

# *Evolution of oceanic near surface stratification in response to an autumn storm*

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1 **Evolution of Oceanic Near Surface Stratification in Response to**

2 **an Autumn Storm**

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## ABSTRACT

18 Understanding the processes that control the evolution of the ocean surface  
19 boundary layer (OSBL) is a prerequisite for obtaining accurate simulations of  
20 air-sea fluxes of heat and trace gases. Observations of the rate of dissipation of  
21 turbulent kinetic energy ( $\epsilon$ ), temperature, salinity, current structure and wave-  
22 field over a period of 9.5 days in the NE Atlantic during the Ocean Surface  
23 Mixing, Ocean Submesoscale Interaction Study (OSMOSIS), are presented.  
24 The focus of this study is a storm which passed over the observational area  
25 during this period. The profiles of  $\epsilon$  in the OSBL are consistent with profiles  
26 from large eddy simulation (LES) of Langmuir turbulence. In the transition  
27 layer (TL), at the base of the OSBL,  $\epsilon$  was found to vary periodically at the  
28 local inertial frequency. A simple bulk model of the OSBL and a parametrisa-  
29 tion of shear driven turbulence in the TL are developed. The parametrisation  
30 of  $\epsilon$  is based on assumptions about the momentum balance of the OSBL and  
31 shear across the TL. The predicted rate of deepening, heat budget and the in-  
32 ertial currents in the OSBL were in good agreement with the observations,  
33 as is the agreement between the observed value of  $\epsilon$  and that predicted using  
34 the parametrisation. A previous study reported spikes of elevated dissipation  
35 related to enhanced wind-shear alignment at the base of the OSBL after this  
36 storm. The spikes in dissipation are not predicted by this new parametrisation,  
37 implying that they are not an important source of dissipation during the storm.

## 38 **1. Introduction**

39 The ocean surface boundary layer (OSBL) is a critical interface in the Earth system, through  
40 which heat, freshwater, momentum and trace gases are fluxed between the atmosphere and the  
41 ocean (Belcher et al. 2012; Rippeth et al. 2014). Because of its importance, there is strong interest  
42 in understanding the processes that determine the characteristics and evolution of the OSBL (e.g.  
43 Kilbourne and Girton (2015); Aijaz et al. (2017)).

44 Mixing by turbulence in the OSBL tends to produce a layer with relatively weak vertical gra-  
45 dients in temperature and salinity which will be referred to as the well-mixed layer (WML). The  
46 WML is separated from the deeper ocean by a stratified transition layer (TL). Current shear across  
47 the transition layer may be associated with near inertial waves (NIW) (Plueddemann and Weller  
48 1999), which are a ubiquitous feature of the surface ocean (Pollard 1980; D'Asaro 1985), and  
49 are a significant energy source driving turbulent mixing in the ocean (Alford 2003; Watanabe and  
50 Hibiya 2002). The generation of inertial motions in the OSBL is highly intermittent, with storms  
51 providing an important source of energy (D'Asaro 1985; Large and Crawford 1995).

52 The shear associated with the NIW is concentrated across the stratified transition layer (Pollard  
53 and Millard 1970; D'Asaro 1985), which is often in a state of marginal stability, with a Richard-  
54 son number  $O(1)$ , so that the shear may result in the generation of turbulence in the TL (Johnston  
55 and Rudnick 2009; Rippeth et al. 2005, 2009). Observations reported by Burchard and Rippeth  
56 (2009); Lenn et al. (2011); Brannigan et al. (2013); Lincoln et al. (2016) suggest that the genera-  
57 tion of turbulence within the transition layer is a result of surface wind and current shear alignment  
58 which produces enhanced shear at the base of the WML. Using a one-dimensional model, Plued-  
59 demann and Farrar (2006) showed that the energy input into the NIW is balanced by the downward

60 propagation of NIW energy, and the local dissipation due to shear generated turbulence within the  
61 TL.

62 Generation of turbulence by shear across the TL is particularly efficient when the rate at which  
63 near surface winds rotate due to the motion of a storm, matching the inertial period of the wind-  
64 driven currents (Large and Crawford 1995; Dohan and Davis 2011; Chen et al. 2015). This reso-  
65 nance condition allows large shears to build at the base of the well-mixed layer, which can lead to  
66 the growth of a stratified shear layer below the WML, without significant impact on the thickness  
67 of the WML (Dohan and Davis 2011; Johnston et al. 2016; Chen et al. 2016).

68 Skillingstad et al. (2000) used large-eddy simulation (LES) to look at shear production in the TL  
69 for resonant and non-resonant situations. Compared to resonant conditions, the predicted current  
70 shear and turbulence were significantly smaller for non-resonant conditions. Grant and Belcher  
71 (2011) have derived a parametrisation for the magnitude of the maximum shear production and  
72 dissipation at the base of the WML, due to resonant wind forcing.

73 Here we present measurements of the dissipation rate,  $\epsilon$ , temperature and salinity of the wa-  
74 ter column, obtained by an Ocean Microstructure Glider over a period of 9.5 days. The mea-  
75 surements were obtained during the process cruise of the OSMOSIS (Ocean Surface Mixing and  
76 Submesoscale Interaction Study) project in the North East Atlantic in September 2012.

77 During the period of the observations a significant storm occurred. The aim of this study is to  
78 investigate the processes responsible for the evolution of the OSBL during the storm. To achieve  
79 this aim we will combine the profiles of  $\epsilon$  from the microstructure glider, with supporting data, to  
80 test a new parametrisation for OSBL mixing.

81 This paper is arranged as follows: Section 2 gives a description of the observational campaign  
82 together with the methods used to collect the data. Section 3 provides a description of the main

83 experimental results, Section 4 describes the turbulence measurements in the transition layer, and  
84 Section 5 concludes the paper with a discussion of the key results.

## 85 **2. Observations and Modelling**

86 The observations used in this study were collected during a multidisciplinary cruise aboard the  
87 Royal Research Ship Discovery (Allen et al. 2012), as part of the NERC OSMOSIS project. The  
88 cruise took place in the vicinity of the Porcupine Abyssal Plain (PAP) observatory (48.69°N,  
89 16.19°W) which is to the south west of the UK. The site is representative of the open ocean, with  
90 a water depth of  $\sim 4800$  m. The measurements were made from the evening of the 17<sup>th</sup> September  
91 2012, to the evening of the 27<sup>th</sup> September (year days 260 to 270).

92 The observations to be discussed were obtained using: 1) an Ocean Microstructure glider  
93 (OMG); 2) a TRIAXYS directional wave buoy; 3) ship borne measurements of meteorological  
94 data and 4) water velocities from an ADCP.

### 95 *a. Ocean Microstructure Glider (OMG)*

96 The OMG was a *Teledyne Webb Research* Slocum coastal electric glider equipped with an un-  
97 pumped *SeaBird* CTD sensor and a *Rockland Scientific International* MicroRider microstructure  
98 package. The OMG microstructure package samples shear microstructure, from which estimates  
99 of the dissipation rate,  $\epsilon$ , of turbulent kinetic energy (TKE) were determined (Fer et al. 2014;  
100 Palmer et al. 2015). During the OSMOSIS cruise, the glider profiled between the sea surface and  
101  $\sim 100$  m depth, capturing 1420 profiles over 9.5 days. A profile was obtained approximately every  
102 10 minutes, with a 20 minute gap for data upload every 10 profiles.

103 Spikes in the raw OMG microstructure shear data were removed by hand, after which the dis-  
104 sipation was calculated in bins of approximately 1 m vertical resolution following the methods

105 outlined in Merckelbach et al. (2010), Fer et al. (2014) and Palmer et al. (2015). Close to the  
106 ocean surface the dissipation estimates can be contaminated by glider motions induced by surface  
107 waves. To account for this, the near surface portion of the glider dissipation profiles have been  
108 truncated to exclude data from the surface to the deepest of: a) the significant wave height; b)  
109 the point where the glider speed drops below one standard deviation from the median (for this  
110 deployment); and c) the point where the glider pitch changes by more than one standard deviation  
111 from the median value (for this deployment). Typically the cutoff depth is about 5m.

112 Conductivity, temperature and depth (CTD) were provided by standard payload sensors (Sea-  
113 bird Electronics) housed in the central section of the OMG and are used to calculate salinity and  
114 density. CTD data were collected at 1 Hz during periods when the MicroRider was operative. Er-  
115 rors in salinity and density may occur due to inconsistencies between temperature and conductivity  
116 sensors, which are partly attributable to the physical separation of sensors and different response  
117 times, both of which can be simply corrected for. The raw temperature data from the un-pumped  
118 CTD sensor was low pass filtered (using a 3rd-order Butterworth filter), subsequently corrections  
119 to account for thermal inertia in the conductivity cell were made following the methods of Lueck  
120 and Picklo (1990) using modified parameters according to Palmer et al. (2015).

121 Temperature and salinity were then calibrated against CTD profiles obtained from the ship.  
122 Between year days 269 - 270.4, the un-pumped CTD sensor on the glider failed, and for this  
123 period temperatures have been obtained from the MicroRider probe. To ensure the MicroRider  
124 temperatures were consistent with the CTD temperatures a regression was made between the two  
125 instruments when they showed the same structure, between the deep water (75 – 100m) and surface  
126 waters (1 – 20m), and was used to reconstruct temperature when the CTD failed. It was not  
127 possible to reconstruct the missing salinity data.

128 *b. The TRIAXYS Wave Buoy*

129 The TRIAXYS directional wave buoy was deployed on the 7<sup>th</sup> September and recovered on  
130 the 27<sup>th</sup> September 2012, providing spectral energy data from 0 to 0.64Hz in frequency bins of  
131 0.01Hz, with directional-dependence resolved to 3° divisions, captured every 20 minutes. The  
132 Stokes drift,  $U_{s0}$ , is the integral of the third moment of the energy spectrum, and is estimated  
133 following Webb and Fox-Kemper (2011), namely:

$$U_{s0} = \frac{16\pi^3}{g} \int_0^{2\pi} \int_0^{\infty} (\cos\theta, \sin\theta) \omega^3 F^2(\omega, \theta) d\omega d\theta \quad (1)$$

134 where  $\omega$  is the wave frequency and  $\theta$  the directional-angle. In practice the wave buoy has a  
135 physical cut-off frequency after 0.64Hz, such that the highest frequency components of the wave  
136 field are not resolved. Thus for each time stamp and direction, a best-fit tail is extrapolated from  
137 the cut-off frequency using a minus 5<sup>th</sup> order power law (Phillips 1977). This directional patch  
138 for the unresolved tail is added to the resolved spectra and similarly integrated over frequency.  
139 Non-directional Stokes drift data used in this study are taken as the absolute values of the total  
140 directional Stokes drift, given at 20 minute intervals.

141 *c. Ship Data*

142 Atmospheric data were sampled throughout the cruise, using the ship's continuous recording  
143 instrumentation. Wind speed, direction, atmospheric pressure, air temperature, relative humidity,  
144 up-welling and down-welling shortwave irradiances were all measured at a height of 18m above  
145 mean sea surface. In all cases raw data was recorded at 10s intervals. Quality control, de-spiking  
146 and smoothing was applied to all data following Inall and Audsley (2012). The  $u$  and  $v$  components  
147 of the wind were smoothed, and obvious spikes removed manually. The remaining data was then  
148 interpolated onto a regular grid and a 120s median smoothing window applied.

149 The surface (air) friction velocity was calculated using:

$$u_{*a}^2 = C_D W_{10}^2 \quad (2)$$

150 where  $u_{*a}$  is the friction velocity on the air side of the air-ocean interface. The drag coefficient,  
151  $C_D$ , and 10m wind speed,  $W_{10}$ , were obtained iteratively by applying a log-law boundary layer to  
152 adjust for measurement height (Beardsley and Pawlowicz 1999).

153 The surface buoyancy flux,  $B_0$ , was calculated from the net surface heat flux,  $H_0$  as:

$$B_0 = -C_T g \frac{H_0}{\rho C_p} \quad (3)$$

154 where  $C_T = 1.6 \times 10^{-4} K^{-1}$  is the thermal expansion coefficient,  $g = 9.81 ms^{-2}$  is gravitational  
155 acceleration,  $\rho$  is the water density and  $C_p = 3993 J kg^{-1} K^{-1}$  is the specific heat capacity of water.

156 The net surface heat flux was calculated using:

$$H_0 = SW + IR + SH + LE \quad (4)$$

157 with shortwave radiation (SW) from the total incident radiation (TIR) sensors on-board, the long-  
158 wave (IR) radiation obtained from re-analysis data (National Oceanography Centre/University of  
159 Southampton, 2008) and the sensible (SH) and latent (LE) heat fluxes obtained using the TOGA  
160 COARE 2.0 algorithm (Fairall et al. 1996). To account for shading of the irradiance sensors, values  
161 of the TIR were created by taking the maximum value recorded by the port and starboard sensors.

162 Currents were determined with an RDI Ocean Surveyor 75 kHz Vessel Mounted-ADCP, config-  
163 ured to sample over 120 second intervals with 96 bins of 8 m length, giving a standard deviation  
164 of  $1.1 cms^{-1}$ . The instrument calibration and calculations of the GPS accuracy are documented in  
165 the D381 Cruise report (Allen et al. 2012). During some high wind/wave events data drop-out was  
166 apparent in the ADCP current profile data, probably due to cavitation below the ship's hull. This  
167 data was identified and masked for any 120s epoch that was more than 35% incomplete between

168 the surface and 200 m depth, this systematically removed most of the bad data, however the data  
169 around these incidents should be treated with caution.

#### 170 *d. Modelling*

171 The dissipation rates in the transition layer obtained from the OMG glider, will be compared  
172 with a simple parametrisation of the dissipation due to shear production. The parametrisation is  
173 based on results from LES, and the derivation of the parametrisation is given in Appendix A.

174 A simple bulk model of the OSBL is used to determine the inertial currents in the OSBL, and  
175 the evolution of the mixed layer depth. The model is described in Appendix B. The thickness of  
176 OSBL is assumed to increase through entrainment, with two parametrisations of entrainment con-  
177 sidered. The first assumes that entrainment is driven by a combination of convective and Langmuir  
178 turbulence (this will be referred to as the Langmuir model). Parametrisation of entrainment due to  
179 Langmuir turbulence have been proposed by Grant and Belcher (2009), McWilliams et al. (2013)  
180 and Li and Fox-Kemper (2017) . The second parametrisation assumes that entrainment is due to a  
181 combination of convective and conventional shear turbulence (referred to as the shear model). The  
182 parametrisation for shear turbulence is taken from Grant and Belcher (2009), which is similar to  
183 the parametrisation due to Li and Fox-Kemper (2017).

184 It is generally thought that Langmuir turbulence is important in the OSBL (McWilliams et al.  
185 1997; D'Asaro 2014), and so in the main part of the paper the results from the Langmuir model  
186 will be shown. However, since data on the occurrence of Langmuir turbulence is limited, and there  
187 is uncertainty as to when it may be a poor representation of turbulence in the OSBL, the results  
188 from the shear model will be considered in section 5.

189 The model is forced using ERA-Interim data, that includes wave data. The friction velocity,  
190 surface Stokes drift and buoyancy fluxes from ERA-Interim are in very good agreement with the



191 estimates obtained from the on-board meteorological measurements and the Stokes drift obtained  
192 from the TRIAXYS wave buoy. Differences in the surface fluxes obtained from ERA-Interim  
193 and from the ship data contribute to the uncertainties in making comparisons between the model  
194 and the observations. In lieu of formal estimates of the surface flux errors, it was decided to use  
195 ERA-Interim to force the models, and where necessary, the ship based flux to derive estimates of  
196 entrainment fluxes from the observations.

197 The initial temperature and salinity profiles that are used to initialise the bulk model were ob-  
198 tained from the glider and resolved to a grid of 1 m. These profiles were used to provide the tem-  
199 perature and salinity structure below the OSBL, which was assumed to remain constant through  
200 the storm period. The initial depth of the WML was taken to be 35 m, the same as the average  
201 mixed layer depth obtained from the glider profiles at the beginning of the storm.

### 202 **3. Surface Forcing and the Evolution of the OSBL**

203 Figures 2(a) and (b) show timeseries of the surface friction velocity, Stokes drift and the surface  
204 buoyancy flux obtained from the ship and buoy data over the full 9.5 days of the glider deployment.  
205 Time-depth cross sections of temperature and the turbulent dissipation rate are shown in Figs. 2(c)  
206 and (d), where the cyan line shows the mixed layer depth determined from the temperature profiles,  
207 defined as the level at which the temperature is  $0.2^{\circ}\text{C}$  lower than the temperature at a depth of 10m  
208 (de Boyer Montégut et al. 2004). The blue line shows the depth of the base of the transition  
209 layer, which is the depth below the MLD of the deepest isopycnal that lies wholly within one  
210 standard deviation of the mean mixed layer depth (see Eq. 1 in Johnston and Rudnick (2009)).  
211 This definition assumes that the transition layer thickness is related to the vertical displacements  
212 of the MLD and deeper isopycnals. These displacements have been found to be similar to the  
213 RMS displacement of a typical open ocean internal-wave spectrum (Johnston and Rudnick 2009;

214 Munk 1981) which suggests that internal waves are heaving the MLD and deeper isopycnals into  
215 and out of contact with surface-intensified mixing, creating the transition layer defined here.

216 The first 5 days (days 261 to 266) of the period are characterised by relatively low winds, and an  
217 average buoyancy flux which is negative, i.e. the ocean is gaining heat. During this early period  
218 the surface buoyancy flux shows a strong diurnal cycle. Although the mixed layer depth, obtained  
219 from the temperature profiles, is approximately constant with time, the depth of the OSBL implied  
220 by the thickness of the layer in which the dissipation rate is high, shows marked diurnal variations.

221 During the daytime, large values of TKE dissipation are generally limited to a layer near the  
222 surface, that is less than about 10m deep. During the night, large values of TKE dissipation extend  
223 down to the stable layer at the base of the WML, and is consistent with the turbulence generated  
224 by the loss of buoyancy at the surface. This pattern of a shallow, stable OSBL during the day,  
225 followed by a deeper convective OSBL at night is repeated over several days, with the exception  
226 of day 263, when the depth of the OSBL remains large during the day coinciding with elevated  
227 winds and reduced buoyancy flux.

228 Between days 266 and 270, a significant storm passed through the area, with maximum winds  
229 speeds reaching  $\sim 20 \text{ m s}^{-1}$  and significant wave heights of  $\sim 6\text{m}$ . The beginning and end of the  
230 storm are marked by the green lines in Fig. 2. During the storm the sensible and latent heat fluxes  
231 at the surface increase, with an average buoyancy flux for the period of the storm which is negative,  
232 indicating cooling of the surface waters.

233 Figure 2(c) shows that the stratification at the base of the OSBL weakens during the storm. Tem-  
234 perature profiles obtained during the storm are shown in Fig. 3. During the storm the WML and  
235 the transition layer tend to cool, although there is significant variability between the profiles, which  
236 is probably associated with submesoscale variations, which are present in the area throughout the

237 year (Thompson et al. 2016). Over the period the mixed layer depth increases from about 32m to  
238 41m while the depth of the base of the TL increases by about 4m.

239 Just prior to the start of the storm ( $\sim$  day 266.5) there is a change in salinity of  $\sim 0.3 \text{ g kg}^{-1}$   
240 below the OSBL (not shown), that coincides with the temperature change at this depth (Fig. 2(c)),  
241 however during the storm the changes in salinity are generally small ( $\sim 0.05 \text{ g kg}^{-1}$ ). At the  
242 start of the storm, Fig. 2(c) shows that there is a warming of the WML, that is accompanied by a  
243 reduction in the MLD.

244 The changes in temperature and salinity at the start of the storm may be due to advection, asso-  
245 ciated with horizontal changes in temperature, or changes in the position of glider relative to the  
246 horizontal gradients (Thompson et al. 2016). However, during the storm the data suggest that it is  
247 reasonable to consider that advective processes can be neglected, and that changes in the OSBL  
248 are primarily due to the surface forcing.

249 The track of the glider during the storm is shown in Fig. 1, and is consistent with the presence  
250 of inertial oscillations during the storm. The glider track shows clockwise rotations, which have a  
251 period of  $\sim 14.7$  hours, which is close to the local inertial period of 15.9 hours at the latitude of  
252 the PAP site.

253 Figure 4 compares the velocity predicted by the bulk model (see Appendix B) and observed  
254 currents from the ship's ADCP. In the model it is assumed that the current below the OSBL is  
255 zero, and so there are no tidal or geostrophic currents. To isolate the wind-driven part of the  
256 current in the WML, Fig. 4 show the difference between the ADCP measured currents in the  
257 WML and at 49m, the base of the transition layer.

258 The model predicts that inertial oscillations grow in amplitude from the start of the storm, and  
259 are superimposed on a mean wind-driven current. Towards the end of the storm the amplitude of  
260 the inertial oscillations is  $\sim 0.1 \text{ ms}^{-1}$ .

261 The observed north-south component of the current (Figure 4b) shows clear inertial oscillations  
262 from day 268, when the ship ADCP data is available. The amplitude of the observed oscillations  
263 are similar to those predicted by the model. The presence of oscillations is not as clear in the east-  
264 west component of the current. Because of the problems with the quality of the ADCP data during  
265 the storm, it is not clear whether the low amplitude of the oscillations in the east-west component  
266 of the current is real. With this caveat, the amplitude and timing of the inertial oscillations obtained  
267 from the model appear to be reasonable.

268 Figure 5 shows a time-depth cross section of the dissipation rate during the storm. The depth  
269 of the boundary between the high and low dissipation rate increases through the storm. However,  
270 in addition to the increase in the depth of the OSBL, there are also oscillations in the depth of the  
271 boundary superimposed on the overall increase.

272 The depth of the base of the OSBL, obtained from the bulk model, is shown by the dashed  
273 line in Fig. 5. The depth of the OSBL from the model increases steadily with time, due to  
274 entrainment. The magnitude of the deepening is consistent with the overall increase in the depth  
275 of the OSBL implied by the dissipation rate, although the model does not reproduce the higher  
276 frequency variation in the depth of the WML shown by the dissipation rate. The high frequency  
277 variations in the depth of the WML are probably not due to a stabilising influence surface buoyancy  
278 flux during daytime. The effects of stabilising surface fluxes on the depth of the OSBL are not  
279 included in the model, since in strong winds these effects should be small. In addition, the shoaling  
280 of the boundary layer due to a stabilising surface buoyancy flux would not lead directly to changes  
281 in the depth of the stable WML determined from the temperature profiles, apparent in Fig. 2(c)  
282 and (d).

283 Figure 6(a) shows the timeseries of the temperatures obtained from the glider, and the temper-  
284 atures obtained from the Langmuir model, averaged over the depth of the OSBL. Between days

285 265, just before the start of the storm, and day 270, at the end of the storm, the upper ocean cools  
286 by about  $1^{\circ}\text{C}$ . However, the cooling rate is not constant with time, and during latter part of day  
287 267, for example, the near surface temperature actually increases.

288 From day 268, until the end of the storm, the change in the temperature of the OSBL obtained  
289 from the bulk model is similar to the observed change. However, before day 268 the model does  
290 not reproduce the variation in the temperature. For example, the rapid cooling observed at the  
291 start is not reproduced by the model, and the model does not reproduce the local minimum in  
292 the observed temperature on day 267. These variations in the observed temperature are probably  
293 due to the presence of submesoscale variations in temperature (Thompson et al. 2016; Whitt and  
294 Taylor 2017).

295 Figure 6(b) shows an expanded view of the period from day 268 to the end of the storm, when  
296 the winds are strongest. During this period the fluctuations in the observed temperatures about the  
297 general cooling trend are small, making this a good period to evaluate the heat budget of the OSBL.  
298 The observed cooling, estimated from a linear fit to the observed temperatures, is  $-0.45 \pm 0.05^{\circ}\text{C}$   
299 (shown by the red line in Fig. 6b). The cooling predicted by the model is  $-0.38^{\circ}\text{C}$ . The overall  
300 heat budget of the OSBL that is implied by the model is therefore consistent with the observed  
301 budget.

302 The cooling in the model is due to the surface heat flux and the entrainment flux. The en-  
303 trainment flux obtained from the model is  $-250 \text{ Wm}^{-2}$ . This is in reasonable agreement with  
304 an entrainment flux of about  $-285 \pm 65 \text{ Wm}^{-2}$ , estimated from the observed cooling, assuming  
305 it is only due to the surface and entrainment fluxes. In the Langmuir model it is assumed that  
306 entrainment is due to a combination of convective and Langmuir turbulence. During this period,  
307 the entrainment flux in the model is primarily due to the Langmuir turbulence, which contributes

308 about  $-200 \text{ Wm}^{-2}$  to the total entrainment. The entrainment flux due to convective turbulence is  
309 about  $-60 \text{ Wm}^{-2}$ .

310 The Langmuir model, described in Appendix B, appears to be able to reproduce the evolution of  
311 important features of the OSBL, such as its thickness and cooling, during the storm. The Langmuir  
312 model assumes that entrainment is associated with Langmuir turbulence. Results obtained by  
313 assuming shear and convective turbulence is responsible for entrainment will be considered in  
314 section 5.

## 315 **4. The Transition Layer**

### 316 *a. The Storm Period*

317 Figures 7(a) and (b) show the dissipation profiles from the glider for two periods, days 266.25  
318 to 267.8 when the winds are increasing, and days 268.25 to 269.8 when the winds were strongest.  
319 The glider profiles have been scaled by  $w_{*L}^3/h_{\text{ml}}$ , where  $w_{*L} = (u_{*w}^2 U_{s0})^{1/3}$  is the velocity scale for  
320 Langmuir turbulence and  $h_{\text{ml}}$  is the depth of the WML (Grant and Belcher 2009). The structure  
321 for the OSBL from the dissipation profiles is consistent with the temperature profiles shown in  
322 Fig. 3, in that both sets of profiles show that the OSBL has two layers, the well-mixed layer and  
323 the stratified transition layer. The thickness of the transition layer appears to decrease between the  
324 two periods, due to the deepening of the WML, from 31.5m to 36m, while the depth of the base  
325 of the transition layer remains at about 47m.

326 A profile of the dissipation rate from one of the LES of Langmuir turbulence used in Grant and  
327 Belcher (2009) is also shown in Fig. 7(a) and (b). In the WML the LES profile is in reasonable  
328 agreement with the observed profiles. The LES dissipation rate profile decreases more rapidly with  
329 depth in the transition zone than the observed dissipation, although this difference is less marked

330 in the second period, due to the reduction in the thickness of the transition layer. The reduction  
331 in the thickness of the transition layer happens because, while the base of the well-mixed layer  
332 deepens, the depth of the base of the transition layer remains approximately constant. However,  
333 the thickness of the transition layer remains larger than the thickness of the transition layer in  
334 the LES profiles. Below the transition layer the observed dissipation rates are much larger than  
335 from the LES. This is because the dissipation rates below the transition layer in the real ocean are  
336 generally less than the noise level of the microstructure probe.

337 Skyllingstad et al. (2000) and Grant and Belcher (2011) have used LES to study the development  
338 of shear layers at the base of the WML. Skyllingstad et al. (2000) considered two cases. In the first,  
339 the surface stress rotated at the inertial period, and remained aligned with the current direction.  
340 Large shears developed across the TL, which increased in thickness. In the second case, the  
341 direction of the surface stress was kept constant, and the direction of the currents in the OSBL  
342 rotated relative to the surface stress. The shear and production of TKE at the base of the WML were  
343 much smaller than in the first case. The storm considered in this study corresponds to the second  
344 (non-resonant) case in Skyllingstad et al. (2000), since the winds associated with the present storm  
345 did not rotate at the inertial frequency.

346 To make a link between the inertial shear and the turbulence in the transition layer, a comparison  
347 is made with a simple parametrisation of the maximum dissipation rate due to shear production at  
348 the base of the WML and the dissipation rates from the glider. This parametrisation is tuned using  
349 the LES (to determine the coefficients alpha and beta) which is described in Appendix A, and is  
350 given by,

$$D = 0.3 \exp\left(-4.5 \frac{f h_{bl}}{u_{*w}}\right) \left( MAX \left\{ \frac{u_{*w}^2 (\langle \mathbf{U} \rangle_{ml} - \mathbf{U}_{ext})}{h_{bl}}, 0 \right\} + \beta MAX \left\{ f U_{s0} \delta \frac{(\langle \mathbf{V} \rangle_{ml} - \mathbf{V}_{ext})}{\Delta h}, 0 \right\} \right) \quad (5)$$

351 where  $D$  is the maximum in the dissipation rate,  $\langle \mathbf{U} \rangle_{ml}$  and  $\langle \mathbf{V} \rangle_{ml}$  are the components of the  
352 current parallel and perpendicular to the direction of the surface stress, averaged over the depth of  
353 the WML,  $\mathbf{U}_{ext}$  and  $\mathbf{V}_{ext}$  are the current components below the OSBL,  $u_{*w}$  is the water-side surface  
354 friction velocity,  $h_{bl}$  is the depth of the boundary layer. The surface friction velocity is defined by,  
355  $u_{*w}^2 = -\overline{\mathbf{u}'\mathbf{w}'_0}$ , where  $\overline{\mathbf{u}'\mathbf{w}'_0}$  is the surface value of the momentum flux,  $U_{s0}$  is the surface Stokes  
356 drift,  $\delta$  is the Stokes penetration depth and  $f$  is the Coriolis parameter.

357 The first term in the brackets, after the exponential function, on the right-hand side of Eq. 5  
358 represents the dissipation due to shear production by the current shear in the direction of the  
359 surface stress, and is the same as the parametrisation given by Grant and Belcher (2011) for the  
360 resonant conditions. The second term represents the shear production that is associated with the  
361 current shear perpendicular to the surface stress. Although  $\overline{\mathbf{v}'\mathbf{w}'}$  at the surface is zero, it increases  
362 rapidly with depth, and reaches maximum value just below the surface. The gradient of  $\overline{\mathbf{v}'\mathbf{w}'}$  above  
363 the maximum is assumed to be balanced by the Stokes-Coriolis force (Polton et al. 2005). The  
364 non-zero value of  $\overline{\mathbf{v}'\mathbf{w}'}$  within the OSBL leads to the production of TKE from the lateral shear at  
365 the base of the WML. Each of the components of the shear production must be greater than zero,  
366 i.e. the shear terms in the TKE budget do not act as a sinks for the TKE.

367 Figure 8(a)-(d) shows a comparison of timeseries of observed and predicted dissipation rate at  
368 different depths relative to the base of the WML. Figure 8(a) shows the dissipation rate 5m above  
369 the base of the WML, i.e. within the lower part of the WML. The dissipation rate at this depth



370 gradually increases with time, as the surface wind increases. The curve in Fig. 8(a) shows the  
371 dissipation rate calculated from,

$$\varepsilon = 0.05 \frac{w_{*L}^3}{h_{ml}} + 0.4B_0 \quad (6)$$

372 where the first term on the right-hand side is the dissipation rate due to Langmuir turbulence  
373 at the base of the WML. Grant and Belcher (2009) show for Langmuir turbulence the dissipation  
374 rate around the base of the WML is  $\sim 0.1 w_{*L}^3/h_{ml}$ , and the lower value for the coefficient in Eq.  
375 6 reflects the rapid variations of the dissipation rate with depth around the base of the WML.  
376 The second term is the dissipation rate due to the convective turbulence, which is assumed to  
377 be constant with depth (Lombardo and Gregg 1989). There may be periodic variations in the  
378 dissipation rate at this level, but if they are present they are not clear.

379 The magnitude of the dissipation rate in the TL decreases with increasing depth (see Fig 7). In  
380 addition, in the layer 5m to 10m below the base of the WML, the magnitude of the dissipation  
381 rate shows clear oscillations in time, the amplitude of the oscillations decreasing with depth. The  
382 black curves in Figs. 8(b)-(d) show the dissipation rates obtained from Eq. 5, assuming that  
383 the thickness of transition layer is 10m. The decrease in the amplitude of the oscillation in the  
384 dissipation rate with depth below the WML, is consistent with the amplitude of the oscillations  
385 going to zero around the base of the TL. Since Eq. 5 gives the dissipation rate at the base of the  
386 WML, to capture the decrease in the dissipation rate within the TL, the values obtained from Eq.  
387 5 have been multiplied by 1.0, 0.5 and 0.25 in Figs. 8(b) to (d). The magnitude of these factors is  
388 reasonable given that the dissipation rate tend to zero at the base of the TL, but having to use them  
389 means that a precise value of the coefficient in Eq. 5 can not be assessed using the data. A more  
390 complete parametrisation of the dissipation rate due to shear production in the TL would specify  
391 the depth dependence of the dissipation rate in the TL.

392 From the start of the storm, until the middle of day 268, the predicted dissipation rates from  
393 Eq. 5 are in good agreement with the observations. At 5m below the base of the WML, the  
394 observations show some high dissipation rates, which may reflect the presence of the relative large  
395 dissipation rates just above this depth. After day 268.5, the dissipation rates calculated from Eq.  
396 5 are about a factor of two larger than the observed dissipation rates, as shown by the red curves  
397 which show results from Eq. 5, multiplied by the factors given above and divided by two. The red  
398 curves match the observations during this period.

399 The bulk model does not give any information on the structure of the transition layer, and in  
400 estimating the dissipation rates from the parametrisation the thickness of the transition layer has  
401 been assumed to be a constant 10 metres. However, Figs. 7(a) and (b) show that the thickness of  
402 the transition layer decreases through the storm, and this may explain why, when matched to the  
403 dissipation rate before day 268.5, the parametrisation overestimates the dissipation rate after day  
404 268.5. A more sophisticated model and parametrisation would be needed to predict the evolution  
405 of the structure of the TL.

406 Grant and Belcher (2011) found that the magnitude of the buoyancy flux at the base of the  
407 WML, due to the shear production of turbulence, was  $\sim 33\%$  of the dissipation rate obtained from  
408 Eq 5. Using this with Eq. 5 suggests that the heat flux at the base of the WML due to shear  
409 production between days 268.25 and 269.8 is  $\sim -30\text{Wm}^{-2}$ . This is about 12% of the entrainment  
410 flux attributed to convective and Langmuir turbulence in the Langmuir model. This implies that  
411 for this storm the effects of shear turbulence on the evolution of the OSBL were small.

412 This analysis shows that (i) the evolution of the dissipation rate within the TL follows a different  
413 behaviour to the evolution of the dissipation rate within the ML, (ii) that the oscillations in the  
414 dissipation rate are coherent through the TL, (iii) that the period of the oscillations is close to the  
415 local inertial period, about 15.9hours.

416 *b. Post Storm Shear Spikes*

417 Burchard and Rippeth (2009) observed that enhanced turbulence was linked to alignment of  
418 the shear across the base of the OSBL with the direction of the surface wind. They called these  
419 periods of enhanced shear, shear spikes. The observations used by Burchard and Rippeth (2009)  
420 were obtained on the continental shelf, with a water depth of  $\sim 100\text{m}$ , where the currents were  
421 affected by tides. Brannigan et al. (2013) showed that shear spikes were present in the open ocean,  
422 although were unable to show that they were associated with periods of enhanced turbulent mixing.  
423 The models of Burchard and Rippeth (2009) and Brannigan et al. (2013) predict the occurrence of  
424 periods of enhanced shear, and so increased likelihood of shear instability. However, they do not  
425 predict the dissipation rate associated with the shear spikes.

426 Rumyantseva et al. (2015) observed similar shear spikes, with enhanced turbulence, at the PAP  
427 site on day 271, after the storm and shortly after the microstructure glider had been recovered. The  
428 surface winds were much lighter on day 271 than during the storm, but the currents continued to  
429 show the large amplitude inertial oscillations generated by the storm. Rumyantseva et al. (2015)  
430 measured the dissipation rate using an MSS90 microstructure profiler, and found that dissipation  
431 rates increased by over an order of magnitude during the shear spikes, reaching a magnitude of  
432  $\sim 10^{-7} \text{ W kg}^{-1}$ .

433 The model simulation was continued to cover the period of the observations of Rumyantseva  
434 et al. (2015) (not shown). The dissipation rates estimated from Eq. 5 for day 271 were much  
435 smaller than the observed dissipation rates during the shear spikes. The temperature-depth cross  
436 section given in Rumyantseva et al. (2015) suggests that the thickness of the pycnocline is smaller  
437 than it was during the storm, and that the temperature change across the pycnocline is smaller.  
438 The appearance of spikes in the dissipation rate during this period may be due to these changes,

439 although they don't explain why Eq. 5 doesn't apply during this period. This point will be consid-  
440 ered further in section 5.

## 441 **5. Discussion**

442 We have presented measurements of the dissipation rate in the North Eastern Atlantic which  
443 were obtained using a microstructure glider. During the period when the glider was deployed a  
444 storm passed over the area, and the data from the microstructure glider showed that there were  
445 oscillations in the dissipation rate in the transition layer at the base of the OSBL. The period of the  
446 oscillations was close to the local inertial period. The main aim of the study has been to compare  
447 the behaviour of the dissipation rate in the transition layer with a simple parametrisation of the  
448 dissipation associated with the production of TKE due to inertial oscillations in the current shear.  
449 The parametrisation was derived using results obtained from LES.

450 Reliable measurements of the current shear were not available, and to determine the current shear  
451 needed by the parametrisation, a simple bulk model (described in Appendix B) was used (Niiler  
452 and Kraus 1977). This model included a parametrisation of entrainment, which for the results  
453 shown in the previous sections assumed that turbulence in the OSBL was due to a combination  
454 of convective and Langmuir turbulence. In addition to predicting the currents during the storm,  
455 the model also predicted the evolution of the temperature and the depth of the base of the OSBL,  
456 which could be compared with the observations.

457 The change in the depth of the OSBL base, and the cooling of the OSBL obtained from the model  
458 were in reasonable agreement with the observed changes (Figs. 5 and 6). The agreement suggests  
459 that the assumption that Langmuir turbulence was present in the OSBL, and the parametrisation  
460 of entrainment by Langmuir turbulence obtained from LES are reasonable.

461 However, variations in the near surface temperature, which are probably due to the presence of  
462 submesoscale variability (Thompson et al. 2016), make it difficult to conclude from this compari-  
463 son that the Langmuir turbulence must be present. In particular, the observed cooling of the OSBL  
464 may have been affected by advection, and it is possible that the observations are consistent with  
465 other assumptions about entrainment. It is useful to compare the results from the Langmuir model  
466 with results obtained from a model in which entrainment is assumed to be due to conventional  
467 shear driven turbulence.

468 Over the last 1.5 days of the storm the cooling from the Langmuir model is  $-0.38^{\circ}\text{C}$ , which  
469 is similar to the observed cooling of  $-0.45 \pm 0.05^{\circ}\text{C}$ . The model suggests that entrainment is a  
470 significant term in the heat budget of the OSBL, and the agreement between the modelled and  
471 observed cooling depends on the parametrisation of entrainment.

472 The parametrisation for entrainment can be changed for one in which entrainment is assumed  
473 to be driven by convective and conventional shear turbulence (see Appendix B). Using this model,  
474 the cooling obtained over the same period is  $-0.31^{\circ}\text{C}$ . The reduction in the cooling is due to  
475 the parameterised entrainment flux being smaller than that in the Langmuir model. The entrain-  
476 ment flux due to shear turbulence, obtained from the shear model, is  $\sim -116\text{Wm}^{-2}$  compared to  
477  $\sim -250\text{Wm}^{-2}$  from the Langmuir model. The cooling from the shear model is just about con-  
478 sistent with the observations, particularly if the observed cooling is influenced by more than just  
479 the surface and entrainment fluxes. In addition to the uncertainties associated with the observa-  
480 tions, the constants used in the parametrisation are derived from LES, and may differ from values  
481 that might be obtained from direct observations. From this comparison it is not possible to con-  
482 clude that the Langmuir model is better than the shear model, although the Langmuir model gives  
483 reasonable results.

484 The change in the thickness of the OSBL during the storm obtained from the models also de-  
485 pends on the parametrisation of entrainment. For the Langmuir model the change in the thickness  
486 of the OSBL over the storm is about 8.8m, while for the shear model the change 5.4m. Figure 5  
487 shows that there is significant variability in the depth of the OSBL base, in addition to the overall  
488 increase in the thickness. This variability may be associated with the submesoscale variability in  
489 the area of the observations. The presence of this variability in the thickness OSBL in the ob-  
490 servations means it is not possible conclude that the Langmuir model is better than shear model,  
491 although again the results from the Langmuir model are reasonable.

492 What might be needed to come to a more definite conclusion? The differences between the  
493 two models used here increase with time, and in a storm of longer duration it is possible that the  
494 differences in the cooling and the change in the depth of the OSBL might become large enough for  
495 a more definite conclusion to be reached. With glider technology it should be possible to obtain  
496 more data during storms to help confirm the general presence of Langmuir turbulence in such  
497 situations, and the usefulness of LES in developing parametrisations, through studies such as this.

498 The agreement between the non-dimensional dissipation rates within the OSBL with the results  
499 from LES of Langmuir turbulence, given by Grant and Belcher (2009), cannot be used as support  
500 for the presence of Langmuir turbulence during the storm. The reason is that, when scaled with  
501  $u_{*w}^3/h_{ml}$ , Grant and Belcher (2009) showed that when the Langmuir number is  $\approx 0.3$ , the non-  
502 dimensional profiles agree with profiles of LES of conventional shear turbulence. Sutherland et al.  
503 (2014) have presented observations which suggest that the dependence of the non-dimensional  
504 dissipation rate on the Langmuir number is consistent with that found by Grant and Belcher (2009),  
505 but the variation in Langmuir number in the present data is not sufficient to confirm this.

506 The parametrisation of the dissipation rate given in Eq. 5 was obtained by assuming the base  
507 of the TL corresponds to the base of the OSBL, and that the profiles of  $\overline{\mathbf{u}'\mathbf{w}'}$  and  $\overline{\mathbf{v}'\mathbf{w}'}$  go to

508 zero at the base of the OSBL/TL. The dissipation rate in the TL varies with time because of the  
509 interaction between the boundary layer stresses and the time varying shear across the TL due to  
510 the inertial oscillations of the currents within the OSBL. In the LES, which were used to develop  
511 the parametrisation of the dissipation rate (Eq. 5), the bulk Richardson number for the TL was  
512 between 0.2 and 0.4 (Grant and Belcher 2011), and the thickness of the shear layer increased  
513 with time. However, during the storm, the bulk Richardson number of the TL was  $\sim 4$  when  
514 the turbulence dissipation was a maximum, and rather than increasing with time, the thickness of  
515 the transition layer decreased with time (see Fig. 7). Despite these differences in the stability of  
516 the TL, the comparison shown in Fig. 8 suggests that the Eq. 5 is a reasonable parametrisation,  
517 although it is not obvious why this should be.

518 A possible reason why Eq. 5 works during the storm is that the TL is not an isolated shear  
519 layer, but is connected to the well-mixed region of the OSBL through the transport of turbulent  
520 kinetic energy into the upper part of the TL. Studies of entrainment in the sheared convective  
521 atmospheric boundary layer show that shear production of turbulence in the inversion can occur  
522 for gradient Richardson number significantly above  $1/3$  (Haghshenas and Mellado 2019), similar  
523 to the situation during the storm. Haghshenas and Mellado (2019) found that as the shear increases,  
524 the gradient Richardson number tends to a value of about  $1/3$ , similar to the values in the LES  
525 (Grant and Belcher 2011). While the present situation is not directly comparable to entrainment  
526 in the atmospheric boundary layer, the interaction between the well-mixed layer and the transition  
527 layer through the transport of TKE may help explain why the results obtained with Eq. 5 are  
528 reasonable. Further studies are needed to improve our understanding of processes in the transition  
529 layer.

530 In this study the parametrisation for the dissipation in the TL has only used diagnostically,  
531 and the effects of the shear generated turbulence were not included in the bulk model. This is

532 reasonable since the shear production of turbulent kinetic energy during this storm was relatively  
533 low, but in a more complete model, in which the effects of the shear production of TKE are  
534 included, a representation of the evolution of the transition layer may be possible. In particular,  
535 the evolution of the depth of the transition layer, which was simply specified in the present study,  
536 would need to be modelled.

537 The microstructure glider was recovered after the end of the storm, but further measurements  
538 of the dissipation were obtained after the storm using a profiler deployed from the Discovery  
539 (Rumyantseva et al. 2015), finding evidence of shear spikes (Burchard and Rippeth 2009; Lenn  
540 et al. 2011; Brannigan et al. 2013; Lincoln et al. 2016). Shear spikes are associated with the  
541 generation of turbulence within the transition layer, as a result of surface wind and current shear  
542 alignment which produces enhanced shear. The dissipation rate during the shear spikes was  $\approx$   
543  $10^{-7} \text{ W kg}^{-1}$ , which is similar to the peak dissipation rates due to shear production that were  
544 observed in the TL during the storm. However, during the post-storm period the surface winds  
545 were much lighter than winds during the storm, and the dissipation rates implied by the present  
546 model are negligible, due to the dependence of the dissipation rate on  $fh_{\text{bl}}/u_{*w}$ .

547 The rate of work by the surface stress acting on the inertial currents in the OSBL is  $u_{*w}^2 U/h_{\text{bl}}$ ,  
548 where  $U$  is the current parallel to the surface stress, averaged over the depth of the OSBL, (Grant  
549 and Belcher 2011). This can be thought of as the divergence of a flux of mean kinetic energy, where  
550 the surface flux is  $u_{*w}^2 U$ . For the post-storm period, currents from the model give  $u_{*w}^2 U/h_{\text{bl}} \approx 10^{-7}$   
551  $\text{W kg}^{-1}$ . The coincidence in the magnitude of the dissipation rate during the shear spikes and the  
552 rate at which work is being done by the surface stress acting on the inertial currents suggests that  
553 the turbulence associated with shear spikes arises directly from the breakdown of the shear at the  
554 base of the OSBL. Since the turbulence is assumed to occur because of the work done on the mean  
555 flow by the surface stress, there is no contribution to the production of TKE from the component



556 of the current that is perpendicular to the surface stress. This is in contrast to the parametrisation  
557 given in Eq. 5 where the production of TKE by the lateral shear is assumed to occur, as the steady-  
558 state momentum balance of the OSBL implies  $\overline{\mathbf{v}'\mathbf{w}'}$  is not zero below the surface. The changes in  
559 the properties of the pycnocline that occurred after the storm, which should have reduced the bulk  
560 Richardson number, would make the generation of turbulence from the simple breakdown of the  
561 shear possible.

562 The data presented in this study has been analysed using a one-dimensional framework, and any  
563 effects due to submesoscale processes have been neglected. Whitt and Taylor (2017) have recently  
564 presented results from a large-domain LES (horizontal domain 1.9x1.9 km) of the storm in this  
565 study. By coincidence their domain size was comparable to the diameter of the circular path taken  
566 by the glider during the storm (see Fig 1a).

567 This simulation shows submesoscale features, with scales of order 1km, develop during the  
568 storm, and help to maintain stable stratification within the mixed layer. The variability in the  
569 temperatures measured by the glider, shown in Fig. 6, may be due to this submesoscale variability.  
570 Whitt and Taylor (2017) also found that turbulence levels showed significant horizontal variability  
571 that was related to the submesoscale variability in the stratification. Given these results, it is  
572 reasonable to ask if the one-dimensional approach used here is valid.

573 The results of this study suggest, that despite the presence of submesoscale variability, the one-  
574 dimensional assumption is reasonable. Dissipation rates within the bulk of the OSBL are consis-  
575 tent with scaling results from LES. The bulk model produced reasonable estimates for the cooling  
576 of the OSBL, and the increase in the thickness of the OSBL. While the presence of submesoscale  
577 variability may have made it difficult to decide which form of turbulence was present in the WML  
578 (Langmuir or shear), the evolution of the OSBL could be described reasonably well using a one-  
579 dimensional framework.

## 580 **6. Summary**

581 This paper has used observations from a microstructure glider, together with a simple bulk model  
582 of the OSBL and dissipation in the transition layer, to help understand the turbulence and evolution  
583 of the OSBL during a storm. The key results from this study are,

- 584 • The OSBL has a two layer structure, a well mixed layer separated from the deeper water by a  
585 stratified transition layer. The flow in the transition layer is turbulent, with the dissipation rate  
586 showing periodic variations, with a period close to the local inertial period ( $\sim 15.9$  hours).
- 587 • A parametrisation of the dissipation rate due to shear turbulence was developed using re-  
588 sults from LES. The dissipation rates obtained from the parametrisation were in reasonable  
589 agreement with the dissipation rates obtained by the microstructure glider in the TL. The  
590 Richardson number for the TL was about 4, suggesting that it was too stable for shear turbu-  
591 lence to develop. It is possible that the transport of TKE from the WML into the TL plays a  
592 role.
- 593 • The evolution of the thickness of the OSBL and its heat budget were obtained using a sim-  
594 ple bulk model in which entrainment was assumed to be due to Langmuir turbulence. The  
595 parametrisation of entrainment due to Langmuir turbulence was obtained from LES. The  
596 model results suggest that cooling of the OSBL due to entrainment was significant. Although  
597 the observations are consistent with this model, and the presence of Langmuir turbulence, the  
598 duration of the storm was not long enough conclude that this model was better than one in  
599 which entrainment is assumed to be due to conventional shear turbulence.
- 600 • The parametrisation of the dissipation rate developed in this study did not predict the occur-  
601 rence of dissipation due to shear spikes after the storm. It is not clear why, but it was noted  
602 that the observed dissipation rate during the shear spikes was comparable to the rate of work

603 done by the surface stress on the mean currents in the OSBL, and that changes to the pycno-  
604 cline probably made the breakdown of the shear likely. However, further work is needed to  
605 understand the generation of turbulence associated with shear spikes.

- 606 • The parametrisations for entrainment in the bulk model were obtained from LES. Since the  
607 constants in the bulk model were obtained from the LES it was not necessary to tune the model  
608 to other observations, and the results from the study provide an example of the usefulness of  
609 LES in developing parametrisations.

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## 615 APPENDIX A

### 616 **Parametrisation of shear production at the base of the OSBL**

617 In this appendix a parametrisation of the shear production of TKE at the base of the OSBL  
618 is developed. The parametrisation is based on the work of Grant and Belcher (2011), which is  
619 extended to include the effects of inertial oscillations in the OSBL. Grant and Belcher (2011)  
620 only considered the case where the direction of the surface stress and the currents in the OSBL  
621 were aligned and constant in time (which was approximated by setting the Coriolis parameter  
622 to zero). They developed the following parametrisation for the generation of turbulence kinetic  
623 energy (TKE) by the shear,

$$S_U = -\overline{\mathbf{u}'\mathbf{w}'}_{ml} \left. \frac{\partial \mathbf{U}}{\partial z} \right|_{ml} \sim \frac{u_{*w}^2 (\langle \mathbf{U} \rangle_{ml} - \mathbf{U}_{ext})}{h_{bl}} \quad (\text{A1})$$

624 where,  $S_U$  is the shear production,  $\mathbf{U}$  is the component of the current in the direction of the surface  
 625 stress,  $\partial \mathbf{U} / \partial z|_{ml}$  is the shear at the base of the well-mixed layer,  $\overline{\mathbf{u}'\mathbf{w}'}_{ml}$  is the turbulent momentum  
 626 flux at the base of the well-mixed layer,  $u_{*w}$  is the surface friction velocity of water,  $\langle \mathbf{U} \rangle_{ml}$  is the  
 627 average velocity in the well-mixed layer,  $h_{bl}$  is the depth of the boundary layer and  $\mathbf{U}_{ext}$  is the  
 628 current velocity at the base of the boundary layer. The surface friction velocity is defined as,  
 629  $u_{*w}^2 = -\overline{\mathbf{u}'\mathbf{w}'}_0$ , where  $\overline{\mathbf{u}'\mathbf{w}'}_0$  is the surface value of the momentum flux.

630 When the currents and surface stress rotate, the total shear production is,

$$S = -\overline{\mathbf{u}'\mathbf{w}'}_{ml} \left. \frac{\partial \mathbf{U}}{\partial z} \right|_{ml} - \overline{\mathbf{v}'\mathbf{w}'}_{ml} \left. \frac{\partial \mathbf{V}}{\partial z} \right|_{ml} \quad (\text{A2})$$

631 where,  $S$  is the total shear production,  $\mathbf{V}$  is the component of the current perpendicular to the  
 632 surface stress,  $\overline{\mathbf{v}'\mathbf{w}'}_{ml}$  is the lateral component of the momentum flux, at the base of the well-mixed  
 633 layer, (and  $\overline{\mathbf{u}'\mathbf{w}'}_{ml}$  is the component in the direction of the surface momentum flux) and  $\partial \mathbf{V} / \partial z|_{ml}$   
 634 is the shear in the lateral component of the current, at the base of the well-mixed layer.

635 Following Grant and Belcher (2011),  $\overline{\mathbf{u}'\mathbf{w}'}_{ml}$  is parameterised as  $-u_{*w}^2 (1 - h_{ml}/h_{bl})$ , where  $h_{ml}$   
 636 is the depth of the mixed layer (which for the LES results is defined as the level of the minimum  
 637 buoyancy flux), and  $\partial \mathbf{U} / \partial z|_{ml} \propto (\langle \mathbf{U} \rangle_{ml} - \mathbf{U}_{ext}) / (h_{bl} - h_{ml})$ , so that the first term of Eq. A2 is  
 638 given by Eq. A1.

639 At the surface,  $\overline{\mathbf{v}'\mathbf{w}'}_0 = 0$ , but within the WML  $\overline{\mathbf{v}'\mathbf{w}'}$  is positive (in the northern hemisphere),  
 640 with a maximum in the lower part of the OSBL (Zikanov et al. 2003). The maximum value of  $\overline{\mathbf{v}'\mathbf{w}'}$   
 641 can be estimated by considering the balance between the Coriolis force on the near surface drift  
 642 and stress gradient. The magnitude of the near surface drift is about 3% of the windspeed (Wu

1983), and in the open ocean is mainly due to the Stokes drift that is associated with the surface waves (Wu 1983). Taking the depth of the maximum in  $\overline{\mathbf{v}'\mathbf{w}'}$  to be  $\sim \delta$ , where  $\delta$  is the Stokes penetration depth, the balance between the stress gradient and the Stokes-Coriolis force gives,

$$\overline{\mathbf{v}'\mathbf{w}'}_{ml} \sim f u_{s0} \delta \quad (\text{A3})$$

where  $f$  is the Coriolis parameter,  $u_{s0}$  is the surface Stokes drift.

Using Eq. A3 the shear production associated with the velocity component perpendicular to the surface stress can be parameterised as,

$$S_v = -\alpha \beta f u_{s0} \delta \frac{(\langle \mathbf{V} \rangle_{ml} - \mathbf{V}_{ext})}{\Delta h} \quad (\text{A4})$$

where  $\langle \mathbf{V} \rangle_{ml}$  is the average of  $\mathbf{V}$  over the well-mixed layer,  $\mathbf{V}_{ext}$  is  $\mathbf{V}$  at the base of the OSBL,  $\Delta h$  is the thickness of the pycnocline and  $\beta$  is a coefficient.

The total shear production is the sum of  $S_u$  from Eq. A1 and  $S_v$  from Eq. A4, and is given by,

$$S = \alpha \left( \text{MAX} \left\{ \frac{u_{*w}^2 (\langle \mathbf{U} \rangle_{ml} - \mathbf{U}_{ext})}{h_{bl}}, 0 \right\} + \beta \text{MAX} \left\{ f u_{s0} \delta \frac{(\langle \mathbf{V} \rangle_{ml} - \mathbf{V}_{ext})}{\Delta h}, 0 \right\} \right) \quad (\text{A5})$$

The results from the LES are consistent with the shear production associated with each of the velocity components having to be greater than zero, which is represented in Eq. A5 by the *MAX* functions.

Figure A1(a) shows the timeseries of maximum shear production from the LES, compared to the parameterised shear production determined from from Eq. A5. The time in Fig. A1 has been normalised by the inertial period,  $T_I = 2\pi/f$ . The LES used to obtain the estimates of the shear production was the same as the simulations described in Grant and Belcher (2011), but with the Coriolis parameter set to  $0.25 \times 10^{-4} \text{ s}^{-1}$ . The averages over the well-mixed layer, the thicknesses

660 of the well-mixed layer and the shear layer that are needed to calculate the shear production from  
661 Eq. A5 were also determined from the LES for this comparison.

662 For the first  $0.4 T_I$  the shear production from the LES is large and approximately constant. From  
663  $0.4 T_I$  to  $0.7 T_I$  the shear production decreases, becoming constant after  $0.7 T_I$ . Before  $0.7 T_I$ , rea-  
664 sonable agreement between the shear production obtained from Eq. A5, and the shear production  
665 from the LES, is obtained with  $\alpha = 0.2$  and  $\beta = 1.5$ .

666 Before  $0.7 T_I$  the time variation on the shear production is associated with the rotation of of the  
667 inertial current with respect to the surface stress. After  $0.7 T_I$  the shear production associated with  
668 the inertial shear is zero, and the shear production is due to current shear in the well mixed layer  
669 that is associated with Langmuir turbulence (Grant and Belcher 2009).

670 The value of  $\alpha = 0.2$  in the parametrisation of the shear production is smaller than  $\alpha = 0.4$   
671 obtained by Grant and Belcher (2011), and suggests that  $\alpha$  is a function of a non-dimensional  
672 parameter. The most obvious candidate for this non-dimensional parameter is  $fh_{bl}/u_{*w}$ , the ratio  
673 of the depth of the OSBL to the Ekman depth,  $u_{*w}/f$ .

674 Figure A1(b) shows the values of  $\alpha$  obtained by Grant and Belcher (2011), the present value and  
675 the value obtained from a third LES with  $f = 0.5 \times 10^{-4} \text{s}^{-1}$ , as a function of  $fh_{bl}/u_{*w}$ . The param-  
676 eter  $\alpha$  decreases as  $fh_{bl}/u_{*w}$  increases. The curve in Fig. 6 shows  $\alpha = 0.4 \exp(-4.5 fh_{bl}/u_{*w})$ ,  
677 and is used as an approximate parametrisation for  $\alpha$  in the main text.

678 The observations used in the present study are of the dissipation rate,  $\varepsilon$  rather than shear produc-  
679 tion. Grant and Belcher (2011) found that the dissipation was about 75% of the shear production.  
680 Assuming that this holds when the Coriolis parameter is not zero, the parametrisation of the dissi-  
681 pation rate is,

$$D = 0.3 \exp(-4.5fh_{bl}/u_{*w}) \left( MAX \left\{ \frac{u_{*w}^2 (\langle \mathbf{U} \rangle_{ml} - \mathbf{U}_{ext})}{h_{bl}}, 0 \right\} + \beta MAX \left\{ fU_{s0} \delta \frac{(\langle \mathbf{V} \rangle_{ml} - \mathbf{V}_{ext})}{\Delta h}, 0 \right\} \right) \quad (A6)$$

## APPENDIX B

### The bulk model

In this appendix we describe the simple bulk model of the OSBL that is used in the body of the paper to understand the evolution of the OSBL shown in the observations. The inertial shear needed to estimate the dissipation is obtained using a bulk model of the OSBL. Following Niiler and Kraus (1977), this model predicts the time evolution of the buoyancy, and components of the current averaged over the OSBL. From the observations, the dissipation rate at the base of the OSBL is small, and so the model does not include the effects of shear turbulence on the evolution of the OSBL. The equations for the currents and buoyancy are,

$$\frac{\partial \langle U \rangle_{ml}}{\partial t} = -\frac{\overline{u'w'_0}}{h_{bl}} - \frac{(\langle U \rangle_{ml} - U_{ext})}{h_{bl}} \frac{\partial h_{bl}}{\partial t} \quad (B1)$$

$$\frac{\partial \langle V \rangle_{ml}}{\partial t} = -\frac{\overline{v'w'_0}}{h_{bl}} - \frac{(\langle V \rangle_{ml} - V_{ext})}{h_{bl}} \frac{\partial h_{bl}}{\partial t} \quad (B2)$$

$$\frac{\partial \langle B \rangle_{ml}}{\partial t} = \frac{(\overline{w'b'_{ent}} - \overline{w'b'_0})}{h_{bl}} \quad (B3)$$

where  $\overline{u'w'_0}$ ,  $\overline{v'w'_0}$  and  $\overline{w'b'_0}$  are the surface momentum and buoyancy fluxes and  $\overline{w'b'_{ent}}$  is the buoyancy flux due to entrainment. In Eqs B1 and B2, the components of the current and turbulent fluxes are relative to a fixed, geographic frame.

Following Grant and Belcher (2009), the entrainment buoyancy flux is parametrised as,

$$\overline{w'b'_{ent}} = -0.2\overline{w'b'_0} - 0.033\frac{w_{*L}^3}{h_{bl}} \quad (\text{B4})$$

695 where the first term on the right-hand side is the entrainment flux associated with the forcing by  
 696 the surface buoyancy flux and the second term represents entrainment due to Langmuir turbulence.  
 697 In Eq. B4 it has been assumed that the total entrainment due to the combination of convective and  
 698 Langmuir turbulence is just the sum of the individual entrainment fluxes.

699 From the results in Grant and Belcher (2009), the entrainment flux due to shear turbulence can  
 700 be parametrized as,

$$\overline{w'b'_{ent}} = -0.2\overline{w'b'_0} - 0.15\frac{u_{*w}^3}{h_{bl}} \quad (\text{B5})$$

701 The equation for the depth of the base of the OSBL is,

$$\frac{\partial h_{bl}}{\partial t} = -\frac{\overline{w'b'_{ent}}}{\Delta B} \quad (\text{B6})$$

702 where,  $\Delta B = \langle B \rangle_{ml} - B_{ext}$

703 Equation B6 is describes the evolution of the depth of an entraining boundary layer in mixed-  
 704 layer models (Niiler and Kraus 1977). The effects of shear turbulence are expected to be small for  
 705 this storm, and so the effects of current shear on the depth of the OSBL have not been included in  
 706 Eq's. B4 & B6. Given the strong winds during the storm, the shortwave irradiance was not large  
 707 enough to lead to the formation of a shallow, stable boundary layer, and the model only considers  
 708 the evolution of the depth of the OSBL due to entrainment.

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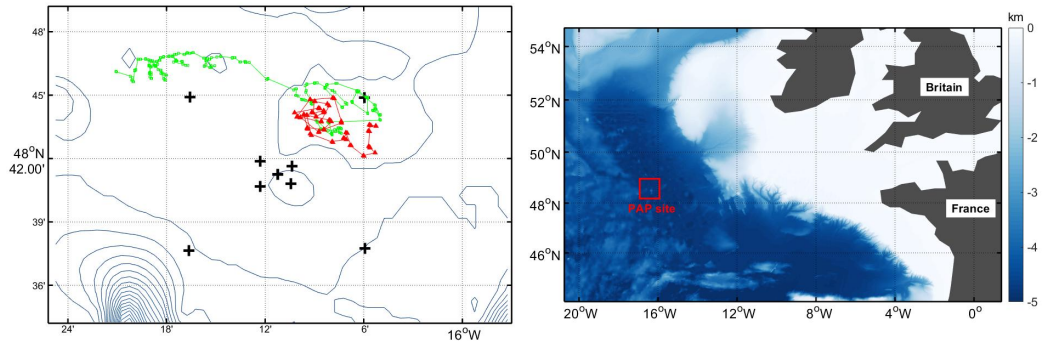
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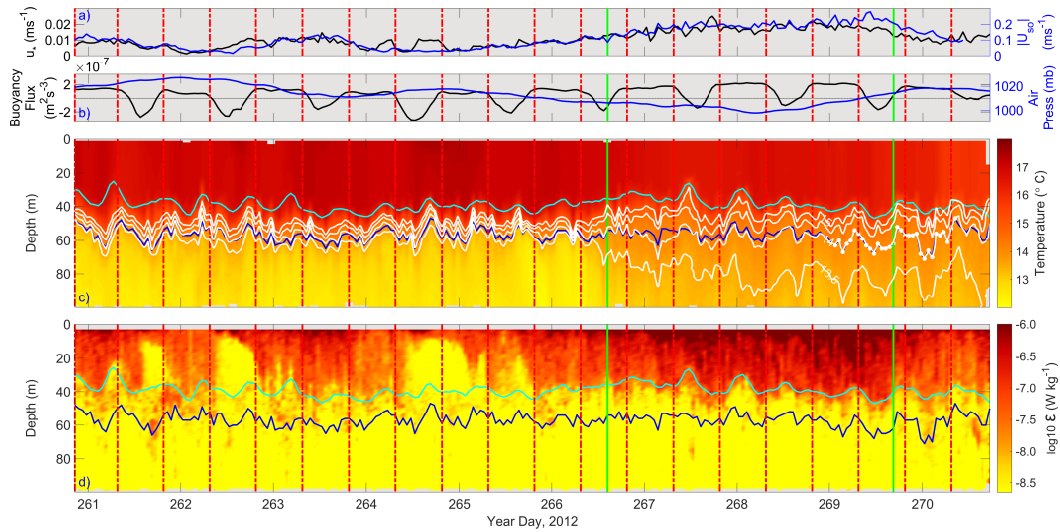
- 852
- 853 **Fig. 1.** Location of the Porcupine Abyssal Plain (PAP) site used for the OSMOSIS project. Panel b)  
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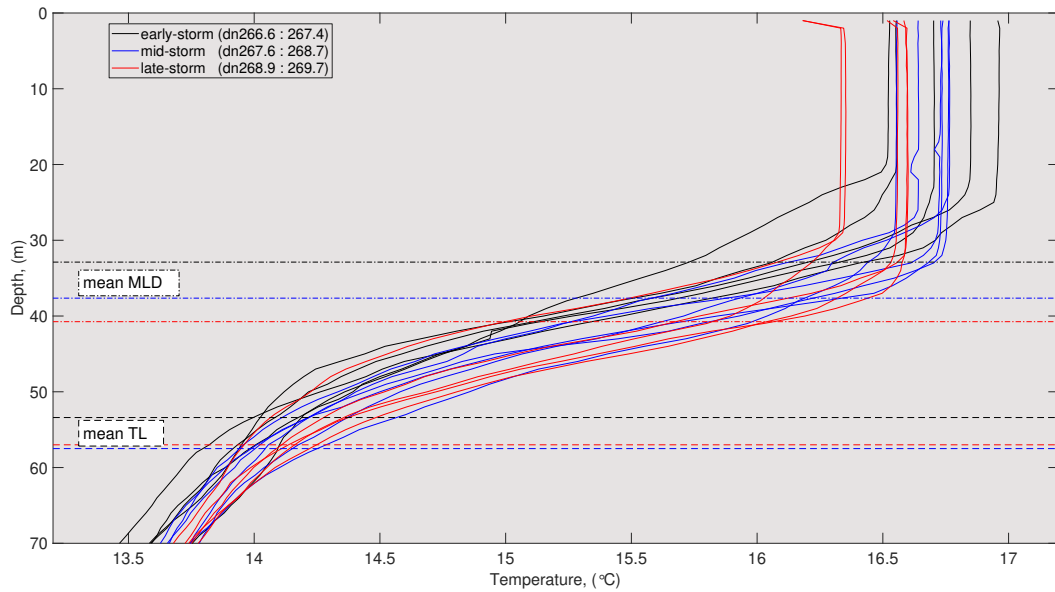
896 **Fig. A1.** Comparison of shear production from the simulation with  $f = 0.25 \times 10^{-4} s^{-1}$  (crosses) and  
897 the parameterisation, Eq. A2 (curve). (b) The parameter  $\alpha$  in Eq. A2 as a function of  
898  $fh_{bl}/u_{*w}$ . The dotted curve is  $\alpha = 0.4 \exp(-4.5 fh_{bl}/u_{*w})$ . . . . . 51



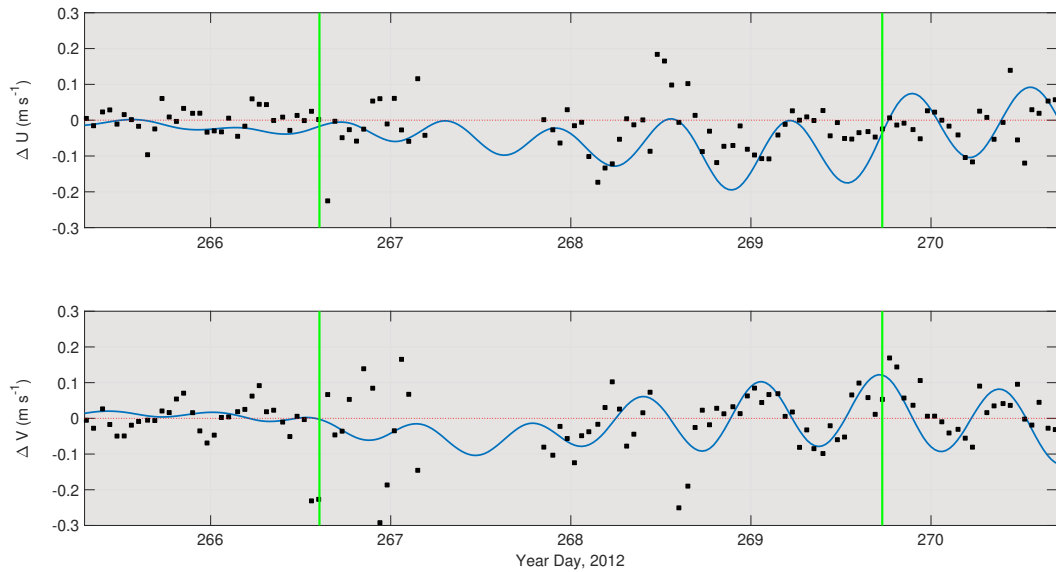
899 FIG. 1. Location of the Porcupine Abyssal Plain (PAP) site used for the OSMOSIS project. Panel b) shows  
 900 the PAP site location, panel a) is the PAP site box-to-scale; Black crosses represent the mooring array, the green  
 901 and red data shows the track of the OMG, which commenced in the North West corner and traversing roughly  
 902 South East. The red colouring denotes the storm period.



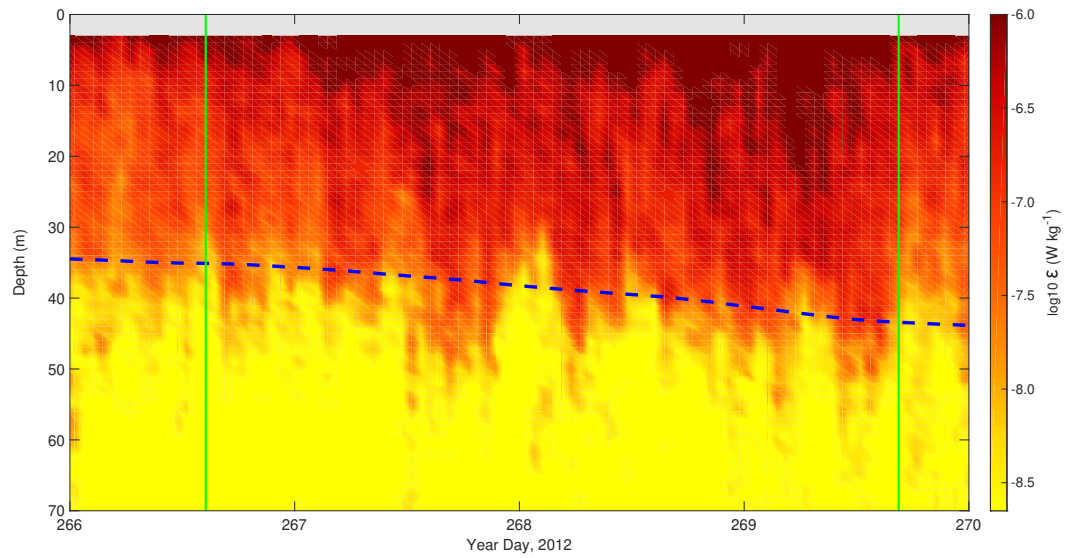
903 FIG. 2. The environmental conditions. Panels a) and b) show the meteorological time-series: Panel a) shows  
 904 the friction velocity  $u_{*w}$  (black) and the Stokes drift amplitude  $U_{so}$  (blue); Panel b) shows the buoyancy flux  $B_0$   
 905 (black) and air pressure (blue). Panels c) - d) show the oceanic time-series with the Mixed Layer Depth (MLD)  
 906 and the Transition Layer Depth (TLD) displayed on each (cyan and blue respectively). Panels c) shows the  
 907 profiling OMG temperature time-series with 0.5 degree Celsius contours (white). Panel d) shows the profiling  
 908 OMG dissipation time-series. The vertical red dashed lines show the approximate sunrise/sunset periods and the  
 909 vertical green lines show the start and end of the 'storm period'.



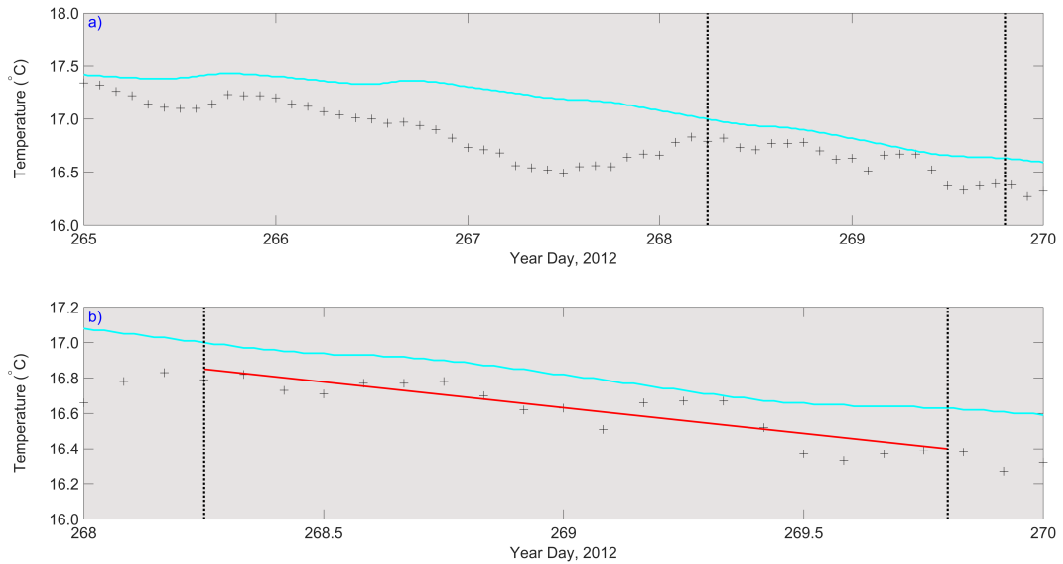
910 FIG. 3. Temperature profiles during the storm period, where the storm is split into three equal periods: early  
 911 storm (black); mid-storm (blue); late-storm (red). The horizontal lines represent the mean MLD and TLD for  
 912 each period. The mixed layer cools in response to the storm, while the Transition Layer warms. The MLD and  
 913 TLD deepen during the storm.



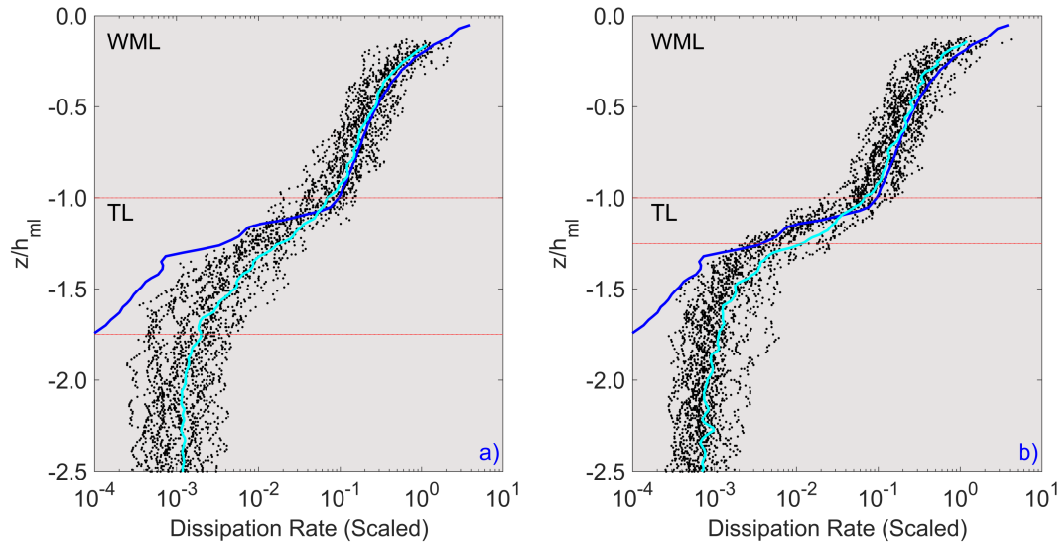
914 FIG. 4. Comparison of velocity components from the bulk model (solid curves) and from the geographical  
 915 components of the ship board ADCP. The observations are the difference between the velocity in the OSBL and  
 916 the velocity at 49m. Note, that due to poor data return from the ship's ADCP, this data stream is intermittent.  
 917 The green vertical lines again represent the storm period.



918 FIG. 5. Time-depth cross section of the dissipation rate during the storm obtained from the OMG. The dashed  
 919 curve shows the depth of the OSBL obtained from the model, captured during the storm deepening process. The  
 920 green vertical lines again represent the storm period.

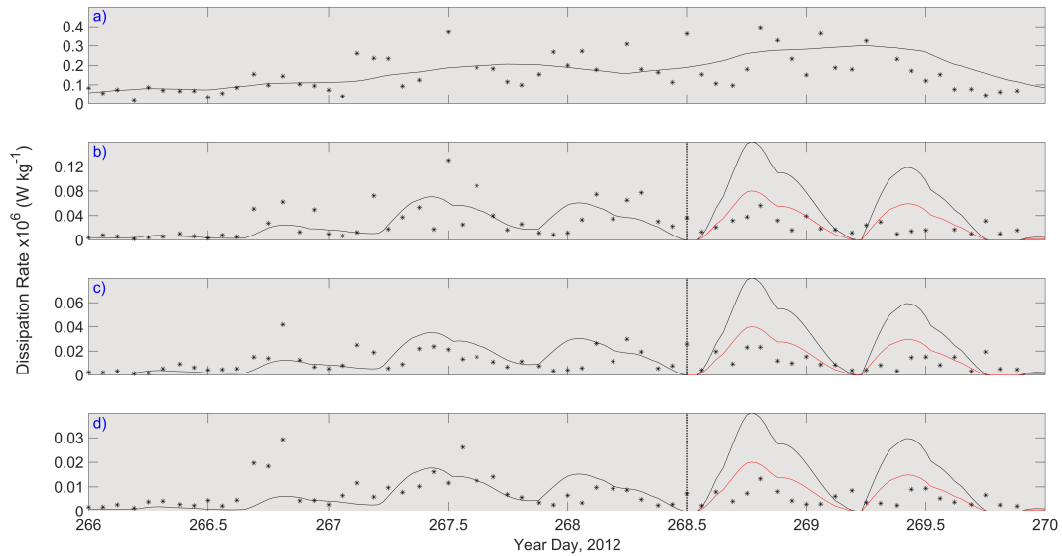


921 FIG. 6. (a) Comparison between temperature from the bulk model (solid curve) and from the glider (crosses).  
 922 The temperatures from the glider and the model curve were obtained from the average over the depth of the  
 923 OSBL. The red line in figure 6(b) is estimated from a linear fit to the observed temperatures between days  
 924 268.25 and 269.75. (b) is as (a) but an expanded view of the last two days.

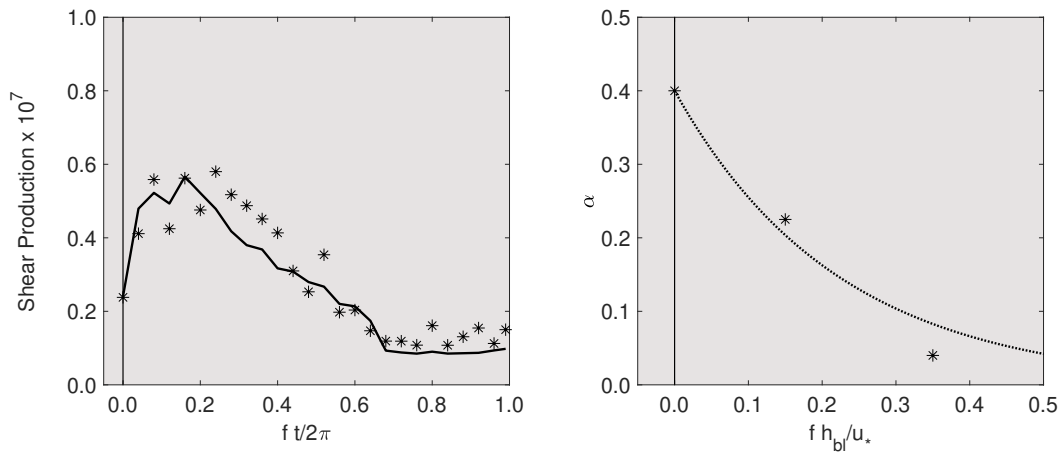


925 FIG. 7. Non-dimensional profiles of the dissipation rate from the OMG (a) between days 266.25 and 267.8  
 926 and (b) between days 268.25 and 269.8. The dissipation rate has been scaled according to the Langmuir scaling  
 927 of Grant and Belcher (2009) by  $w_{*L}^3/h_{ml}$ , and depth by the mixed layer depth from the temperature profiles. The  
 928 blue solid curve is the dissipation rate profile from one of the LES used in Grant and Belcher (2009), the cyan  
 929 solid curve is the mean of the observational OMG profiles.





930 FIG. 8. Time series of the dissipation rate at different depths below the base of the WML determined from  
 931 the temperature profiles. The stars show the dissipation rate from the glider, where (a) 5m above the base of the  
 932 WML, with the curve showing the dissipation calculated using Eq. 6, (b) 5.5m below the base of the WML,  
 933 (c) 7.5m below, (d) 9.5m below. In (b) to (d) the black curves show the dissipation rates calculated from Eq.  
 934 5, multiplied by 1.0, 0.5 and 0.25 to account for the decrease in the dissipation rate with depth. The red curves  
 935 after day 268.5 are just the black curves divided by two. Note the different scales on the y-axis.



936 Fig. A1. Comparison of shear production from the simulation with  $f = 0.25 \times 10^{-4} s^{-1}$  (crosses) and the  
 937 parameterisation, Eq. A2 (curve). (b) The parameter  $\alpha$  in Eq. A2 as a function of  $f h_{bl}/u_{*w}$ . The dotted curve is  
 938  $\alpha = 0.4 \exp(-4.5 f h_{bl}/u_{*w})$ .