trapped waves, as predicted by *McCreary* [1981]. The paucity of observations revealing such undercurrents may result from their small spatial extent, both vertically and horizontally: they may have remained undetected in coarse-resolution hydrographic sections and mooring arrays across the Antarctic continental slope. Moreover, undercurrents may not develop in areas of downslope flow of dense water [*Baines*, 2009] and in the presence of wide continental shelves [*Middleton and Cirano*, 1999].

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References

Baines, P. G. (2009), A model for the structure of the Antarctic Slope Front, *Deep Sea Res., Part II*, *56*, 859–873, doi:10.1016/j.dsr2.2008.10.030.

Clarke, A. J. (1978), On wind-driven quasi-geostrophic water movements near fast-ice edges, *Deep Sea Res.*, *25*, 41–51.

Fahrbach, E., G. Rohardt, and G. Krause (1992), The Antarctic Coastal Current in the southeastern Weddell Sea, *Polar Biol.*, *12*, 171–182, doi:10.1007/BF00238257.

Fahrbach, E., R. G. Peterson, G. Rohardt, P. Schlosser, and R. Bayer (1994), Suppression of bottom water formation in the southeastern Weddell Sea, *Deep Sea Res., Part I*, *41*, 389–411, doi:10.1016/0967-0637(94)90010-8.

Fennel, W., and O. M. Johannessen (1998), Wind forced oceanic responses near ice edges revisited, *J. Mar. Syst.*, *14*, 57–79, doi:10.1016/S0924-7963(97)00018-3.

Gill, A. E. (1973), Circulation and bottom water production in the Weddell Sea, *Deep Sea Res.*, *20*, 111–140.

Heywood, K., R. Locarnini, R. Frew, P. Dennis, and B. King (1998), Transport and water masses of the Antarctic Slope Front system in the eastern Weddell Sea, in *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, vol. 75, edited by S. S. Jacobs and R. F. Weiss, pp. 203–214, AGU, Washington, D. C.

Jacobs, S. S. (1991), On the nature and significance of the Antarctic Slope Front, *Mar. Chem.*, *35*, 9–24, doi:10.1016/S0304-4203(09)90005-6.

McCreary, J. P. (1981), A linear stratified ocean model of the Coastal Undercurrent, *Philos. Trans. R. Soc. London, Ser. A*, *302*(1469), 385–413, doi:10.1098/rsta.1981.0176.

McDougall, T. J., D. R. Jackett, and F. J. Millero (2009), An algorithm for estimating absolute salinity in the global ocean, *Ocean Sci. Discuss.*, *6*, 215–242, doi:10.5194/osd-6-215-2009.

Middleton, J. F., and M. Cirano (1999), Wind-forced downwelling slope currents: A numerical study, *J. Phys. Oceanogr.*, *29*, 1723–1743, doi:10.1175/1520-0485(1999)029<1723:WFDSCA>2.0.CO;2.

Middleton, J. H., T. D. Foster, and A. Foldvik (1982), Low-frequency currents and continental shelf waves in the southern Weddell Sea, *J. Phys. Oceanogr.*, *12*, 618–634, doi:10.1175/1520-0485(1982)012<0618:LFCACS>2.0.CO;2.

Nicholls, K. W., E. P. Abrahamsen, K. J. Heywood, K. Stansfield, and S. Østerhus (2008), High-latitude oceanography using the Autosub autonomous underwater vehicle, *Limnol. Oceanogr.*, *53*, 2309–2320.

Nicholls, K. W., et al. (2006), Measurements beneath an Antarctic ice shelf using an autonomous underwater vehicle, *Geophys. Res. Lett.*, *33*, L08612, doi:10.1029/2006GL025998.

Nøst, O. A. (2004), Measurements of ice thickness and seabed topography under the Fimbul Ice Shelf, Dronning Maud Land, Antarctica, *J. Geophys. Res.*, *109*, C10010, doi:10.1029/2004JC002277.

Núñez-Riboni, I., and E. Fahrbach (2009), Seasonal variability of the Antarctic Coastal Current and its driving mechanisms in the Weddell Sea, *Deep Sea Res., Part I*, *56*, 1927–1941, doi:10.1016/j.dsr.2009.06.005.

Ohshima, K. I., T. Takizawa, S. Ushio, and T. Kawamura (1996), Seasonal variations of the Antarctic coastal ocean in the vicinity of Lützow-Holm Bay, *J. Geophys. Res.*, *101*(C9), 20,617–20,628, doi:10.1029/96JC01752.

Padman, L., H. A. Fricker, R. Coleman, S. Howard, and S. Erofeeva (2002), A new tidal model for the Antarctic ice shelves and seas, *Ann. Glaciol.*, *34*, 247–254, doi:10.3189/172756402781817752.

Pauly, T., S. Nicol, I. Higginbottom, G. Hosie, and J. Kitchener (2000), Distribution and abundance of Antarctic krill (Euphausia superba) off East Antarctica (80–150°E) during the Austral summer of 1995/1996, *Deep Sea Res., Part II*, *47*, 2465–2488, doi:10.1016/S0967-0645(00)00032-1.

Smedsrud, L. H., A. Jenkins, D. M. Holland, and O. A. Nøst (2006), Modeling ocean processes below Fimbulisen, Antarctica, *J. Geophys. Res.*, *111*, C01007, doi:10.1029/2005JC002915.

Suginohara, N. (1982), Coastal upwelling: Onshore-offshore circulation, Equatorward Coastal Jet and Poleward Undercurrent over a continental shelf-slope, *J. Phys. Oceanogr.*, *12*, 272–284, doi:10.1175/1520-0485(1982)012<0272:CUOCEC>2.0.CO;2.

Sverdrup, H. U. (1954), The currents off the coast of Queen Maud Land, *Nor. Geogr. Tidsskr.*, *14*(1), 239–249, doi:10.1080/00291955308542731.

Thoma, M., K. Grosfeld, and M. A. Lange (2006), Impact of the Eastern Weddell ice shelves on water masses in the eastern Weddell Sea, *J. Geophys. Res.*, *111*, C12010, doi:10.1029/2005JC003212.

Visbeck, M. (2002), Deep velocity profiling using lowered Acoustic Doppler Current Profilers: Bottom track and inverse solutions, *J. Atmos. Oceanic Technol.*, *19*, 794–807, doi:10.1175/1520-0426(2002)019<0794:DVPULA>2.0.CO;2.

Whitworth, T., III, A. H. Orsi, S.-J. Kim, and W. D. Nowlin Jr. (1998), Water masses and mixing near the Antarctic Slope Front, in *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, vol. 75, edited by S. S. Jacobs and R. F. Weiss, pp. 1–27, AGU, Washington, D. C.

Wooster, W. S., and J. H. Jones (1970), California Undercurrent off Baja California, *J. Mar. Res.*, *28*, 235–250.

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