



HAL
open science

Measuring vertical velocities with ADCPs in low-energy ocean

Caroline Comby, Stéphanie Barrillon, Jean-Luc Fuda, Andrea M. Doglioli, Roxane Tzortzis, Gérald Grégori, Melilotus Thyssen, Anne Petrenko

► **To cite this version:**

Caroline Comby, Stéphanie Barrillon, Jean-Luc Fuda, Andrea M. Doglioli, Roxane Tzortzis, et al.. Measuring vertical velocities with ADCPs in low-energy ocean. *Journal of Atmospheric and Oceanic Technology*, 2022, 39 (11), pp.1669-1684. 10.1175/JTECH-D-21-0180.1 . hal-03746757

HAL Id: hal-03746757

<https://amu.hal.science/hal-03746757>

Submitted on 2 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Measuring vertical velocities with ADCPs in low-energy ocean**

2 Caroline Comby,^a Stéphanie Barrillon,^a Jean-Luc Fuda,^a Andrea M. Doglioli,^a Roxane
3 Tzortzis,^a Gérald Grégori,^a Melilotus Thyssen,^a and Anne A. Petrenko^a

4 ^a*Aix Marseille Univ., Université de Toulon, CNRS, IRD, MIO UM 110, 13288, Marseille, France*

5 *Corresponding author: Caroline Comby, caroline.comby@mio.osupytheas.fr*

6 ABSTRACT: Vertical velocities knowledge is essential to study fine-scale dynamics in the surface
7 layers of the ocean and to understand their impact on biological production mechanisms. However,
8 these vertical velocities have long been neglected, simply parameterized, or considered as not
9 measurable, due mainly to their order of magnitude ($< \text{mm s}^{-1}$ up to cm s^{-1}), generally much lower
10 than the one of the horizontal velocities (cm s^{-1} to dm s^{-1}), hence the challenge of their *in situ*
11 measurement. In this paper, we present an upgraded method for direct *in situ* measurement of
12 vertical velocities using data from different Acoustic Doppler Current Profilers (ADCPs) associated
13 with CTD probes, and we perform a comparative analysis of the results obtained by this method.
14 The analyzed data were collected during the FUMSECK cruise, from three ADCPs: two Workhorse
15 (conventional ADCPs), one lowered on a carousel and the other deployed in free-fall mode, and
16 one Sentinel V (a new generation ADCP with four classical beams and a fifth vertical beam),
17 also lowered on a carousel. Our analyses provide profiles of vertical velocities on the order of
18 mm s^{-1} , as expected, with standard deviations of a few mm s^{-1} . While the fifth beam of the Sentinel
19 V exhibits a better accuracy than conventional ADCPs, the free-fall technique provides a more
20 accurate measurement compared to the carousel technique. Finally, this innovative study opens up
21 the possibility to perform simple and direct *in situ* measurements of vertical velocities, coupling
22 the free-fall technique with a five-beam ADCP.

23 1. Introduction

24 The study of the oceanic vertical velocities arises increasing interest in the oceanographic
25 community. Numerous studies are conducted in high-energy ocean regions, with estimation
26 of large vertical motions. Vertical velocities are generally estimated by the omega equation,
27 hereinafter noted ω -equation (Tintoré et al. 1991; Pollard and Regier 1992; Fiekas et al. 1994;
28 Strass 1994; Pinot et al. 1996; Shearman et al. 1999; Allen et al. 2001; Giordani et al. 2006;
29 Canuto and Cheng 2017). According to these studies, performed in high-energy circulation areas
30 (California Current System, Alboran Sea, Northeast Atlantic during the winter season, etc.), the
31 authors report vertical velocities of 4 to 40 m day⁻¹ ($\simeq 10^{-5}$ to 10^{-4} m s⁻¹). Yu et al. (2019) used the
32 non-diffusive density equation for measurements at fixed moorings and estimated sub-mesoscale
33 vertical velocities of 38.0 ± 6.9 m day⁻¹ ($\simeq 10^{-4}$ m s⁻¹). Lindstrom and Watts (1994) used, among
34 others comparative methods, the heat equation and thermal wind imbalance combining temperature
35 and current measurements. On the eastern boundary of the Gulf Stream, these authors estimated
36 vertical velocities reaching values of $1 - 2 \cdot 10^{-3}$ m s⁻¹, with rare values up to $3 \cdot 10^{-3}$ m s⁻¹.

37 Bower and Rossby (1989), Lindstrom and Watts (1994), Steffen and D'Asaro (2002), and D'Asaro
38 et al. (2017) directly integrate vertical displacement measurements of their Lagrangian drifters,
39 and obtain vertical velocities ranging from 10^{-3} to 10^{-2} m s⁻¹. Merckelbach et al. (2010), Frajka-
40 Williams et al. (2011), Fuda et al. (2013), and Margirier et al. (2017) analyze the vertical velocity
41 anomalies of gliders with respect to their flight models. According to these studies, the authors
42 determine average vertical velocities of 1 to $6 \cdot 10^{-2}$ m s⁻¹. For rare deep convection events, oceanic
43 vertical velocities reach 0.1 m s⁻¹ according to Merckelbach et al. (2010) and 0.18 m s⁻¹ according
44 to Margirier et al. (2017). These techniques, based on the vertical displacement integration of
45 immersed instruments, are not widely spread but enable to state vertical velocities ranging from
46 10^{-3} to 10^{-1} m s⁻¹.

47 Direct *in situ* measurement of vertical velocities with current-meters is rather limited in the
48 literature (Thurnherr 2011; D'Asaro et al. 2017; Tarry et al. 2021). For local studies in regions
49 with strong vertical displacements, vertical velocities are quite well characterized (e.g. deep winter
50 convection in Schott and Leaman (1991), and Schott et al. (1996) $\simeq 0.05 - 0.1$ m s⁻¹, or strong
51 internal waves in Lien et al. (2005) up to 0.2 m s⁻¹). However, for low-energy ocean regions,

52 representing the majority of the global ocean, direct *in situ* measurement of vertical velocities is
53 still currently one of the biggest challenges in physical oceanography.

54 In this study, we estimate vertical velocities based on a method suitable for a low-energy region
55 characterized by finescale structures, where we expected a magnitude of few mm s^{-1} . The finescales,
56 grouping the meso- and sub-mesoscales, are characterized by typical spatio-temporal scales: a
57 horizontal spatial scale ranging from 1 to 100 km, a vertical spatial scale which can extend from
58 0.1 to 1 km deep (Thomas et al. 2008; McWilliams 2016; Ruiz et al. 2019), as well as a lifetime
59 ranging from a few days to a few weeks for the physical and biological processes generated in
60 these structures (Giordani et al. 2006; Ferrari and Wunsch 2009). In addition, a Rossby number
61 close to one ($\text{Ro} \approx 1$) is typical of fine-scale processes and involves an oceanic circulation which
62 deviates from geostrophic balance with the emergence of vertical velocities (Klein and Lapeyre
63 2009; Mahadevan and Tandon 2006; Sasaki et al. 2014). The general interest in finescale and, more
64 precisely, in the determination of vertical velocities, is explained by their key role in global oceanic
65 balance and their impact on the vertical transfer of nutrients and carbon budget despite their low
66 intensity (Martin et al. 2001; Lévy et al. 2012; Mahadevan 2016; McGillicuddy 2016; Lévy et al.
67 2018; Rousselet et al. 2019; Boyd et al. 2019). With the increasing global warming issues linked
68 to the forcing of the carbon cycle by anthropogenic activities, the estimation of vertical velocities
69 becomes an essential information for a better representation of biogeochemical budgets.

70 The French-American SWOT mission (Surface and Water Ocean Topography) will enable very
71 high spatio-temporal resolution altimetry measurements, opening up the possibility of evaluating
72 vertical velocity by satellite. These SWOT-derived vertical velocities will have to be compared with
73 *in situ* measurements. Hence, in the framework of BioSWOT, a component of the SWOT project,
74 we aim at developing dedicated instruments and methodologies for vertical velocity measurement.
75 BioSWOT main objective is to study the finescale coupling between physics and biology. The
76 Mediterranean Institute of Oceanography has already been principal investigator of two short
77 BioSWOT cruises (2015, 2019). In 2015, during the OSCAHR cruise (Observing Submesoscale
78 Coupling At High Resolution, Doglioli 2015), we studied a finescale structure located in the
79 Ligurian Sea (northeast of the western Mediterranean Sea) and found a link between biology and
80 vertical velocities obtained with the ω -equation (Rousselet et al. 2019).

81 The present study was performed in the framework of the FUMSECK cruise (Facilities for
82 Updating the Mediterranean Submesoscale - Ecosystem Coupling Knowledge, Barrillon 2019),
83 back in this same study area. One of the main objectives of this second cruise, carried out during
84 spring 2019 in the Ligurian Sea, was to directly measure the vertical component of the current in
85 the ocean surface layer by deploying classical instruments as well as new prototypes.

86 The different datasets acquired during the FUMSECK cruise aim at obtaining a direct *in situ*
87 measurement based on four different methods using three Acoustic Doppler Current Profilers
88 (ADCP): two classic Workhorse and one Sentinel V (next generation ADCP providing two types
89 of vertical velocity measurements), and ultimately, comparing the four methods.

90 The paper is structured as follows. In Section 2, after a general description of the sampling
91 methodology, we present a single, upgraded and generalized method for processing acoustic data
92 to obtain vertical velocities. In Section 3, we analyze the ADCPs measurements acquired with the
93 four different methods mentioned above. Following the discussion of these results (Section 4), the
94 main outcome of this work is to recommend a platform, which measurement sensitivity is sufficient
95 to measure vertical velocities on the order of several 10^{-3} to 10^{-2} m s⁻¹. In order to establish a solid
96 foundation for the study, we also provide a detailed analysis of the potential sources of error in the
97 measurements.

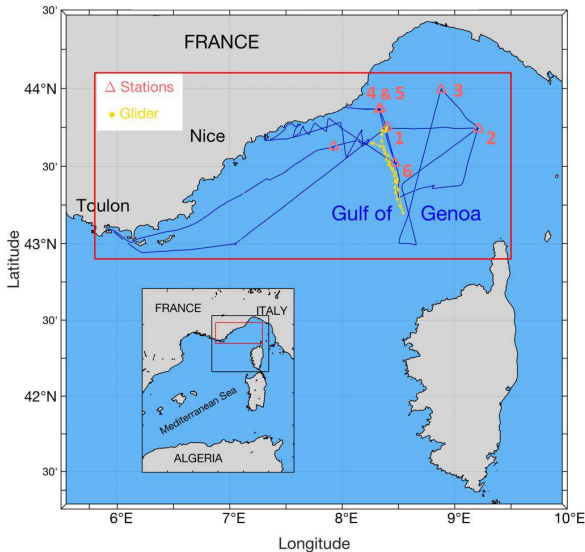
98 **2. Data and Methods**

99 *a. Sampling methodology*

103 The FUMSECK cruise took place from 30 April to 7 May 2019, in the Ligurian Sea, between 43
104 to 44° N and 7 to 10° E (Fig.1). Three ADCPs, developed by Teledyne RD Instrument, were used *in*
105 *situ* during this study: i) two Workhorse 300 kHz (ADCP with the standard four beams), deployed
106 according to one method each (either lowered from the CTD-ADCP package on a carousel, or
107 dropped in free fall), and ii) one Sentinel V 500 kHz (ADCP with a vertical fifth beam to measure
108 directly the vertical component of the current, in addition to the four conventional beams).

109 To simplify the reading thereafter, we will use the following terms to distinguish both the
110 instruments and their use:

- 111 - L-ADCP, corresponding to the lowered Workhorse;



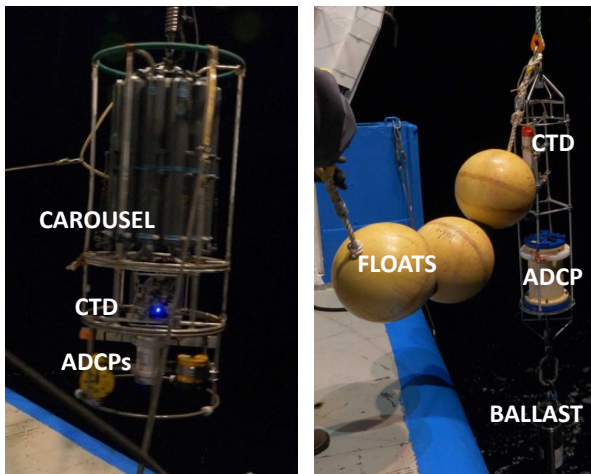
100 FIG. 1. Positioning of the vertical velocity stations (in orange, with their number) and round-trip transect of
 101 the SeaExplorer glider (yellow dots). These data are superimposed on the route traveled by the oceanographic
 102 vessel Tethys II during the FUMSECK cruise (blue).

- 112 - L-V4, corresponding to the measurements from the four conventional beams of the lowered
 113 Sentinel V;
- 114 - L-V5th, corresponding to the measurements from the fifth beam (vertical beam) of the same
 115 lowered Sentinel V;
- 116 - FF-ADCP, corresponding to the free-falling Workhorse.

117 The L-ADCP and the Sentinel V were fixed under a SeaBird SBE 911+ Conductivity - Tem-
 118 perature - Depth (CTD) probe (acquisition frequency at 24 Hz), and used, only one ADCP at
 119 a time, to perform profiles within the first 150 meters of the water column at six chosen sta-
 120 tions. The two types of ADCPs have the same data sampling frequency of 1 Hz. The FF-
 121 ADCP was associated with a RBR Concerto CTD probe ([https://rbr-global.com/products/
 122 standard-loggers/rbrduo-ct](https://rbr-global.com/products/standard-loggers/rbrduo-ct)) which sampling frequency was set to correspond to the one of
 123 the Workhorse ADCP (1 Hz). In addition, all the instruments have been parameterized to perform
 124 vertical velocity measurements in 5-m thick cells.

125 Note that the locations of the stations were decided in order to grid the study area by carrying out
126 butterfly-shaped transects, as shown in Fig.1. Moreover, the positioning of the stations was chosen
127 to sample a variety of situations, in a region characterized by a low-energy cyclonic recirculation
128 (Astraldi et al. 1990; Millot 1999; Rousselet et al. 2019), bounded by a coastal southwestward
129 current (the Northern Current) (Millot 1999; Petrenko 2003; Meloni et al. 2019).

132 The station measurements were performed first with an immersion of the CTD-ADCP package
133 (Fig.2 a) at a fixed depth (about 10 m) for 10 minutes, followed by three successive vertical profiles
134 between the surface and 150 m. This sampling technique has been used for several decades to
135 establish vertical profiles of horizontal currents (Weller et al. 1990; Firing and Gordon 1990;
136 Fischer and Visbeck 1993; Polzin et al. 2002), but has only rarely been applied specifically for the
137 measurement of vertical velocities (Thurnherr 2011). In order to avoid any acoustic interference
138 between the two lowered instruments, the L-ADCP and the Sentinel V were used alternately on
each of the stations during the cruise.



130 FIG. 2. ADCP deployment configuration for the lowered technique (left panel) and the free-fall technique
131 (right panel).

139
140 After these measurements, series of three to five profiles were performed with the ADCP dropped
141 in free-fall (FF-ADCP). The FF-ADCP, also associated with a CTD probe (Fig.2 b), was connected
142 to the ship by a simple rope with enough slack to allow the package to fall freely in the water
143 column, before being raised back to the ocean surface thanks to the rope.

144 Note that the first station (station 1) was not sampled with the FF-ADCP, and one other station
145 (station 4) was sampled only with the Sentinel V and the FF-ADCP, due to a swell that was too
146 strong to carry out safely the second sampling with the L-ADCP.

147 *b. Conventional 4 beams ADCP dataset processing*

148 When the ADCP is submerged in the water column, its orientation is free to deviate from the
149 gravimetric vertical direction due to several forces applied to the CTD-ADCP package. In particular,
150 when the instruments are connected to the boat by the electric carrier cable, the restoring force of
151 the boat, as well as the forces due to the horizontal currents and the swell, are acting on the package,
152 in addition to its weight. All these forces acting on the instrument package cause deviations relative
153 to the gravimetric vertical direction that must be taken into account when processing data from
154 the ADCPs. Otherwise, they cause errors in the vertical velocity computation. The analysis
155 chain described below corrects for these anomalies, subtracts the instrument vertical velocity, and
156 synchronizes it with the CTD data.

157 1) STEPS 0 AND 1: PREPARATION OF DATASETS

158 Before performing any processing on the measurements, preliminary steps are performed.

159 Indeed, the analysis method involving two sets of data (CTD and ADCP data), it is essential to
160 synchronize these two sequences (step 0).

161 To do so, if the data acquisition by the CTD probe is made at a higher frequency than the one
162 made by the ADCP (e.g. CTD Seabird at 24 Hz versus Workhorse and Sentinel V at 1 Hz), a time
163 smoothing over a period similar to the acquisition rate of the ADCP (here 1 Hz) is applied to the
164 CTD sequence.

165 Following this optional smoothing, the CTD and ADCP sequences are systematically synchro-
166 nized in time with the following method: i) the distribution of the pressure differences between
167 the two datasets is evaluated as a function of a time offset imposed on one of the sequences, ii) the
168 synchronization is considered optimal when the standard deviation of this distribution is minimal.
169 Great attention is paid to possible data gaps in each instrument time series, which would induce
170 the desynchronization of the subsequent data.

171 Then, according to different quality criteria, a data selection is applied in order to discard
172 potentially erroneous measurements (step 1). These quality criteria are based on:

173 - A retrodiffused echo intensity greater than 40 counts. This inferior limit is fixed by the
174 instrument manufacturer RDI. The counts represent a linear scale on which retrodiffused echo
175 intensity is encoded, and the threshold of 40 counts equals about 16 % of emitted signal
176 intensity.

177 - A correlation between the emitted and retrodiffused signal greater than 64 counts. This
178 inferior limit is fixed by the instrument manufacturer RDI. Here, the counts represent a linear
179 scale on which signals correlation is encoded, and the threshold of 64 counts equals about
180 25 % of correlation. This correlation threshold also allows to locate possible recordings
181 of acoustic interference by punctual decreases in the correlation value. In the presence of
182 acoustic interference, their estimated constant velocity propagation in the recordings is used
183 to easily isolate them from the rest of the vertical velocity recordings and then remove them
184 by NaN flag.

185 - An absolute error velocity lower than 0.1 m s^{-1} . Two vertical velocity estimates being
186 calculated by the two pairs of opposed beams, the error velocity represents the difference
187 between the two estimates.

188 2) STEP 2: REFERENCE FRAME TRANSFORMATION AND DEPTH VECTOR PROJECTION

189 As mentioned above, when the ADCP is immersed in the water column, its vertical axis is free
190 to deviate from the gravimetric vertical direction. The magnetic compass integrated in the ADCP
191 allows to determine the orientation of the instrument in the water column. This orientation is
192 characterized by three attitude angles, also called gimbal angles: pitch (θ_P), roll (θ_R) and heading
193 (θ_H).

194 The recording of vertical velocities by the four beams having been configured in Earth coordinates
195 (w_t , terrestrial reference frame), these data must be associated with the appropriate depths in the
196 same reference frame. In order to obtain the Earth coordinates of the depth vector (x_t, y_t, z_t), the
197 principle is to project the tilted ADCP acoustic cell ($(0, 0, z_s)$ in the ADCP reference frame) on the

198 vertical axis, using the attitude angles as shown in the following equation:

$$z_t = \cos \theta_P \cdot \cos \theta_R \cdot z_s \quad (1)$$

199 3) STEP 3: ABSOLUTE VERTICAL VELOCITIES

200 Once the depth has been projected, the oceanic vertical velocity is calculated in the water column
 201 (w). For this step, we consider that the measurement of the vertical component of the velocity,
 202 given by the ADCP configuration in Earth coordinates (w_t , zenith-oriented vertical axis), is the
 203 result of two vertical components, expressed in the same frame of reference (also zenith-oriented
 204 vertical axis):

- 205 - the vertical velocity, w , of the oceanic current in the water column ;
- 206 - the vertical velocity of the instruments package, w_{pkg} , calculated from the hydrostatic approx-
 207 imation, considering:

$$w_{\text{pkg}} = -\frac{1}{\rho g} \frac{\partial p}{\partial t} \quad (2)$$

208 where p is pressure, ρ density, and g the gravitational acceleration constant.

209 The dynamic pressure, resulting from the instrument vertical velocity estimated at 1 m s^{-1} in
 210 the lowered method and 0.3 m s^{-1} in the free fall method, reaches respectively 500 Pa and 50 Pa,
 211 representing an error on the depth estimation of about 5 cm and 0.5 cm, which is below the accuracy
 212 of the pressure sensors (see Table 1). This justifies the use of the hydrostatic hypothesis in this
 study.

TABLE 1. Characteristics of the pressure sensors

Sensor	SBE 911	RBR concerto	Sentinel V50	WorkHorse 300	WorkHorse 300
Technique	Lowered	Free Fall	L-V4 & L-V5	L-ADCP	FF-ADCP
full scale [m]	6800	750	300	6000	200
accuracy [m]	1.02	0.365	0.3	15	0.5
resolution [cm]	6.8	0.75	0.1	15	0.5

213
 214 Each ADCP has its own pressure sensor, and each of the sampling methods (lowered and
 215 free fall) is associated with a CTD probe (SBE 911 and RBR concerto respectively) to ensure a

216 second pressure measurement. The characteristics of all the pressure sensors used in the study are
217 presented in Table 1. The accuracy of the pressure data is a very important constraint on estimating
218 the instrument vertical velocity.

219 For the estimation of the Sentinel V vertical velocity, we directly use the data from its internal
220 pressure sensor. Indeed, this sensor is much more accurate and has a better resolution than the
221 CTD probe (SBE 911), due to its smaller full scale.

222 Our SBE 911 probe is adapted to measurements reaching 6800 m. Thus, for measurements limited
223 to the first 200 meters, this pressure sensor is no longer well suited. However, we performed a
224 calibration of the SBE pressure dataset using the corresponding Sentinel V pressure dataset. To
225 do this, we performed a linear regression between the Sentinel V and SBE pressure records for
226 each sampling phase (fixed at 10 m, downcast, upcast). These coefficients barely fluctuate between
227 stations, hence the use of average coefficients calculated for all the stations. These regression
228 coefficients are then applied to the SBE pressure data recorded in the corresponding sampling
229 phases, to obtain calibrated pressure data. We validate this calibration by the excellent agreement
230 between the final ocean vertical velocity profiles using calibrated SBE and Sentinel V pressure
231 data.

232 For the L-ADCP method, the pressure sensor associated with the Workhorse is dedicated to
233 sampling as deep as the SBE, and far beyond the sampling range of our study. For this reason, we
234 use the calibrated SBE pressure data for the L-ADCP fall rate estimation.

235 Finally, for the FF-ADCP method, the use of the CTD pressure sensor (RBR concerto) provides
236 the more accurate estimation of the instrument velocity.

237 Thereafter, the vertical oceanic velocity is obtained from:

$$w = w_t + w_{pkg} \quad (3)$$

238 4) STEPS 4 AND 5: TEMPORAL SMOOTHING AND FINAL VERTICAL PROFILES

239 Two final steps are applied in this data processing chain.

240 The measurements recorded at the ADCP rate (one measurement by "ping", every second) are
241 usually showing a high standard deviation. Thus, a temporal smoothing over an optimized window

242 of 20 seconds is applied and reduces the uncertainties of the measurement caused by isotropic
243 turbulence and background noise.

244 Finally, due to this statistical approach, a cut at the upper and lower ends of the vertical profiles
245 of w is applied, to overcome the potential bias linked to a much smaller data occurrence at these
246 ends. Indeed, the "yo-yo" cast between the top and the bottom of the profile being recorded at
247 approximately 1 m s^{-1} with the lowered method and 0.3 m s^{-1} with the free-fall method, the body
248 of the profile is sampled a great number of times during the downward / upward movement due
249 to the range of the ADCP used (between 30 and 80 m). Therefore, there is a higher number of
250 measurement occurrences in the thickness defined by the range of the instrument when the ADCP
251 data overlaps compared to the two ends of the profiles.

252 Hence, we have eliminated the first four bins of the ADCP close to the surface, where the
253 measurements are the most affected by noise, leading to the beginning of the profile at 25 m depth.
254 At the bottom of the profiles, we define the cut-off depth as the minimal level reached by the
255 instrument among the downcast phases, for each corresponding station. Note that in the case of
256 FF-ACDP, dropped at about 80 m instead of 150 m depth, the lower cut-off depth is chosen at the
257 minimum depth among the downcast phases where the vertical velocity data start to be cut by the
258 correlation criteria (step 1).

259 *c. New 5th beam ADCP dataset processing*

260 As mentioned above, forces acting on the instrument and causing deviations relative to the
261 gravimetric vertical direction must be taken into account, especially when processing data from the
262 fifth beam (in the main axis of the instrument) of the Sentinel V. Indeed, the measurements from
263 the fifth beam, expressed in the instrument reference frame, are directly affected by these forces
264 and cause major vertical velocity anomalies on recordings. To correct the measurement from this
265 fifth beam, we use the processing chain described above and add two specific steps, as follows.

266 1) STEP 2A: ADCP ATTITUDE ANGLES AND GENERALIZATION IN SPHERICAL CONVENTION

267 The values of the attitude angles (pitch, roll and heading) measured by the Teledyne RD Instru-
268 ments (Sentinel V) follow a convention based on intervals between 0° and $\pm 90^\circ$ (RD Instrument
269 2008). Such a convention, initially adopted for deployments with fixed mooring, is not optimal for

270 widespread use of vertical profiles in the water column. Indeed, with this convention, the direction
 271 of the beams of the instrument (towards the surface or the bottom) can not be distinguished, which
 272 implies adapting the measurement reference system for each use.

273 This is why we carry out the generalization of the angles in spherical convention, characterized by
 274 angular intervals ranging between 0° and 360° , as shown in Fig.3. This spherical convention is much
 275 more conducive for data processing: on one hand, it eliminates the need to adapt the measurement
 276 reference system for each use of the Sentinel V and, on the other hand, it is applicable to all types
 of measurements made by other ADCPs based on various conventions.

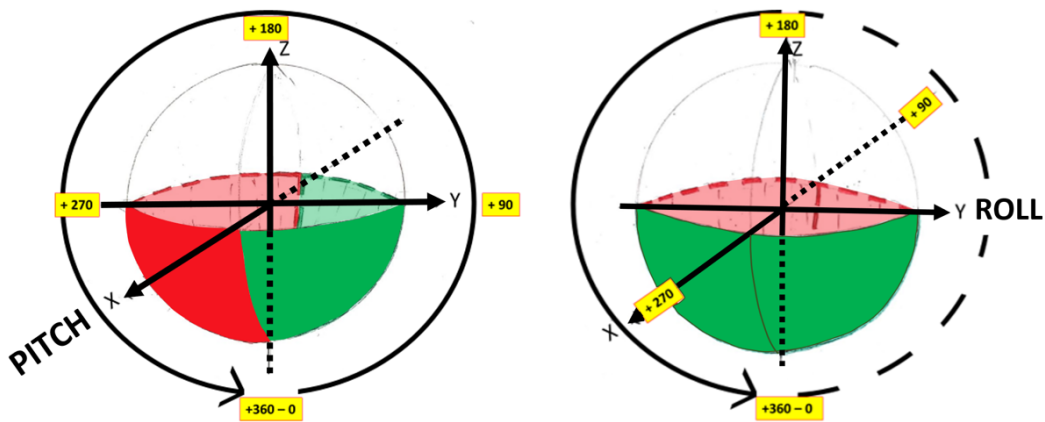


FIG. 3. Schemes of spherical conventions for pitch (left panel) and roll (right panel) data.

277

278 2) STEP 2B: REFERENCE FRAME TRANSFORMATION AND CORRECTIONS BY PROJECTION

279 When the orientation of the Sentinel V deviates from the gravimetric vertical direction, the fifth
 280 beam of the ADCP records a signal resulting from different proportions of both horizontal and
 281 vertical components of the current. This effect is enhanced by the significantly different orders of
 282 magnitude between these three components: on the order of $10^{-2} - 10^{-1} \text{ m s}^{-1}$ for the two horizontal
 283 components, and on the order of $10^{-3} - 10^{-2} \text{ m s}^{-1}$ for the vertical component. In order to obtain
 284 only the vertical component of the current, it is therefore necessary to correct the measurement
 285 of the fifth beam of the ADCP. This correction is determined by the use of the rotation matrices
 286 which project any vector measured in one given reference frame to another. Here, the use of
 287 rotations around the axes of Sentinel V, listed below (with the angles having been set in spherical
 288 convention), allows to project any vector initially expressed in the reference frame of the instrument

289 (orthonormal basis composed by beams 1 - 2, beams 3 - 4 and beam 5 axes) towards the Earth
 290 coordinates (orthonormal basis composed by East, North and zenith axes):

- 291 - Heading (**H**, clockwise rotation around the axis of the vertical beam - beam 5);
- 292 - Pitch (**P**, trigonometric rotation around the X axis - beam 1 to beam 2);
- 293 - Roll (**R**, trigonometric rotation around the Y axis - beam 3 to beam 4).

294 Here we use the rotation matrices to project any vector in Earth coordinates. The rotations
 295 must be applied successively, with the rotation signs as follows: first **R**, then **-P**, and finally **H**,
 296 corresponding to **H.-P.R** as shown by the matrix product below:

$$\mathbf{M} = \begin{bmatrix} \cos \theta_H & \sin \theta_H & 0 \\ -\sin \theta_H & \cos \theta_H & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_P & -\sin \theta_P \\ 0 & \sin \theta_P & \cos \theta_P \end{bmatrix} \begin{bmatrix} \cos \theta_R & 0 & -\sin \theta_R \\ 0 & 1 & 0 \\ \sin \theta_R & 0 & \cos \theta_R \end{bmatrix} \quad (4)$$

$$\Leftrightarrow \mathbf{M} = \begin{bmatrix} \cos \theta_H \cdot \cos \theta_R - \sin \theta_H \cdot \sin \theta_P \cdot \sin \theta_R & \sin \theta_H \cdot \cos \theta_P & -\cos \theta_H \cdot \sin \theta_R - \sin \theta_H \cdot \sin \theta_P \cdot \cos \theta_R \\ -\sin \theta_H \cdot \cos \theta_R - \cos \theta_H \cdot \sin \theta_P \cdot \sin \theta_R & \cos \theta_H \cdot \cos \theta_P & \sin \theta_H \cdot \sin \theta_R - \cos \theta_H \cdot \sin \theta_P \cdot \cos \theta_R \\ \cos \theta_P \cdot \sin \theta_R & \sin \theta_P & \cos \theta_P \cdot \cos \theta_R \end{bmatrix} \quad (5)$$

297 **M** is applied to the components of the velocity measured in the reference frame of the Sentinel
 298 $\mathbf{V} (u_s, v_s, w_s)$ to obtain these same components in Earth coordinates (u_t, v_t, w_t) , according to the
 299 following formula:

$$\begin{bmatrix} u_t \\ v_t \\ w_t \end{bmatrix} = \mathbf{M} \cdot \begin{bmatrix} u_s \\ v_s \\ w_s \end{bmatrix} \quad (6)$$

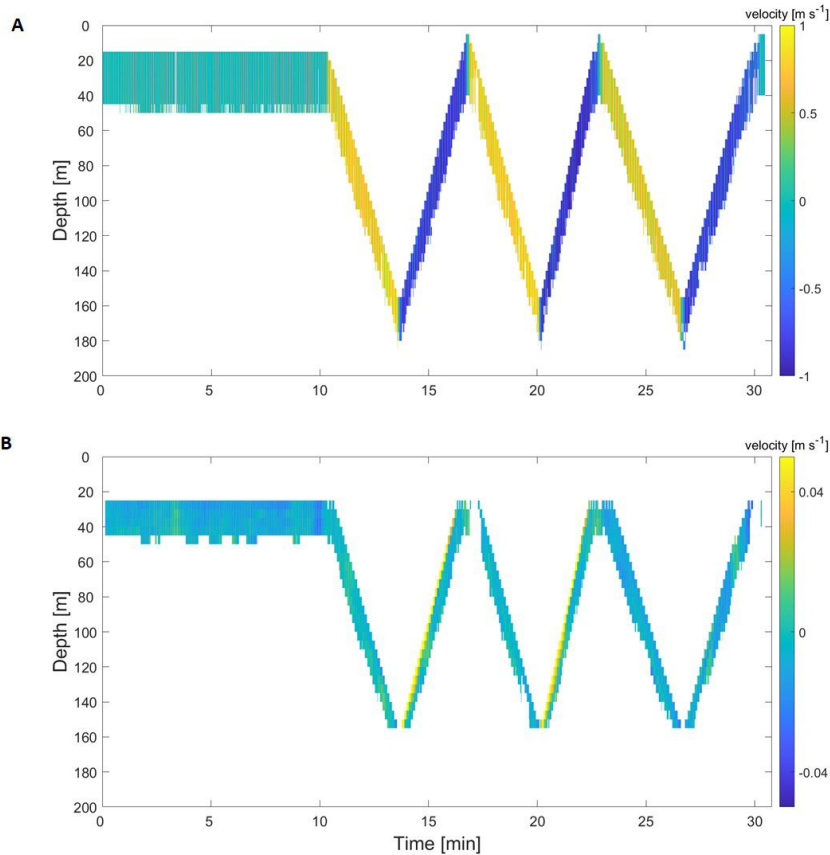
300 From the measurements of the components u_t and v_t , obtained from the four beams, as well as
 301 the component w_s from the fifth beam, and knowing that this passage matrix is invertible, we can
 302 calculate the vertical component of the current in Earth coordinates (w_t) according to:

$$w_t = \frac{w_s + u_t(\cos \theta_H \cdot \sin \theta_R + \sin \theta_H \cdot \sin \theta_P \cdot \cos \theta_R) + v_t(-\sin \theta_H \cdot \sin \theta_R + \cos \theta_H \cdot \sin \theta_P \cdot \cos \theta_R)}{\cos \theta_R \cdot \cos \theta_P} \quad (7)$$

303 Furthermore, it is important to note that this step of referential changes, specific to the velocity
304 measurement acquired by the fifth beam of the Sentinel V, does not intervene in the data processing
305 chain measured by the four beams of the Sentinel V and conventional ADCPs, if the data used are
306 already in Earth coordinates.

307 In addition the depth projection of the acoustic cells in Earth coordinates, with the approximation
308 of $(0, 0, z_s)$ and the application of \mathbf{M} , leads to Equation (1) and to what follows in the processing
309 chain.

313 The effect of this processing chain on the data is illustrated in Fig.4, showing the vertical velocity
314 profiles before and after the application of the processing chain, for the example of station 6. In
315 this example, after the analysis, the magnitude of the vertical velocity has diminished by an order
of 10^2 , and the upcasts and downcasts records tend to match.



310 FIG. 4. Vertical velocities profiles measured by the 5th beam of Sentinel V (L-V5th) before (A) and after (B)
311 the application of the processing chain displayed as a function of time and depth for *in situ* measurements at
312 station 6 of the FUMSECK cruise.

316 *d. Error propagation method*

317 Four sources of error, identified and estimated by the manufacturer of the ADCPs, relate to: i)
318 the slope of the acoustic tiles; ii) the estimation of the tilts (pitch and roll); iii) the estimation of
319 the horizontal components (u and v); and, in the specific case of the L-V5th measurements, iv) the
320 estimation of the vertical component (w_s). A series of error propagation tests were performed on the
321 vertical velocity measurements to highlight the contribution of each of the identified instrumental
322 error sources in the estimation of oceanic vertical velocities.

323 Except for the first identified source, the tile slope, which is a constant error (set between -2° and
324 $+2^\circ$ with 0.5° steps), all the other errors are characterized as random noise whose uncertainties
325 are provided by the manufacturer. Each test was performed following the same principle. First, a
326 uniform random sub-sampling of 100 oceanic vertical velocities measured in downcast phase by a
327 given ADCP and for a given station is performed (noted w_{sub}). Then, for each of these 100 sub-
328 samples, a random error is added, with a normal distribution centered on the value corresponding
329 to the uncertainty provided by the manufacturer. Adding this noise is performed 500 times for
330 each sub-sample, to obtain 100 artificial distributions (noted w') of statistically representative size
331 ($5 \cdot 10^4$ data per test).

332 To summarize, we have run five series of tests:

- 333 1. tile slope: a constant error on the inclination of the acoustic tile is added. This first series
334 contains nine tests with fixed error values ranging from -2° to $+2^\circ$ with a step of 0.5° ;
- 335 2. pitch/roll: we add, to the tile slope test series, a random error on the pitch/roll measurement
336 with a Gaussian distribution (accuracy 0.05°);
- 337 3. horizontal components u and v : we add, to the tile slope test series, a random error on the u/v
338 measurement with a Gaussian distribution (accuracy $3 \cdot 10^{-3} \text{ m s}^{-1}$);
- 339 4. vertical component w_s : we add, to the tile slope test series, a random error on the w_s
340 measurement with a Gaussian distribution (accuracy $3 \cdot 10^{-3} \text{ m s}^{-1}$);
- 341 5. combination of all error tests: we add, to the tile slope test series, the three random errors on
342 the measurements presented above.

343 The results, presented in the dedicated section, correspond to the tests performed on the L-V5th
344 measurements - station 1.

345 **3. Results**

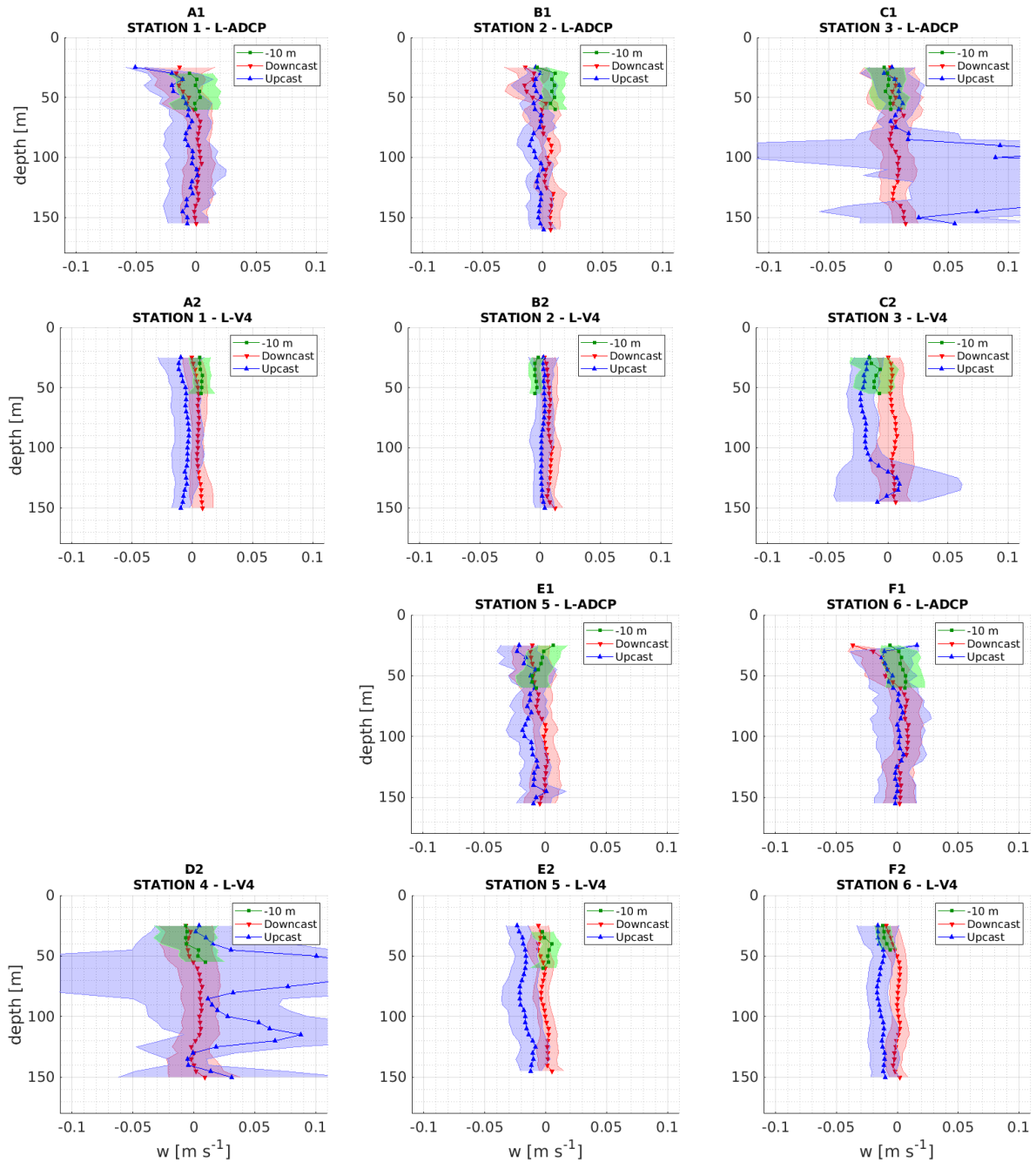
346 *a. Comparison of vertical velocity measurements obtained with the classic lowered method and* 347 *the conventional four beams*

348 The analysis chain, set up in Section 2.b to estimate vertical velocity measurements, is first
349 applied on two datasets: i) the four beams of the first Workhorse (classic L-ADCP), and ii) those
350 of the Sentinel V (L-V4), both provided by the processing software of these ADCPs. These
351 measurements, recorded using the same deployment technique, are analyzed simultaneously in
352 order to compare the two sets of results. Note that we use the standard deviation, defined as
353 the square root of the sum of squared differences from the mean divided by the size of the data
354 set minus one, without considering the NaN values, in order to appreciate the variability of the
355 measurements within each station.

359 Figure 5 shows the mean vertical profiles of the vertical velocities measured by the four beams
360 of both the L-ADCP and the L-V4 in the CTD-ADCP package, for each station and differentiating
361 the three acquisition phases: fixed immersion (at 10 m), downcasts and upcasts. Station 4 was not
362 sampled by the L-ADCP due to weather conditions unfavorable for the deployment. However, for
363 the remaining stations, it is possible to compare the results from the two instruments lowered on
364 the CTD-ADCP package.

365 Whatever the instrument, the whole analysis leads to a significant reduction in both the mean
366 values (from 1 m s^{-1} to 10^{-3} m s^{-1}) and the standard deviations (from 10^{-1} m s^{-1} to 10^{-2} m s^{-1}) of
367 the vertical velocities, reaching the expected orders of magnitude.

368 We observe an agreement between the fixed immersion profiles and the downcast ones, while the
369 upcast profiles are characterized by greater variability in the mean vertical velocity as a function
370 of depth and by higher standard deviations. This specificity of upcast profiles probably results
371 from two combined effects. On one hand, a vibration phenomenon of the wire cable connecting
372 the CTD-ADCP package to the ship can disturb the measurements due to the cable tension which
373 is more important during the upcasts. On the other hand, the ADCP ringing phenomenon, or
374 resonance, seems to be more important during the upcasts for a reason still uncertain. Indeed,



356 FIG. 5. Vertical velocities measured for stations 1 to 6 by the classic L-ADCP (A1 to F1) and by the L-V4 (A2
 357 to F2). Means (lines and markers) and standard deviations (shaded areas) of vertical velocities are shown as a
 358 function of the depth for each of the acquisition phases: fixed at 10 m (green), downcast (red), upcast (blue).

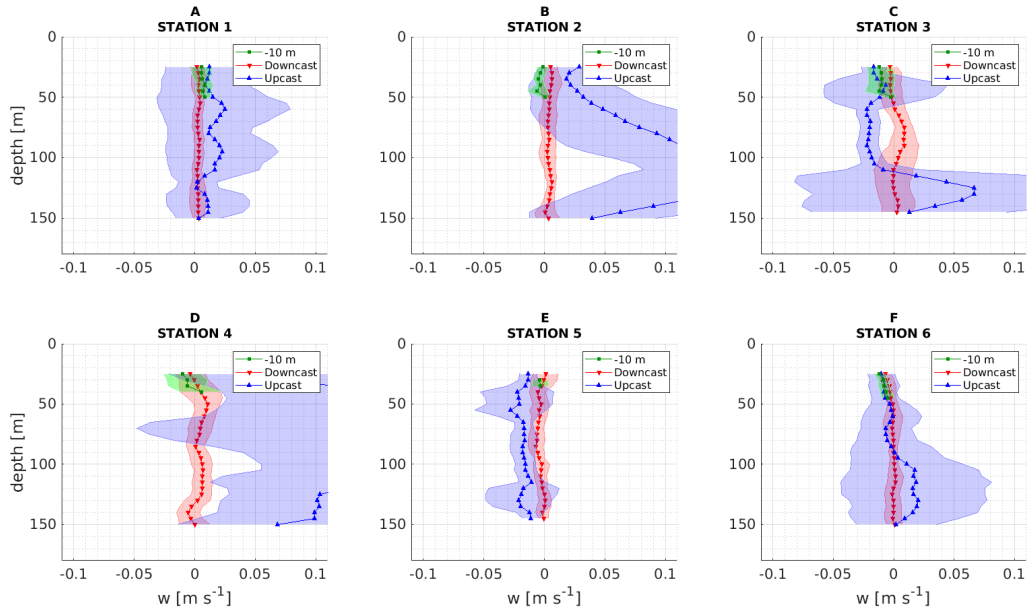
375 if the acoustic tile of an ADCP is still vibrating (or vibrating again) when a part of the outgoing
376 acoustic signal, having backscattered on the marine particles near the tile, returns to that tile, this
377 creates interference, called ringing or resonance effect. Usually, to avoid this bias, a blanking area
378 - where the data is not taken into account - is applied in the immediate proximity of the tiles,
379 allowing them to stop vibrating before recording the return signals. In our case, this blanking zone
380 seems insufficient during the upcasts. These combined effects were particularly visible at stations
381 3 and 4 (Fig.5 C1, C2 and D2), where we observe high values of positive velocities associated with
382 large standard deviations on the upcasts. The sea state at station 4 was the worst of the cruise, but
383 reasons of these effects at station 3 remain unknown. Hence, despite the good agreement of the
384 recordings between the downcast and upcast phases on the other stations for the two ADCPs, the
385 analysis of vertical velocities is subsequently carried out on the downcast profiles exclusively. This
386 is a common method used for horizontal velocity measurements in vertical profiles by ADCPs (e.g.
387 Polzin et al. 2002).

388 *b. Vertical velocity measurements obtained with the classic lowered method and the new Sentinel*
389 *V 5th beam*

393 The results achieved by the analysis chain described above for the recordings of the L-V5th
394 (Section 2.c) are presented in Fig. 6. This figure shows the profiles of the mean vertical velocity
395 and its standard deviation, as in Fig.5.

396 The results show profiles comparable to those of the conventional four beams. Here, the
397 difference between downcast and upcast profiles is significant, for the same reasons as described in
398 the previous section. The analysis of the downcast profiles highlights a low vertical variability of
399 the mean vertical velocity. The orders of magnitude obtained by using the L-V5th reach 10^{-3} m s^{-1}
400 for means, and several 10^{-3} m s^{-1} to 10^{-2} m s^{-1} for standard deviations.

401 We note that the raw vertical velocity data, measured by the Sentinel V, have standard deviations
402 on the order of several tens of 10^{-2} m s^{-1} , with an average on the order of 1 m s^{-1} , which corresponds
403 to the recording of the predominant velocity component: the vertical movement of the instrument
404 (w_{CTD}). The estimate of the decrease in standard deviations following our data processing is
405 approximately a factor of 20.

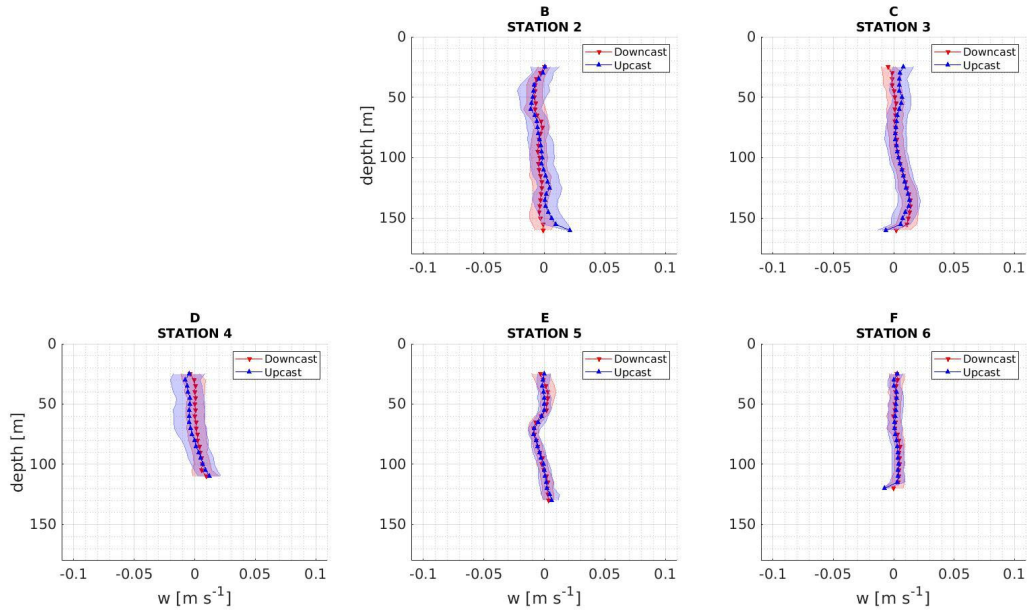


390 FIG. 6. Vertical velocities measured by the L-V5th for stations 1 to 6 (A to F). Means (lines and markers)
 391 and standard deviations (shaded areas) of vertical velocities are shown as a function of the depth for each of the
 392 acquisition phases: fixed at 10 m (green), downcast (red), upcast (blue).

406 *c. Vertical velocity measurements obtained with the new free-fall method and the conventional four*
 407 *beams*

408 In this last section, we applied our processing chain, described in Section 2.b, on the measure-
 409 ments performed by the second Workhorse deployed in free-fall (FF-ADCP).

413 Figure 7 shows the vertical velocity profiles from the FF-ADCP differentiating the downcast and
 414 upcast phases according to the two previous figures. Here the means and standard deviations of
 415 downcast and upcast profiles match each other very well, which could be due to a greater stability
 416 of the ADCP caused by the use of a floating polypropylene rope rather than a wire cable. The free
 417 falling technique provides great stability in the horizontal plane (pitch/roll variations) but foremost
 418 in the vertical axis. This limitation of vertical recalls is essential for the measurement of the vertical
 419 component of the current for which any disturbance in the same axis leads to the largest possible
 420 error. Despite this good agreement, we focus on the profiles in the downcast phase only, to be
 421 coherent with the rest of the analysis.



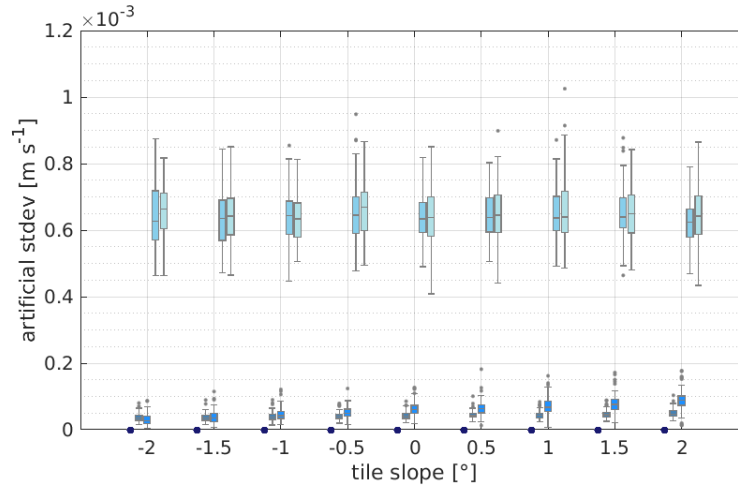
410 FIG. 7. Vertical velocities measured by the FF-ADCP for stations 2 to 6 (B to F). Means (lines and markers)
 411 and standard deviations (shaded areas) of vertical velocities are shown as a function of the depth for each of the
 412 acquisition phases: downcast (red) and upcast (blue).

422 All downcast profiles are rather homogeneous with respect to depth. The largest variation can
 423 be seen at station 5 (Fig.7 E), between 50 and 100 m depth, where the observed vertical velocity
 424 variation is statistically significant and corresponds to a negative vertical velocity signal (downward
 425 movement) in this part of the water column. This last analysis with our processing chain leads
 426 once again to measurements of average vertical velocities on the order of 10^{-3} m s^{-1} with standard
 427 deviations of several 10^{-3} m s^{-1} . Finally, it should be noted that these orders of magnitude, and more
 428 specifically that of the standard deviations, are systematically stable from one station to another.

429 *d. Error propagation results*

432 After generating the artificial distributions, we studied the standard deviation produced by each
 433 test (Fig.8) for the L-V5th data. First, we notice that the variation of the tile slope has no effect
 434 on the standard deviation, as expected. Secondly, for the tests on the pitch/roll and horizontal
 435 velocities, the standard deviations generated by the error sources at the end of the processing are
 436 less than 10^{-4} m s^{-1} , therefore largely negligible. Third, the error in the measurement of the vertical

437 component (w_s) generates a standard deviation on the order of 10^{-3} m s^{-1} . Among all the identified
 438 error sources, this latter contributes to most (over 99 %) of the standard deviation generated by the
 error propagation test.



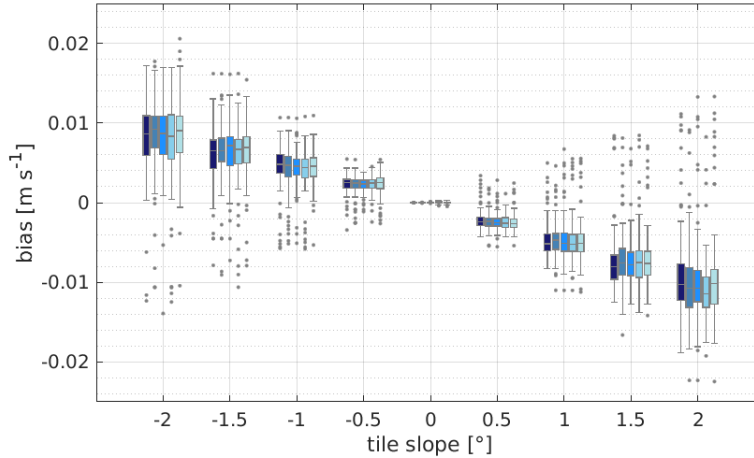
430 FIG. 8. Standard deviations presented for each error propagation test on: tile slope, pitch/roll, horizontal
 431 velocities, vertical component w_s , and combined errors (respectively from dark blue to light blue).

439
 440 In summary, among the tests performed, the measurement error on the vertical component (w_s)
 441 is the only identified source of error leading to an increase in the standard deviation at the end
 442 of the treatment. However, this source of error remains an order of magnitude smaller than the
 443 standard deviation observed in the final vertical velocity profiles.

444 For the tests on the tile slope, we found, beyond a negligible difference in standard deviation,
 445 a bias between the sub-samples (w_{sub}) and the artificial distribution mean generated from the
 446 sub-samples ($\overline{w'}$).

449 The comparison of these biases with boxplot (Fig.9) suggests that the greater the tile slope, the
 450 greater the bias, as expected, but also the greater the standard deviation of these biases. Yet it must
 451 be noted that only the variation of the tile slope causes this bias. Indeed, for the same tile slope
 452 there is no significant difference between the different tests. The information $< \pm 2^\circ$ indicated by
 453 RDI results in biases of up to $\pm 2 \text{ cm s}^{-1}$. Considering that standard deviations of up to 1 cm s^{-1}
 454 are observed, we assume that this error on the tile slope is below $\pm 1^\circ$.

455 Finally, the velocity estimated from the pressure measurements, w_{pkg} , is also a potential source
 456 of error. However, given the two extreme resolution of the pressure sensors used (0.1 and 6.8



447 FIG. 9. Biases generated by each error propagation test on: tile slope, pitch/roll, horizontal velocities, vertical
 448 component w_s , and combined errors (respectively from dark blue to light blue), with $\text{bias} = w_{\text{sub}} - \overline{w'}$.

457 cm respectively associated to the Sentinel V and the SBE 911, see Table 1), we estimate the
 458 propagation of such an uncertainty in the final vertical velocity profiles to be from the order of
 459 $2 \cdot 10^{-4} \text{ m s}^{-1}$ for the L-V4 and L-V5th resulting profiles, to $1 \cdot 10^{-2} \text{ m s}^{-1}$ for the L-ADCP resulting
 460 profiles. Depending on the method used, the error in the pressure measurement may or may not
 461 represent a significant contribution to the final standard deviation.

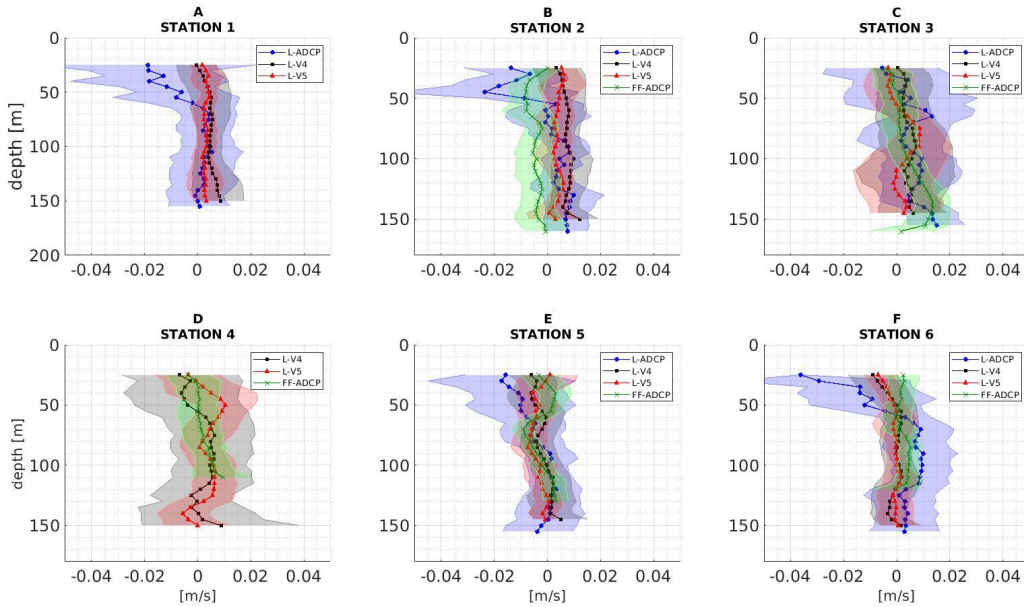
462 Thus, two conclusions can be drawn:

- 463 - the main sources of error contributing to the standard deviations correspond to the tile slope
 464 one and to the pressure-derived w_{pkg} one;
- 465 - the spatio-temporal variation for each profile should not be neglected, and also contributes to
 466 the observed standard deviation.

467 4. Discussion

471 The comparison of all the downcast profiles (Fig.10) highlights a systematic good agreement in
 472 terms of both mean values and standard deviations between the two Sentinel V recordings (with the
 473 four beams - L-V4 - and the fifth beam - L-V5th). In contrast, the profiles measured by the L-ADCP
 474 are more variable with depth. This vertical variability is particularly pronounced in the first 50 m of
 475 the water column. In addition, the downcast profiles acquired, on one hand, with the new L-V5th and,
 476 on the other hand, with the FF-ADCP, are more stable over the entire sampled water column, with

477 smaller and more homogeneous standard deviations than those obtained with the L-ADCP. Note
 478 that the higher the frequency of the acoustic pulse, the lower the uncertainty of the measurement (K.
 479 Grangier, ADCP engineer, Teledyne RDI France, 2020, personal communication). As expected,
 480 the uncertainty on the Sentinel V (500 kHz) measurement is lower than the one of the L-ADCP
 (300 kHz).



481
 482
 483
 484
 485
 486
 487
 488
 489
 490
 491
 492
 493
 FIG. 10. Vertical velocities measured during downcast by the L-ADCP (blue), the L-V4 (black), the L-V5th (red) and the FF-ADCP (green), for stations 1 to 6 (A to F). Means (lines and markers) and standard deviations (shaded areas) of vertical velocities are plotted as a function of depth.

482 Furthermore, Fig.10 also shows that standard deviations of the FF-ADCP measurements are not
 483 affected by the sea state at the surface. Indeed, the standard deviation values remain stable around
 484 a few 10^{-3} m s^{-1} , even at station 4, when we had rough sea conditions.

488 The mean values of w , and associated standard deviations, are estimated at each station in three
 489 different layers of the water column: 25 - 50 m, 50 - 100 m, and 100 - 150 m deep (Fig.11). These w
 490 mean values are in the order of magnitude of 10^{-3} m s^{-1} without a predominant trend. The greatest
 491 uncertainty in vertical velocities is contained in the upper layer (until 50 meters depth), under the
 492 direct influence of weather conditions resulting in a natural variability of these velocities. Below
 493 this depth, the means and standard deviations are reduced, and the differences between the layers

494 50 - 100 m and 100 - 150 m, for a given station and ADCP, are minor. Standard deviations show
495 greater uncertainty depending on the measuring instrument. Then we consider vertical velocities
496 in the water column over its entire sampled depth (i.e. 25 - 150 m) and we evaluate the average
497 standard deviation for the 2, 3, 5 and 6 stations. The orders of magnitude of these standard
498 deviations range from 10^{-3} to 10^{-2} m s⁻¹. They can be classified in decreasing order as follows:
499 L-ADCP ($= 1.3 \cdot 10^{-2} \pm 0.2 \cdot 10^{-2}$ m s⁻¹), L-V4 ($= 0.9 \cdot 10^{-2} \pm 0.3 \cdot 10^{-2}$ m s⁻¹), L-V5th ($= 0.7 \cdot 10^{-2} \pm 0.2$
500 10^{-2} m s⁻¹) and FF-ADCP ($= 0.6 \cdot 10^{-2} \pm 0.1 \cdot 10^{-2}$ m s⁻¹).

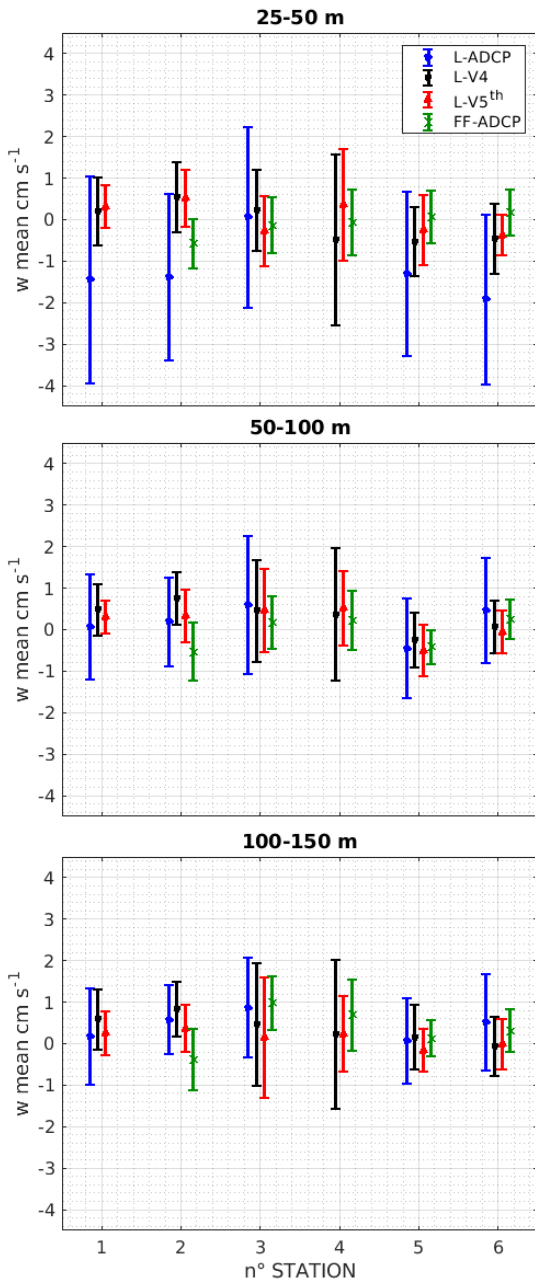
501 We evaluate the occurrence of data acquisitions for each method dividing the vertical profiles in
502 bins of 5-m thickness. For each type of ADCP, the occurrence is greater than or equal to 50 (without
503 counting NaN values, obviously), and it is stable between stations for a given method. It should
504 be noted that the free-fall sampling presents three times more occurrences than the measurements
505 by the lowered method, due to its three times slower free falling speed. Nevertheless, an artificial
506 reduction of this occurrence by using only one or two downcasts for the elaboration of the final
507 FF-ADCP profiles (not shown), does not significantly influence the resulting standard deviation.
508 Therefore, there is no significant error in the measurement statistics caused by data occurrence.

509 We know that the acoustic measurement technique, especially in the first 200 meters of the water
510 column, is likely to encounter numerous interferences and generate measurement errors. Therefore,
511 we have taken into account the different sources of acoustic interference in this study.

512 First of all, the measured vertical velocity profiles are studied below 25 m depth, which allows to
513 avoid acoustic interference with the surface as well as swell and orbital current effects or divergence.

514 Then, an acoustic interference with the vessel mounted ADCP was observed in the FF-ADCP
515 profiles. This interference was clearly identified in the vertical velocity time series by the linear
516 propagation of noise over a constant thickness of two bins (10 m). Measurements showing this
517 interference have been removed. This type of interference was not observed in the measurements
518 from the lowered method, due to the distance between the vessel mounted ADCP and the position
519 of the L-ADCP and the Sentinel V launched at the stern of the ship, in contrast to the FF-ADCP,
520 launched by the side of the ship.

521 Finally, we investigated the speed of sound variation's potential effects on the following param-
522 eters: particle's size detection, vertical bin length estimation and radial velocity.



485 FIG. 11. Means and standard deviations of the downcast profiles of vertical velocities, averaged between three
 486 layers 25 - 50 m (upper panel), 50 - 100 m (middle panel) and 100 - 150 m (lower panel), depending on the
 487 stations, and according to the ADCP: L-ADCP (blue), L-V4 (black), L-V5th (red) and FF-ADCP (green).

523 The ADCPs used in this study detect particles larger than 3 mm for the Sentinel V and 4.9 mm
 524 for the two WorkHorses. This detection limit slightly fluctuates in the first 200 meters because

525 the speed of sound itself is estimated between 1506 and 1514 m s⁻¹, representing a variation of
526 0.3% over this thickness. The use of quality criteria such as correlation and echo intensity in the
527 processing chain ensures that interferences due to mineral or organic particles, which is a potential
528 source of significant error in the measurement, is avoided to a certain extent. Moreover, the stations
529 were carried out in relatively clear waters and during daylight hours, thus avoiding nycthemeral
530 migration processes, source of acoustic interference. This type of interference is apparent in the
531 vessel mounted ADCP data (not shown) at night fall or day rise with the migration of zooplankton
532 such as pteropods or krill swarms (usually *Cavolinia inyexa* and *Meganyctiphanes norvegica*) well
533 known in this region of the northwestern Mediterranean Sea (Sardou et al. 1996; Tarling et al. 1999,
534 2001). Finally the sound speed variation, here estimated to be $\frac{C_{\text{TEOS-10}}}{C_{\text{ADCP}}} < 0.3\%$, involves an error
535 on the vertical bin length on the order of 1.5 cm for 5-m cells. If we consider that the mean values
536 of L-V5th measurements vary between stations on the order of 4 mm s⁻¹ (in average), its effect
537 ($4 \times 0.3\%$) on the radial velocity amounts to ± 0.012 mm s⁻¹. Consequently, the errors associated
538 with the estimation of the speed of sound are largely negligible, which is why our implementation
539 method does not require significant correction on this parameter.

540 **5. Conclusion**

541 In conclusion, we have compared four independent methods for the *in situ* measurement of vertical
542 velocities in an oceanic region characterized by a low-energy circulation. We tested two different
543 instruments (ADCP with 4 and 5 beams) and two different deployment techniques (classical rosette
544 casts, free-fall casts). Our results show that the fifth beam of the Sentinel V provides the most
545 precise measurement (mean values on the order of a few 10⁻³ m s⁻¹ with standard deviations on the
546 order of 10⁻² m s⁻¹) among those tested with the same lowered technique. Meanwhile, the free-fall
547 sampling technique has shown the best stability in standard deviation variations between stations,
548 with values on the order of a few 10⁻³ m s⁻¹.

549 The Ligurian Sea is characterized by a cyclonic general circulation pattern with a geostrophic
550 flow along the coastal line (Esposito and Manzella 1982). Most of the sampling stations were
551 located in this general circulation. Only stations 4 and 5 were positioned on the outer edge of
552 the Northern Current (Millot 1999). Except for the rougher sea state conditions of station 4
553 driven by an intense but time limited storm event, the study area was characterized by low-energy

554 dynamics and the cyclonic recirculation present on site remained stable throughout the cruise.
555 Despite the limited size of our dataset, due to meteorological conditions encountered during the
556 FUMSECK cruise, our accurate analysis of all the possible error sources allowed us to emphasize
557 that instrumental errors have a contribution of few 10^{-3} m s^{-1} when the environmental variability
558 in our study area is of the same order of magnitude. Indeed, in the period and region during which
559 the FUMSECK stations took place, the oceanic circulation is characterized by a moderate coastal
560 current and a weak cyclonic gyre. Furthermore, we show that the free-fall methodology provides
561 better precision, in particular with rough sea conditions, by removing noise due to the anchoring to
562 the vessel. Hence we conclude that the best methodology will be to deploy a free-falling Sentinel
563 V.

564 Compared to classical studies performed in high-energy ocean (Thurnherr 2011; D'Asaro et al.
565 2017; Tarry et al. 2021), our work provides a method for measuring vertical velocities also
566 applicable to a low-energy ocean, where Tzortzis et al. (2021) showed that finescale dynamics
567 can have an important role in structuring the microbial community. These low-energy ocean
568 conditions actually represent the majority of the oceans. This new possibility of measuring low-
569 energy vertical velocities sets the stage for more specific studies of physical-biological coupling in
570 finescale structures.

571 Knowing that the methodology for *in situ* measurement of vertical velocities is ready for use,
572 and after this first test in real conditions, it will be interesting to validate and generalize the
573 direct acquisition of the vertical component of the oceanic current, during other cruises. This
574 will contribute to investigations in different fields: physical, biological or biogeochemical. In
575 the framework of the international project related to the new generation altimetry satellite SWOT
576 (launch planned in 2022), several cruises (JULIO-VVPTest2022 PI: J.-L. Fuda, PROTEVS 2022
577 PI: F. Dumas, BIOSWOT-Med 2023 PIs: A. Doglioli and G. Grégori) currently in preparation will
578 use this method in order to obtain *in situ* measurement of vertical velocities in oceanic areas with
579 finescale dynamics and/or at periods for which this vertical component of the current should be
580 much more intense and contrasted. Let us recall that the interest of developing such an analytical
581 method for direct *in situ* measurement of the vertical component of ocean currents is based on the
582 growing need for information in all fields of oceanographic studies: vertical velocities playing a
583 key role in the export of CO_2 as well as organic and mineral matter.

584 *Acknowledgments.* We thank the captain and the crew of the R/V Tethys II for help in deployment
585 of instruments. We thank Kévin Grangier for providing the Sentinel V and helpful comments. We
586 also thank Nagib Bhairy for the post-cruise processing of the CTD data, and all the members of
587 the Service Atmosphère Mer for their punctual help. This study was initiated by the OPLC team
588 of the Mediterranean Institute of Oceanography. Caroline Comby is now supported by a MENRT
589 Ph.D. grant. All of this research is supported by the BioSWOT project and the FUMSECK-vv
590 LEFE project.

591 *Data availability statement.* Supporting data cannot be made openly available at this
592 time. As soon as all the FUMSECK papers are published, the data will be publicly
593 available: [https://dataset.osupytheas.fr/geonetwork/srv/eng/catalog.search#](https://dataset.osupytheas.fr/geonetwork/srv/eng/catalog.search#/metadata/5bda8ab8-79e7-4dec-9bcb-25a3196e2f9a)
594 [/metadata/5bda8ab8-79e7-4dec-9bcb-25a3196e2f9a](https://dataset.osupytheas.fr/geonetwork/srv/eng/catalog.search#/metadata/5bda8ab8-79e7-4dec-9bcb-25a3196e2f9a)

595 **References**

- 596 Allen, J. T., D. A. Smeed, A. J. G. Nurser, J. W. Zhang, and M. Rixen, 2001: Diagnosis of vertical
597 velocities with the QG omega equation: an examination of the errors due to sampling strategy.
598 *Deep-Sea Res. I*, **48**, 315–346, [https://doi.org/10.1016/S0967-0637\(00\)00035-2](https://doi.org/10.1016/S0967-0637(00)00035-2).
- 599 Astraldi, M., G. P. Gasparini, G. M. R. Manzella, and T. S. Hopkins, 1990: Temporal variability of
600 currents in the eastern Ligurian Sea. *J. Geophys. Res. Oceans*, **95**, 1515–1522, [https://doi.org/](https://doi.org/10.1029/JC095iC02p01515)
601 [10.1029/JC095iC02p01515](https://doi.org/10.1029/JC095iC02p01515).
- 602 Barrillon, S., 2019: FUMSECK cruise, RV Téthys II. <https://doi.org/10.17600/18001155>.
- 603 Bower, A. S., and T. Rossby, 1989: Evidence of cross-frontal exchange processes in the Gulf
604 Stream based in isopycnal RAFOS float data. *J. Phys. Oceanogr.*, **19**, 1177–1190.
- 605 Boyd, P. W., H. Claustre, M. Levy, D. A. Siegel, and T. Weber, 2019: Multi-faceted particle
606 pumps drive carbon sequestration in the ocean. *Nature*, **568**, 327–335, [https://doi.org/10.1038/](https://doi.org/10.1038/s41586-019-1098-2)
607 [s41586-019-1098-2](https://doi.org/10.1038/s41586-019-1098-2).
- 608 Canuto, V. M., and Y. Cheng, 2017: Contribution of sub-mesoscales to the vertical velocity: The
609 ω -equation. *Ocean Modelling*, **115**, 70–76, <https://doi.org/10.1016/j.ocemod.2017.05.004>.

- 610 D'Asaro, E. A., and Coauthors, 2017: Ocean convergence and the dispersion of flotsam. *Proc.*
611 *Natl. Acad. Sci. (USA)*, **115**, 1162–1167, <https://doi.org/10.1073/pnas.1718453115>.
- 612 Doglioli, A., 2015: OSCAHR cruise, RV Téthys II. <https://doi.org/10.17600/15008800>.
- 613 Esposito, A., and G. Manzella, 1982: Current circulation in the ligurian sea. *Elsev. Oceanogr.*
614 *Serie*, **34**, 187–203.
- 615 Ferrari, R., and C. Wunsch, 2009: Ocean circulation kinetic energy: Reservoirs, sources, and sinks.
616 *Annu. Rev. Fluid Mech.*, **41**, 253–282, <https://doi.org/10.1146/annurev.fluid.40.111406.102139>.
- 617 Fiekas, V., H. Leach, K. Mirbach, and J. Woods, 1994: Mesoscale instability and upwelling. part
618 1: Observations at the north atlantic intergyre frontsmesoscale instability and upwelling. part 1:
619 Observations at the North Atlantic intergyre front. *J. Phys. Oceanogr.*, **24**, 1750–1758.
- 620 Firing, E., and R. Gordon, 1990: Deep ocean acoustic Doppler current profiling. *Proceedings*
621 *of the IEEE Fourth Working Conference on Current Measurements*, Clinton, MD, Current
622 Measurements Technology Committee of the Oceanic Engineering Society, 192–201.
- 623 Fischer, J., and M. Visbeck, 1993: Velocity profiling with self-contained ADCPs. *J. Atmos. Oceanic*
624 *Technol.*, **10**, 764–773.
- 625 Frajka-Williams, E., C. C. Eriksen, P. B. Rhines, and R. R. Harcourt, 2011: Determining vertical
626 water velocities from seaglider. *J. Atmos. Oceanic Technol.*, **28**, 1641–1656, <https://doi.org/10.1175/2011JTECHO830.1>.
- 627
- 628 Fuda, J.-L., F. Marin, F. Durand, and T. Terre, 2013: Diagnosing ocean vertical velocities off New
629 Caledonia from a SPRAY glider. *Geophys. Res. Abstracts*, **15**, EGU2013-9721.
- 630 Giordani, H., L. Prieur, and G. Caniaux, 2006: Advanced insights into sources of vertical velocity
631 in the ocean. *Ocean Dyn.*, **56**, 513–524, <https://doi.org/10.1007/s10236-005-0050-1>.
- 632 Klein, P., and G. Lapeyre, 2009: The oceanic vertical pump induced by mesoscale and subme-
633 soscale turbulence. *Annu. Rev. Mar. Sci.*, **1**, 351–375, [https://doi.org/10.1146/annurev.marine.](https://doi.org/10.1146/annurev.marine.010908.163704)
634 [010908.163704](https://doi.org/10.1146/annurev.marine.010908.163704).
- 635 Lien, R. C., T. Y. Tang, M. H. Chang, and E. A. D'Asaro, 2005: Energy of nonlinear internal waves in
636 the South China Sea. *Geophys. Res. Lett.*, **32**, L05 615, <https://doi.org/10.1029/2004GL022012>.

- 637 Lindstrom, S. S., and D. R. Watts, 1994: Vertical motion in the Gulf Stream Near 68°W. *J. Phys.*
638 *Oceanogr.*, **24**, 2321–2333.
- 639 Lévy, M., P. J. S. Franks, and K. S. Smith, 2018: The role of submesoscale currents in structuring
640 marine ecosystems. *Nat. Commun.*, **9**, 4758, <https://doi.org/10.1038/s41467-018-07059-3>.
- 641 Lévy, M., D. Iovino, L. Resplandy, P. Klein, G. Madec, A.-M. Tréguier, S. Masson, and K. Taka-
642 hashi, 2012: Large-scale impacts of submesoscale dynamics on phytoplankton: Local and
643 remote effects. *Ocean Modelling*, **43**, 77–93, <https://doi.org/10.1016/j.ocemod.2011.12.003>.
- 644 Mahadevan, A., 2016: The impact of submesoscale physics on primary productivity of plankton.
645 *Annu. Rev. Mar. Sci.*, **8**, 161–184, <https://doi.org/10.1146/annurev-marine-010814-015912>.
- 646 Mahadevan, A., and A. Tandon, 2006: An analysis of mechanisms for submesoscale vertical motion
647 at ocean fronts. *Ocean Modelling*, **14**, 241–256, <https://doi.org/10.1016/j.ocemod.2006.05.006>.
- 648 Margirier, F., A. Bosse, P. Testor, B. L'Hévéder, L. Mortier, and D. Smeed, 2017: Characterization
649 of convective plumes associated with oceanic deep convection in the Northwestern Mediter-
650 ranean from high-resolution in situ data collected by gliders. *J. Geophys. Res. Oceans*, **122**,
651 9814–9826, <https://doi.org/10.1002/2016JC012633>.
- 652 Martin, A. P., K. J. Richards, and M. J. Fasham, 2001: Phytoplankton production and com-
653 munity structure in an unstable frontal region. *J. Mar. Syst.*, **28**, 65–89, [https://doi.org/10.1016/S0924-7963\(00\)00084-1](https://doi.org/10.1016/S0924-7963(00)00084-1).
- 654
- 655 McGillicuddy, D. J., 2016: Mechanisms of Physical-Biological-Biogeochemical Interaction
656 at the Oceanic Mesoscale. *Annu. Rev. Mar. Sci.*, **8**, 125–159, <https://doi.org/10.1146/annurev-marine-010814-015606>.
- 657
- 658 McWilliams, J. C., 2016: Submesoscale currents in the ocean. *Proc. Roy. Soc. A*, **472**, 20160117,
659 <https://doi.org/10.1098/rspa.2016.0117>.
- 660 Meloni, M., J. Bouffard, A. M. Doglioli, A. A. Petrenko, and G. Valladeau, 2019: Toward science-
661 oriented validations of coastal altimetry: Application to the Ligurian Sea. *Remote Sens. of*
662 *Environ.*, **224**, 275–288, <https://doi.org/10.1016/j.rse.2019.01.028>.

663 Merckelbach, L., D. Smeed, and G. Griffiths, 2010: Vertical water velocities from underwater
664 gliders. *J. Atmos. Oceanic Technol.*, **27**, 547–563, <https://doi.org/10.1175/2009JTECHO710.1>.

665 Millot, C., 1999: Circulation in the western mediterranean sea. *J. Mar. Syst.*, **20**, 423–442.

666 Petrenko, A. A., 2003: Variability of circulation features in the Gulf of Lion NW Mediterranean
667 Sea. Importance of inertial currents. *Oceanologica Acta*, **26**, 323–338, [https://doi.org/10.1016/](https://doi.org/10.1016/S0399-1784(03)00038-0)
668 [S0399-1784\(03\)00038-0](https://doi.org/10.1016/S0399-1784(03)00038-0).

669 Pinot, J.-M., J. Tintoré, and D.-P. Wang, 1996: A study of the omega equation for diagnosing
670 vertical motions at ocean fronts. *J. Mar. Res.*, **54**, 239–259.

671 Pollard, R. T., and L. A. Regier, 1992: Vorticity and vertical circulation at an ocean front. *J. Phys.*
672 *Oceanogr*, **22**, 609–625.

673 Polzin, K., E. Kunze, J. Hummon, and E. Firing, 2002: The finescale response of lowered ADCP
674 velocity profiles. *J. Atmos. Oceanic Technol.*, **19**, 205–224.

675 Rousselet, L., and Coauthors, 2019: Vertical motions and their effects on a biogeochemical tracer
676 in a cyclonic structure finely observed in the Ligurian Sea. *J. Geophys. Res. Oceans*, **124**,
677 3561–3574, <https://doi.org/10.1029/2018JC014392>.

678 Ruiz, S., and Coauthors, 2019: Effects of oceanic mesoscale and submesoscale frontal pro-
679 cesses on the vertical transport of phytoplankton. *J. Geophys. Res. Oceans*, **124**, 5999–6014,
680 <https://doi.org/10.1029/2019JC015034>.

681 Sardou, J., M. Etienne, and V. Andersen, 1996: Seasonal abundance and vertical distributions
682 of macroplankton and micronekton in the northwestern mediterranean sea. *Oceanol. Acta*, **19**,
683 645–656.

684 Sasaki, H., P. Klein, B. Qiu, and Y. Sasai, 2014: Impact of oceanic-scale interactions on the seasonal
685 modulation of ocean dynamics by the atmosphere. *Nat. Commun.*, **5**, 5636, [https://doi.org/](https://doi.org/10.1038/ncomms6636)
686 [10.1038/ncomms6636](https://doi.org/10.1038/ncomms6636).

687 Schott, F., and K. D. Leaman, 1991: Observations with moored acoustic doppler current profilers
688 in the convection regime in the golfe du lion. *J. Phys. Oceanogr.*, **21**, 558–574.

- 689 Schott, F., M. Visbeck, U. Send, J. Fischer, L. Stramma, and Y. Desaubies, 1996: Observations
690 of deep convection in the gulf of lions, northern mediterranean during the winter of 1991/92. *J.*
691 *Phys. Oceanogr.*, **26**, 505–524.
- 692 Shearman, R. K., J. A. Barth, and P. M. Kosro, 1999: Diagnosis of the three-dimensional circulation
693 associated with mesoscale motion in the California current. *J. Phys. Oceanogr.*, **29**, 651–670.
- 694 Steffen, E. L., and E. A. D’Asaro, 2002: Deep convection in the Labrador Sea as observed by
695 lagrangian floats. *J. Phys. Oceanogr.*, **32**, 475–492, [https://doi.org/10.1175/1520-0485\(2002\)](https://doi.org/10.1175/1520-0485(2002)032<0475:DCITLS>2.0.CO;2)
696 [032<0475:DCITLS>2.0.CO;2](https://doi.org/10.1175/1520-0485(2002)032<0475:DCITLS>2.0.CO;2).
- 697 Strass, V. H., 1994: Mesoscale instability and upwelling. part 2: Testing the diagnostics of vertical
698 motion with a three-dimensional ocean front model. *J. Phys. Oceanogr.*, **24**, 1759–1767.
- 699 Tarling, G., F. Buchholz, and J. Matthews, 1999: The effect of a lunar eclipse on the vertical
700 migration behaviour of *Meganyctiphanes norvegica* (crustacea: Euphausiacea) in the ligurian
701 sea. *J. Plankton Res.*, **21**, 1475–1488, <https://doi.org/10.1093/plankt/21.8.1475>.
- 702 Tarling, G., J. Matthews, P. David, O. Guerin, and F. Buchholz, 2001: The swarm dynamics of
703 northerne krill (*Meganyctiphanes norvegica*) and pteropods (*Cavolinia inflexa*) during vertical
704 migration in the ligurian sea observed by an acoustic doppler current profiler. *Deep-Sea Res. I*,
705 **48**, 1671–1686, [https://doi.org/10.1016/S0967-0637\(00\)00105-9](https://doi.org/10.1016/S0967-0637(00)00105-9).
- 706 Tarry, D. R., and Coauthors, 2021: Frontal convergence and vertical velocity measured by drifters
707 in the alboran sea. *J. Geophys. Res.*, **126**, <https://doi.org/10.1029/2020JC016614>.
- 708 Thomas, L., A. Tandon, and A. Mahadevan, 2008: Submesoscale ocean processes and dynamics.
709 *Ocean modeling in an eddying regime*, M. W. Hecht, and H. Hasume, Eds., Vol. 177.
- 710 Thurnherr, A. M., 2011: Vertical velocity from LADCP data. *IEEE/OES 10th Current, Waves and*
711 *Turbulence Measurements (CWTM)*, Monterey, CA, 198–204.
- 712 Tintoré, J., D. Gomis, S. Alonso, and G. Parrilla, 1991: Mesoscale dynamics and vertical motion
713 in the Alboran Sea. *J. Phys. Oceanogr.*, **21**, 811–823.

- 714 Tzortzis, R., and Coauthors, 2021: Impact of moderately energetic fine-scale dynamics on the
715 phytoplankton community structure in the western mediterranean sea. *Biogeosciences*, **18**, 6455–
716 6477, <https://doi.org/10.5194/bg-18-6455-2021>.
- 717 Weller, R. A., D. L. Rudnick, N. J. Pennington, R. P. Trask, and J. R. Valdes, 1990: Measuring
718 Upper Ocean Variability from an Array of Surface Moorings in the Subtropical Convergence
719 Zone. *J. Atmos. Oceanic Technol.*, **7**, 68–84.
- 720 Yu, X., A. C. N. Garabato, A. P. Martin, C. E. Buckingham, L. Brannigan, and Z. Su, 2019: An
721 Annual Cycle of Submesoscale Vertical Flow and Restratification in the Upper Ocean. *J. Phys.*
722 *Oceanogr.*, **49**, 1439–1461, <https://doi.org/10.1175/JPO-D-18-0253.1>.