Vertical Velocity from LADCP Data

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***Abstract*—Vertical velocity is important for ocean dynamics on a vast range of scales, from isotropic turbulence to the global overturning circulation, and directly affects transport of biogeochemical tracers. In spite of this importance, vertical-velocity measurements in the ocean are scarce. In an effort to remedy this situation, a new method has been developed to obtain full-depth profiles of vertical velocity from data collected with standard Lowered Acoustic Doppler Current Profiler (LADCP) systems, such as the ones used during the CLIVAR repeat hydrography sections. Data from LADCP systems, which consist of CTDs and ADCPs lowered on hydrographic wires, are typically processed to obtain full-depth profiles of horizontal velocity. The fundamental difficulty underlying LADCP data processing is that the velocity measurements are relative to the moving instrument package. In order to obtain absolute ocean velocities, the instrument motion must be removed from each ADCP velocity profile. One method for achieving this consists in vertically integrating vertical shear of velocity, which can easily be obtained from LADCP velocity records and is independent of instrument motion, and to reference the resulting baroclinic velocity profiles with external constraints, such as package motion derived from bottom tracking. While this method can, in principle, be applied both to horizontal and to vertical velocity data the resulting uncertainties of $\approx$3–5 $\mathrm{cm \cdot s^{-1}}$ are larger than the typical signal expected for vertical velocity in the ocean.**

In the new method presented here, vertical instrument motion is estimated from the temporal derivative of CTD pressure. While conceptually extremely simple, practical difficulties arise because vertical package motion (winch speed plus surface-wave induced heave) is usually associated with velocities on the order of $1\,\mathrm{m \cdot s^{-1}}$, whereas instantaneous vertical velocities in the ocean are typically 2 orders of magnitude smaller. Nevertheless, it is found that absolute vertical velocities accurate to $\approx 0.5\,\mathrm{cm \cdot s^{-1}}$ can be obtained with available off-the-shelf instrumentation (Teledyne/RDI Workhorse ADCP, SeaBird 9plus CTD), as long as suitably lowpass-filtered high-frequency CTD pressure data are matched carefully to the corresponding ADCP time series.

The new method can potentially be applied to available CTD/LADCP data from thousands of profiles collected all over the world's oceans. It is expected that the resulting vertical velocity data will provide novel insights into many dynamical processes, including internal waves, boundary currents, hydraulics, mesoscale and sub-mesoscale eddies, fronts, etc. It may furthermore be possible to use the vertical velocity data to improve "finestructure parameterization methods" that are increasingly being used to study turbulence and mixing from CTD/LADCP data.

I. INTRODUCTION

Vertical velocity is important for ocean dynamics on a vast range of scales, from the dissipation scale of turbulence to the global overturning circulation. It directly influences transport of biogeochemical tracers and larvæ of many marine organisms. In spite of this importance, vertical velocity measurements in the ocean are scarce. An important reason for this is that, for many years, velocity data in the ocean were collected primarily with mechanical current meters designed to measure the two horizontal components of the velocity field (e.g. [1]), presumably primarily for reasons of instrument cost and complexity. Vertical velocity measurements therefore had to be made with expensive custom instruments, such as the "vertical current meter," a neutrally buoyant float with horizontal propeller blades that cause the float to spin when encountering vertical flow [2], [3], or with mechanical current meters equipped with multiple rotors measuring flow along different axes (e.g. [4]). Such custom instruments were used primarily in the study of deep convection (e.g. [2]) and internal waves (e.g. [5]), where vertical velocities of several $\mathrm{cm \cdot s^{-1}}$ are common. Development of the Acoustic Doppler Current Profiler (ADCP) dramatically changed the way velocity in the ocean is measured. In addition to being suitable for moored deployments, ADCPs can also be installed on ships where they measure the velocity field of the upper ocean, and they can be lowered on CTD platforms to collect full-depth velocity profiles. Use of ADCPs has led to a great increase, in particular in spatial coverage of velocity measurements in the ocean.

An important property of ADCP measurements is that they yield profiles of all three spatial components of the velocity field. While there is some published work on vertical velocities from moored ADCP deployments, e.g. in the context of deep

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convection (e.g. [6]) and zooplankton diurnal migration (e.g. [7]), vertical velocity measurements from moored ADCPs are not frequently discussed in the literature. This may be due to a combination of the fact that moored ADCPs are often programmed with sampling intervals that are insufficient to resolve the internal-wave motions that dominate the vertical velocity field at most locations [5] and that unknown vertical mooring motion can potentially contaminate the measurements. Using fixed platforms and a high sampling rate can solve these problems as illustrated by the detection of upstream propagating hydraulic jumps associated with vertical-velocity pulses of several $\mathrm{cm \cdot s^{-1}}$ in a two-week bottom-mounted ADCP record from an overflow in the rift valley of the Mid-Atlantic Ridge [8].

In addition to replacing point-measurement current meters on moorings, ADCPs can be lowered together with CTDs in so-called "Lowered Acoustic Doppler Current Profiler (LADCP) systems," to derive full-depth profiles of horizontal velocities [9]–[13]. This is particularly important because the routine use of LADCP systems on hydrographic transects carried out in the context of the WOCE and CLIVAR programs, as well as during many other cruises, implies that there are tens of thousands of full-depth velocity profiles covering most regions of the global ocean. While the instantaneous horizontal velocity field at many locations in the ocean is dominated by tidal flows and/or near-inertial waves, LADCP measurements resolve at least part of the finescale-shear signal in the internal-wave band [14], making the available data set particularly useful in the context of diapycnal mixing and turbulence studies (e.g. [15]).

In the present paper, a new method for obtaining full-depth profiles of vertical velocity from standard CTD/LADCP measurements is presented (Section II). Applying the new method to data collected during a 7-hour yo-yo cast in the rift valley of the Mid-Atlantic Ridge (Section III) indicates that the method is associated with uncertainties of $\approx 0.5\,\mathrm{cm \cdot s^{-1}}$ and, therefore, suitable for measuring vertical velocities associated with internal waves and other energetic processes. The main results are discussed in Section IV. Several independent efforts to measure vertical velocity in the ocean are currently underway elsewhere. In addition to vertical velocity measurements using floats (e.g. [16], [17]), new methods have recently been developed to calculate vertical velocities with accuracies of $\approx 0.5\,\mathrm{cm \cdot s^{-1}}$ from data collected by autonomous gliders [18], [19]. Most closely related to the work presented here are on-going efforts to combine the time derivative of instrument depth and 3D relative velocity measurements from an acoustic travel time current meter on the free-fall HRP-2 full-depth fine/microstructure profiler of Woods Hole Oceanographic Institution to derive ocean vertical velocity profiles (J. Toole, personal communication).

II. VERTICAL VELOCITY FROM CTD/LADCP DATA

Obtaining profiles of vertical velocity from CTD/LADCP data is conceptually simple. With every acoustic pulse ("ping") an ADCP records four discrete profiles of along-beam velocities $b(\tau_i)$ relative to the instrument, where τ_i is the time delay between the acoustic pulse and the echo return for the velocities in bin i. Simultaneously recorded instrument attitude information (pitch, roll and heading) allow transformation from beam coordinates into a system that is fixed with respect to the horizontal component of the Earth's magnetic field lines and a "vertical" direction that is parallel to the instantaneous acceleration of the instrument. Using a sound-speed profile derived from the hydrographic measurements of conductivity, pressure and temperature recorded by the CTD, the ADCP velocities can be corrected for sound-speed variations, and the time delays τ_i can be converted into vertical distances from the transducer $\mathrm{d}z_i$, yielding the relative velocity profiles $u_r(\mathrm{d}z_i)$, $v_r(\mathrm{d}z_i)$ and $w_r(\mathrm{d}z_i)$ (for details, see [20]).

Using the latitude at which the data were obtained, the pressure measurements $p(t)$ from the CTD can be transformed into estimates of depth $z(t)$, which allow the vertical package velocity $w_{\mathrm{CTD}}(t)$ to be estimated by taking the time derivative. Combining the CTD and LADCP data, every LADCP bin i of every ping yields an estimate of absolute vertical velocity

$$w(z(t) + \mathrm{d}z_i + \mathrm{d}z_S) = w_r(\mathrm{d}z_i, t) - w_{\mathrm{CTD}}(t), \qquad (1)$$

where dz_S is the vertical offset between the ADCP transducer and the CTD pressure sensor. Expression (1) is valid for "downward-looking" ADCPs; for uplookers, $\mathrm{d}z_i$ has to be subtracted rather than added. The resulting estimates of absolute vertical velocity can be gridded in depth, yielding full-depth profiles. There are typically many erroneous velocity measurements in ADCP data collected on lowered platforms (e.g. [10]). In order to minimize the effect of these velocity "glitches" the raw data are "edited" before estimating averages and uncertainties at a given depth using median and mean-absolute-deviation statistics. Bins with fewer than 20 samples are not used. The following data-editing steps are carried out:

1) For each velocity sample Teledyne/RDI broadband ADCPs report a "correlation" value, which is a measure of the spectral similarity between the transmitted acoustic pulse and the returned echo. Beam velocities based on acoustic backscatter with correlations below 70 are discarded.
2) Experience with horizontal velocities from CTD/LADCP data indicates that the quality of the ADCP velocity measurements decreases with increasing instrument tilt. This effect can be caused by inaccurate pitch/roll sensors or perhaps also by horizontal accelerations misinterpreted as instrument tilt. Velocity profiles recorded at apparent instrument tilts $>10°$ from the vertical are discarded.
3) The individual beam-velocity measurements of a 4-beam ADCP can be linearly transformed to yield u, v and two separate estimates for w or, as is usually done in case of Teledyne/RDI ADCPs, a single estimate for w and a measure of the mutual consistency of the two underlying w estimates, called "error velocity." Velocity

samples with error velocities greater than $0.1\,\mathrm{m{\cdot}s^{-1}}$ are discarded.

4) Teledyne/RDI ADCPs must be programmed with the maximum along-beam velocity that can be measured — this parameter is called the "ambiguity velocity." In case of lowered deployments, the maximum expected velocity depends primarily on the vertical package motion, which is the sum of the winch speed and vertical heave associated with ship motion due to surface waves. When the measured relative velocity is greater than the ambiguity velocity, the measurement is aliased into the expected range, resulting in very large apparent vertical ocean velocities. Therefore, ocean velocities greater than $1\,\mathrm{m{\cdot}s^{-1}}$ are discarded.

The accuracy of this simple method for deriving vertical ocean velocity from CTD/LADCP measurements depends on the accuracy of ADCP-derived single-ping estimates of vertical velocity, on the number of samples in each depth bin of the final profile — this, in turn, depends on the mean vertical velocity of the CTD package (winch speed) and the sampling rate of the ADCP — and on the accuracy of the estimates of vertical package velocity from the CTD's pressure measurements. In order to derive accurate vertical package velocities the CTD must sample pressure at a high rate and with an accurate sensor. A high sampling rate is required because ship motion due to surface waves causes large vertical accelerations. In the main data set used here, the *rms* vertical acceleration is $0.24\,\mathrm{m{\cdot}s^{-2}}$ but in profiles from rough seas values twice as high are not uncommon. The most popular CTD system in use today is the SeaBird 911 system, which samples nominally[1] at $24\,\mathrm{Hz}$. Without synchronization between the CTD and the ADCP the expected value of the time mismatch between any ADCP ping and the closest CTD scan is $0.021\,\mathrm{s}$, which implies an expected package-velocity error of 0.5–$1\,\mathrm{cm{\cdot}s^{-1}}$ for *rms* vertical accelerations between 0.24 and $0.5\,\mathrm{m{\cdot}s^{-2}}$. Since even the upper limit of this range is smaller than the manufacturer-specified single-ping velocity standard deviation for the instrument considered here ($2\,\mathrm{cm{\cdot}s^{-1}}$ for $8\,\mathrm{m}$ bins collected with a Teledyne/RDI $300\,\mathrm{kHz}$ Workhorse ADCP), time mismatch is not expected to dominate the uncertainty in vertical velocity. For the data presented in this paper, CTD pressure measurement noise was suppressed by low-pass filtering the $24\,\mathrm{Hz}$ time series with a simple frequency-domain filter with a cut-off at $0.5\,\mathrm{Hz}$.

III. VERTICAL VELOCITY TIME SERIES IN AN OVERFLOW

The primary data set used in this paper to illustrate the validity of the new method described in Section II was collected during a "partial-depth yo-yo cast" in an overflow a few km downstream from a sill in the rift valley of the Mid-Atlantic Ridge near $37°15'$N $32°15'$W. The cast was carried out with a standard oceanographic rosette equipped with a SeaBird 9plus CTD and a Teledyne/RDI Workhorse $300\,\mathrm{kHz}$ ADCP installed in a downward-looking orientation. The ADCP was programmed with parameters known to work well for LADCP work ($10\,\mathrm{m}$ bins, pinging every $1.5\,\mathrm{s}$). Data collection took place on August 19, 2010, in the course of the F/S Poseidon cruise P403. During the 7-hour cast the CTD/LADCP package was lowered and raised 17 times between $1300\,\mathrm{m}$ and the seabed near $2100\,\mathrm{m}$ at $\approx 1\,\mathrm{m{\cdot}s^{-1}}$ winch speed. The station was occupied about $1.5\,\mathrm{km}$ downstream from a sill associated with strong, predominantly northward along-valley flow and high levels of turbulence and mixing [21], [22]). The CTD data were minimally processed with standard SeaBird Software and using nominal sensor calibrations to produce $24\,\mathrm{Hz}$ time series of pressure and sound speed. The left panel of Fig. 1 shows horizontal along-valley velocities[2] superimposed on arbitrarily spaced potential-density contours. Below $\approx 1800\,\mathrm{m}$ the overflow is essentially unidirectional and associated with peak velocities exceeding $20\,\mathrm{cm{\cdot}s^{-1}}$. Above that depth, the along-valley flow is much more variable, with both the time scales of this variability and the correspondence between along-valley velocities and density gradients suggesting internal gravity waves.

The right panel of Fig. 1 shows the vertical velocities (on a different scale) derived from the same data with the new method described in Section II, superimposed on the same isopycnal surfaces. Except for a thin region near the seabed, the active overflow layer is associated with downwelling up to $3\,\mathrm{cm{\cdot}s^{-1}}$, which is consistent with a dense gravity current flowing down the downstream flank of a sill. Above $1800\,\mathrm{m}$, there are regions of both up- and downwelling with magnitudes up to $3\,\mathrm{cm{\cdot}s^{-1}}$ and a pattern that is suggestive of internal gravity waves. The clear association above $1800\,\mathrm{m}$ between upwelling and density increase, as well as between downwelling and density decrease, provides strong qualitative support for the validity of the inferred vertical velocities. More quantitatively, the maximum upwelling velocity of $3\,\mathrm{cm{\cdot}s^{-1}}$ observed about 3 hours 45 minutes into the cast near $1700\,\mathrm{m}$ agrees closely with the vertical displacement of the corresponding isopycnal ($80\,\mathrm{m}$ uplift in 45 minutes). Similarly, the vertical velocity implied by the downward displacement of the isopycnals between 1300 and $1600\,\mathrm{m}$ beginning around 4 hours 15 minutes ($65 \pm 17\,\mathrm{m}$ in $133\,\mathrm{min}$, i.e. $-0.8 \pm 0.2\,\mathrm{cm{\cdot}s^{-1}}$) agrees with the mean vertical velocity calculated from the same section of the yo-yo data ($-1.1 \pm 0.5\,\mathrm{cm{\cdot}s^{-1}}$). Both these comparisons suggest that any errors in the CTD/LADCP-derived vertical velocities are smaller than $0.5\,\mathrm{cm{\cdot}s^{-1}}$.

Probably one of the most important future applications of the method presented here consists in the study of internal waves. In the yo-yo data shown in Fig. 1 the clearest suggestion for approximately regular wave-like motion is apparent near $1600\,\mathrm{m}$, in particular during the first 4 hours of the cast. Based on estimates in $25\,\mathrm{m}$-thick layers the buoyancy period

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[1] Unfortunately, SeaBird 911 systems simply assume a $24\,\mathrm{Hz}$ sampling rate and time-stamp the received CTD scans in the deck box. If there are communications problems, scans can be dropped, which results in incorrect time stamps and an apparent drift of the CTD clock when CTD time series are matched to LADCP time series.

[2] The horizontal velocities were derived with a re-implementation of the shear method (e.g. [10]) that draws heavily on the UH code by E. Firing. Bottom tracking was used to reference the relative velocity profiles.

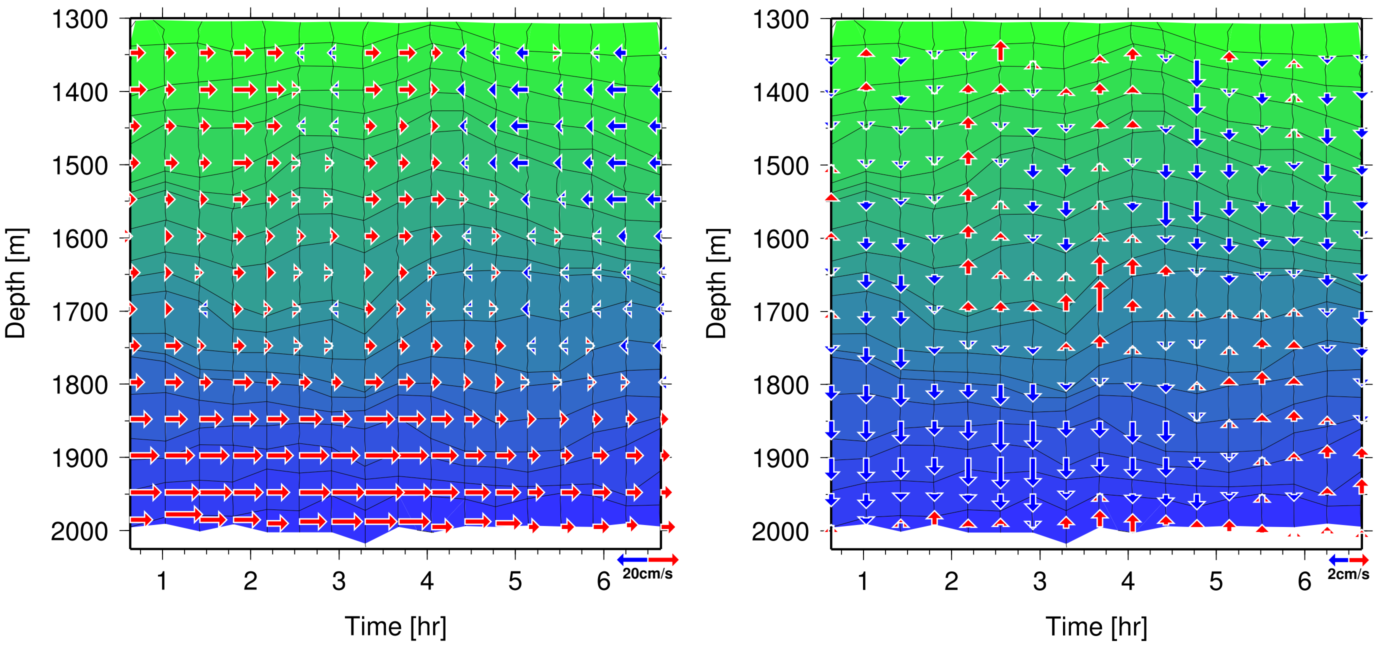

Fig. 1. Potential density (shading and contours) and LADCP-derived velocities (arrows) from a CTD/LADCP yo-yo cast carried out in the rift valley of the Mid-Atlantic Ridge $\approx 1.5\,\mathrm{km}$ downstream from an overflow sill. Left panel: Approximately northward along-valley velocities. Right panel: Vertical velocities calculated with the new method described in this paper. Note the different velocity scales for the two panels.

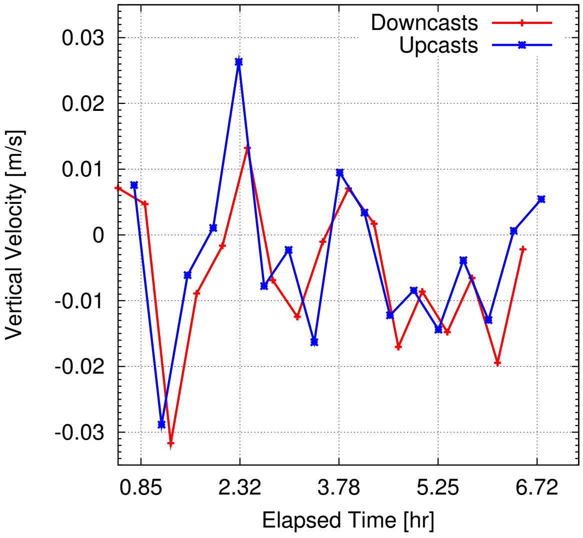

Fig. 2. Vertical velocity time series at $1600\,\mathrm{m}$, estimated separately from down- and from upcast data. The horizontal gridline interval equals the mean buoyancy period at this depth ($88\,\mathrm{min}$).

near $1600\,\mathrm{m}$ during the cast was $88 \pm 23\,\mathrm{min}$. Independent time series of vertical velocities from the down- and upcasts at that depth both show wave-like motion with a time scale that closely matches the mean buoyancy period (Fig. 2). The clarity of the pattern provides additional support for the validity of the new method. Treating the down- and upcast data separately is useful because it allows constraining any measurement biases that depend on the vertical motion of the package, including ADCP-velocity measurement bias. Due to the different direction of the winch the vertical velocity ranges measured by the ADCP during down- and upcasts are markedly different. Any velocity-dependent bias errors will therefore manifest themselves as a consistent difference between the down- and the upcast-derived vertical velocities. While somewhat ambiguous (the down- and upcast measurements at $1600\,\mathrm{m}$ are not coincident in time) Fig. 2 nevertheless suggests that there is a small bias ($<0.2\,\mathrm{cm{\cdot}s^{-1}}$, if the down- and upcast biases are assumed to be of similar magnitude).

Near the seabed it is possible to calculate an alternate set of vertical velocity profiles from LADCP data alone (i.e. without using the CTD pressure measurements) by bottom tracking, i.e. by directly determining the vertical package velocity from the Doppler shift of the acoustic echo reflected off the seabed. In the case of the yo-yo data set presented here, the two estimates of vertical velocity near the seabed agree quite closely, both in terms of magnitude and vertical shear (Fig. 3). Errors associated with both methods contribute to the *rms* vertical velocity discrepancy of $0.8\,\mathrm{cm{\cdot}s^{-1}}$. It is interesting to note that the profiles associated with strong horizontal velocity near the seabed (all but the last 5, c.f. Fig. 1, left panel) are associated with significant vertical convergence below $1900\,\mathrm{m}$ but the others are not. The fact that this convergence appears in both sets of vertical velocity estimates suggests that the observation is real, rather than a processing artifact.

The vertical gradient of vertical velocity can be estimated in another way, using "standard" shear-method LADCP processing software [10]. In particular, the implementation by E. Firing at the University of Hawaii uses "diagnostic w profiles,"

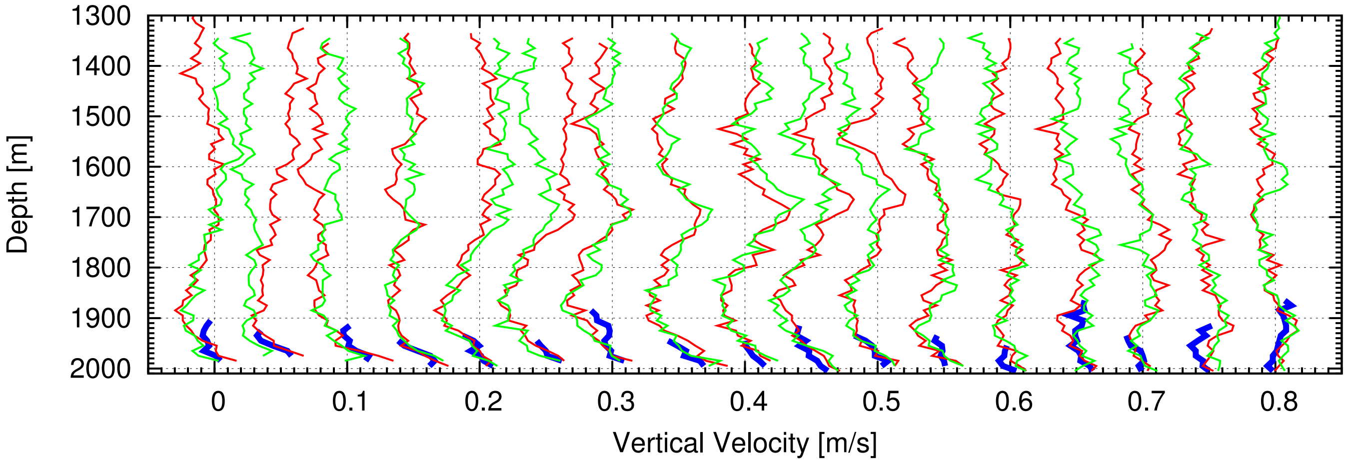

Fig. 3. Profiles of vertical velocity; subsequent profiles are horizontally offset by $5\,\mathrm{cm\cdot s^{-1}}$. Red: Downcasts. Green: Upcasts. Blue: Bottom-tracked profiles, calculated without using the CTD pressure data.

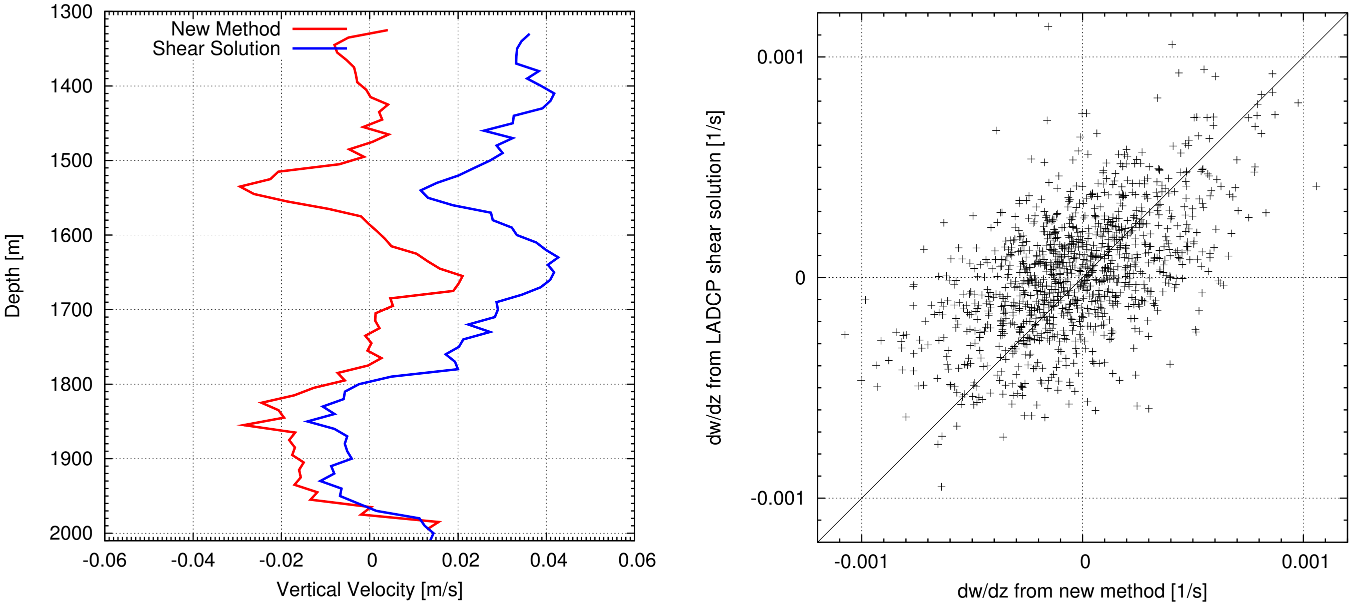

Fig. 4. Comparison of results from the new method with "diagnostic w" calculated using the shear method of LADCP processing. Left panel: Example profiles of vertical velocity. Right panel: Scatter plot of $\partial w/\partial z$ at $10\,\mathrm{m}$ vertical resolution.

derived by vertically integrating $\partial w/\partial z$, to help detect casts with bad LADCP data. While $\partial w/\partial z$ calculated with the shear method is not entirely independent of the vertical gradient of w calculated with the new method — they are based on the same LADCP measurements — it is nevertheless a useful quantity, because it is derived much more directly and, in particular, without having to take instrument motion into account. Additionally, data editing in the UH implementation of the shear method is based on much more elaborate screening algorithms than the simple data editing steps described in Section II above. The left panel of Fig. 4 shows an example profile contrasting shear-method derived "diagnostic vertical velocity" (blue) with the corresponding solution derived with the new method presented here (red). While the "diagnostic w profile" is associated with an unrealistic low-vertical-mode gradient of several $\mathrm{cm\cdot s^{-1}}$ over the $700\,\mathrm{m}$ vertical extent, the high-wavenumber signals apparent in the two profiles agree quite well. This visual inference is supported by a scatter plot of all $10\,\mathrm{m}$ $\partial w/\partial z$ values from the yo-yo cast (Fig. 4, right panel).

IV. DISCUSSION

The CTD/LADCP data collected during a 7-hour partial-depth yo-yo cast in an overflow in the rift valley of the MAR reveal a dynamic environment characterized by a swift gravity current flowing down the lee slope of a sill, underlying a layer of comparatively weak low-frequency flow dominated by motions associated with internal gravity waves. The horizontal

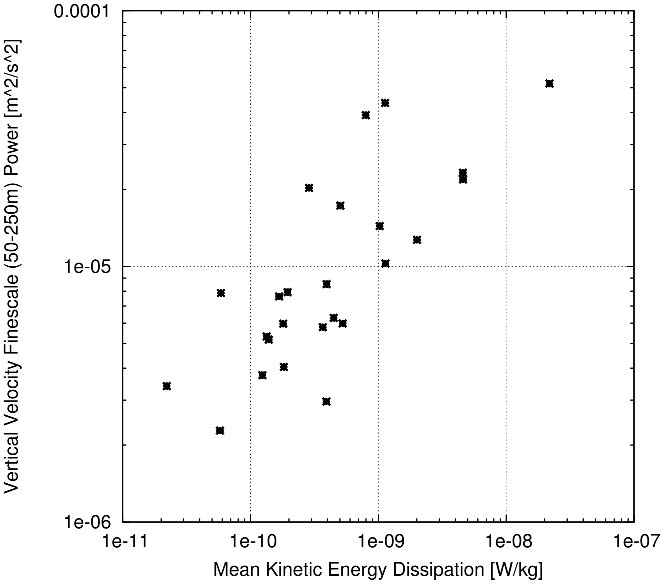

Fig. 5. Scatter plot of finescale vertical-velocity energy vs. microstructure-derived kinetic energy dissipation in the bottom 320 m of all simultaneous full-depth CTD/LADCP/microstructure profiles collected in the Southern Ocean during the DIMES UK2 cruise (December 2010–January 2011).

velocities in the overflow layer are much stronger than the corresponding vertical velocities ($13\,\mathrm{cm{\cdot}s^{-1}}$ vs. $1.5\,\mathrm{cm{\cdot}s^{-1}}$ *rms),* whereas the difference is less pronounced above $1800\,\mathrm{m}$ ($5.5\,\mathrm{cm{\cdot}s^{-1}}$ vs. $1.1\,\mathrm{cm{\cdot}s^{-1}}$ *rms).* While it would have been possible to derive qualitatively similar inferences from the horizontal velocities and the evolution of the density field alone, the availability of vertical velocities significantly strengthens the conclusions and, in particular, allows quantification of important aspects of the dynamics.

Comparisons between the vertical velocities derived separately from the down- and upcasts and between those calculated with the new method and bottom-tracked velocities near the seabed indicate an accuracy of $\approx 0.5\,\mathrm{cm{\cdot}s^{-1}}$, which is similar to the accuracy estimated for vertical velocities determined from autonomous glider data [18], [19]. In contrast to horizontal LADCP velocities, the vertical-velocity uncertainties should be approximately uniform throughout the water column, at least as long as the number of samples contributing to each bin of the final profile does not vary very much due to changes in winch speed or acoustic scattering environment. In case of the data considered here, each $5\,\mathrm{m}$ vertical bin of each down- and upcast contains $\approx 40 \pm 10$ individual vertical velocity samples. This implies that random single-ping ADCP measurement errors of $2\,\mathrm{cm{\cdot}s^{-1}}$ introduce an uncertainty of $\approx 0.3\,\mathrm{cm{\cdot}s^{-1}}$ to the final vertical velocity estimates. However, it must be noted that any errors associated with the vertical package-motion estimates derived from the CTD pressure measurements have not yet been considered.

Vertical velocities in the ocean are important in a variety of different contexts, and on a large range of scales. The apparent accuracy of the new method presented here restricts it to the study of energetic dynamical processes, such as overflow hydraulics and internal waves (including high-mode internal tides, lee waves, solitons, $\ldots$) and perhaps also fronts and sub-mesoscale vortices, in particular in the upper ocean. There are theoretical considerations suggesting that vertical velocities are particularly suited to the study of internal gravity waves [5], which suggests that the new method may be particularly useful in the context of finestructure parameterizations of diapycnal mixing. This inference is supported by a preliminary analysis of CTD/LADCP/microstructure data collected during the DIMES UK2 cruise (led by M. Meredith and A. Naveira-Garabato), which shows a clear correlation between vertical-velocity finestructure and kinetic-energy dissipation near the sea bed (Fig. 5).

While additional work is needed to validate the vertical velocity estimates derived with the new method presented here and to quantify the uncertainties more accurately, the results presented above suggest that useful vertical velocity profiles in the ocean can be collected with standard CTD/LADCP instrumentation. It is particularly important to note that the new method can, in principle, be applied to the large set of existing CTD/LADCP data.

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REFERENCES

[1] W. J. Emery and R. E. Thomson, *Data Analysis Methods in Physical Oceanography*. Pergamon, 1997.

[2] A. D. Voorhis and D. C. Webb, "Large vertical currents observed in a winter sinking region of the North Western Mediterranean," *Cahiers Oceanographique*, 1970.

[3] D. C. Webb, D. L. Dorson, and A. D. Voorhis, "A new instrument for the measurement of vertical currents in the ocean," *Proceedings of the Conference on Electronic Engineering in Ocean Technology*, September 1971.

[4] J. Dahlen and J. Shillingford, "The Microscale Sensing Array," *J. Geophys. Res.*, vol. 83, pp. 3108–3112, 1978.

[5] C. C. Eriksen, “Measuremetns and models of fine structure, internal gravity waves, and wave breaking in the deep ocean,” *J. Geophys. Res.*, vol. 83, pp. 2989–3009, 1978.
[6] F. Schott, M. Visbeck, and J. Fischer, “Observations of vertical currents and convection in the Central Greenland Sea during the winter of 1988–1989,” *J. Geophys. Res.*, vol. 98, pp. 14 404–14 421, 1993.
[7] J. Fischer and M. Visbeck, “Seasonal variation of the daily zooplankton migration in the Greenland Sea,” *Deep Sea Res. I*, vol. 40, pp. 1547–1557, 1993.
[8] A. M. Thurnherr and S. Thomsen, “Mixing associated with upstream-propagating hydraulic jumps near an overflow sill,” *in prep.*, 2011.
[9] E. Firing and R. Gordon, “Deep ocean acoustic Doppler current profiling,” *IEEE Fourth Working Conf. on Current Measurements*, pp. 192–201., 1990.
[10] J. Fischer and M. Visbeck, “Deep velocity profiling with self-contained ADCPs,” *J. Atm. Oc. Tech.*, vol. 10, pp. 764–773, 1993.
[11] B. A. King, E. Firing, and T. M. Joyce, “Shipboard observations during WOCE,” in *Ocean Circulation & Climate*, G. Siedler, J. Church, and J. Gould, Eds. Academic Press, 2001, pp. 99–122.
[12] M. Visbeck, “Deep velocity profiling using Lowered Acoustic Doppler Current Profilers: Bottom track and inverse solutions,” *J. Atm. Oc. Tech.*, vol. 19, pp. 794–807, 2002.
[13] A. M. Thurnherr, “A practical assessment of uncertainties in full-depth velocity profiles obtained with Teledyne/RDI Workhorse Acoustic Doppler Current Profilers,” *J. Atm. Oc. Tech.*, vol. 27, pp. 1215–1227, 2010.
[14] K. Polzin, E. Kunze, J. Hummon, and E. Firing, “The finescale response of lowered ADCP velocity profiles,” *J. Atm. Oc. Tech.*, vol. 19, pp. 205–224, 2002.
[15] E. Kunze, E. Firing, J. M. Hummon, T. K. Chereskin, and A. M. Thurnherr, “Global abyssal mixing inferred from Lowered ADCP shear and CTD strain profiles,” *J. Phys. Oceanogr.*, vol. 36, pp. 1553–1576, 2006.
[16] K. L. Lavender, R. E. Davis, and W. B. Owens, “Observations of open-ocean deep convection in the Labrador Sea from subsurface floats,” *J. Phys. Oceanogr.*, vol. 32, pp. 511–526, 2002.
[17] E. L. Steffen and E. A. D’Asaro, “Deep convection in the Labrador Sea as observed by Lagrangian floats,” *J. Phys. Oceanogr.*, vol. 32, pp. 475–492, 2002.
[18] L. Merckelbach, D. Smeed, and G. Griffiths, “Vertical water velocities from underwater gliders,” *J. Atm. Oc. Tech.*, vol. 27, pp. 547–563, 2010.
[19] E. Frajka-Williams, C. C. Eriksen, P. B. Rhines, and R. R. Harcourt, “Determining vertical water velocities from Seaglider,” *J. Atm. Oc. Tech. (under review)*, 2011.
[20] RD Instruments, “ADCP coordinate transformation: Formulas and calculations,” *RDI Manual*, 1998.
[21] L. C. St. Laurent and A. M. Thurnherr, “Intense mixing of lower thermocline water on the crest of the Mid-Atlantic Ridge,” *Nature*, vol. 448, pp. 680–683, 2007.
[22] A. M. Thurnherr, G. Reverdin, P. Bouruet-Aubertot, L. St. Laurent, A. Vangriesheim, and V. Ballu, “Hydrography and flow in the Lucky Strike segment of the Mid-Atlantic Ridge,” *J. Mar. Res.*, vol. 66, pp. 347–372, 2008.