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## Contrasted mixing efficiency in energetic versus quiescent regions: insights from microstructure measurements in the Western Mediterranean Sea

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### Abstract :

Microstructure and CTD/LADCP measurements from the Western Mediterranean basin east of revealed two types of dynamical regions (Ferron et al., 2017, Geophysical Research Letters, 44:7845-7854, Ferron et al., 2017), contrasted in terms of current magnitude, vertical shear, stratification and turbulent kinetic energy dissipation rate: energetic regions (Corsica Channel, Egadi Valley and Sicily Channel) and quiescent regions (Ligurian Sea, around Sardinia, and Tyrrhenian Sea). On average, the current speed and the buoyancy frequency in the energetic regions were twice as large as in the quiescent regions, and the vertical shear was five times as large. Turbulence properties inferred from the microstructure measurements were also contrasted, dissipation rates in the energetic regions being two orders of magnitude larger than in the quiescent regions. The present study investigates the variability of the dissipation flux coefficient, a measure of the mixing efficiency, in a rich assortment of dynamical regimes. This dataset covers the full range of turbulence intensities observed in previous studies based on field measurements, direct numerical simulations, and laboratory experiments alike. The dependency of the dissipation flux coefficient as a function of turbulence intensity for the quiescent and energetic regions frames the previously observed lower and upper bounds, respectively. A contrasting behaviour was revealed between the two types of regions. In the quiescent regions, the dissipation flux coefficient linearly decreases on average by one order of magnitude with turbulence intensity increasing by four orders of magnitude. On the other hand, in the energetic regions the dissipation flux coefficient exhibits a nearly constant value over 4 decades of turbulence intensity, before decreasing for very strong turbulence intensities. In contrast with other studies, this dataset shows no relationship between the Richardson number and the dissipation flux coefficient. This may be due to inadequate vertical sampling resolution of the currents, or to the high diversity of sampled turbulent regimes, contrary to previous studies focused on a single type of dynamical region or framework (such as the thermocline or shear instabilities).

# 1 Introduction

Mixing efficiency ( $\Gamma$ ) quantifies the change in background potential energy due to mixing relative to the turbulent kinetic energy expended through mixing (Gregg et al., 2018)

$$\Gamma = \frac{J_b}{\varepsilon}, \quad (1)$$

where  $J_b$  is buoyancy flux and  $\varepsilon$  is turbulent kinetic energy dissipation rate. The buoyancy flux can be expressed as

$$J_b = -\frac{g}{\rho_0} \overline{\rho'w'} = -\frac{g}{\rho_0} K_\rho \frac{d\bar{\rho}}{dz} = K_\rho N^2, \quad (2)$$

where  $g$  is gravitational acceleration,  $\rho$  density and  $\rho_0$  mean density,  $w$  vertical velocity,  $K_\rho$  turbulent diapycnal diffusivity,  $N$  buoyancy frequency, overlines denote a mean quantity and primes fluctuations from the mean. For a homogeneous, isotropic, stratified, vertically sheared steady flow, the turbulent kinetic energy production is equivalent to (Osborn, 1980)

$$P = \varepsilon - J_b \Leftrightarrow \overline{u'w'} \frac{\partial U}{\partial z} = \varepsilon - K_\rho N^2. \quad (3)$$

The flux Richardson number  $R_f$  is defined as the ratio between the buoyancy flux and the production of turbulent kinetic energy

$$R_f = \frac{J_b}{P} = \frac{(g/\rho_0) \overline{\rho'w'}}{\overline{u'w'} \partial U / \partial z}. \quad (4)$$

The Osborn (1980) turbulence model, valid for shear driven mixing but not for convective or double diffusive mixing, assumes  $K_\theta = K_\rho$  and

$$\Gamma_t = \frac{K_\rho N^2}{\varepsilon}, \quad (5)$$

with  $\Gamma_t$  the shear driven turbulence mixing efficiency. In this case  $R_f$  can also be expressed as

$$R_f = \frac{\Gamma_t}{1 + \Gamma_t}. \quad (6)$$

The Osborn and Cox (1972) relation for turbulent thermal diffusivity  $K_\theta$

$$K_\theta = \frac{\chi}{2(\partial\bar{\theta}/\partial z)^2}, \quad (7)$$

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where  $\chi$  is the dissipation rate of temperature variance, gives the relation for the dissipation flux coefficient  $\Gamma_d$  (also referred to as dissipation ratio, dissipation coefficient, or mixing coefficient; Oakey 1985; Moum 1997; Ruddick et al. 1997; Gregg et al. 2018)

$$\Gamma_d = \Gamma_t \frac{K_\theta}{K_\rho} = \frac{\chi N^2}{2\varepsilon \left(\frac{\partial\theta}{\partial z}\right)^2}. \quad (8)$$

The dissipation flux coefficient  $\Gamma_d$  is commonly inferred from measurements as an equivalent of the mixing efficiency, assuming that convective and double diffusive mixing are negligible compared to mechanically driven turbulent mixing. Double diffusive mixing is driven by the release of potential energy through buoyancy due to a destabilising temperature or salinity vertical gradient, a process thus fundamentally different from turbulent mixing. Equation (8) is equivalent to

$$\Gamma_d = \left(\frac{R_f}{1-R_f}\right) \frac{K_\theta}{K_\rho}. \quad (9)$$

In the case of pure double diffusion ( $\frac{\partial U}{\partial z} = 0$  and  $K_\theta \neq K_\rho$ ),  $\Gamma_d$  is not representative of the mixing efficiency:  $\Gamma_t = \frac{R_f}{1-R_f} = -1$  and the mixing efficiency is  $\Gamma_{DD} = -\frac{K_\theta}{K_\rho}$  (St. Laurent and Schmitt, 1999).

$R_f$  has generally been adopted as a universal constant derived from the estimation that one sixth of the turbulent kinetic energy produced is converted into potential energy, the rest being lost through friction, resulting in  $\Gamma_t = 0.2$  (Osborn, 1980). However, more recent studies have revealed a great variability in mixing efficiency, inferred from field measurements (van Haren et al., 1994; Moum, 1997; Ruddick et al., 1997; Inoue et al., 2007; Sundfjord et al., 2007; Davis and Monismith, 2011; Dunckley et al., 2012; Ijichi and Hibiya, 2018; Monismith et al., 2018), direct numerical simulations (DNS, Slim and Riley, 1996, 1998; Smyth et al., 2001; Peltier and Caulfield, 2003; Umlauf and Burchard, 2011; Mashayek and Peltier, 2013; Chalamalla and Sarkar, 2015; Salehipour and Peltier, 2015; Mashayek et al., 2017), as well as laboratory experiments (Ivey and Nokes, 1989; Strang and Fernando, 2001). Notably, the numerical simulations of Shih et al. (2005), based on the laboratory experiments of Barry et al. (2001), showed that the mixing efficiency may be expressed as a function of the turbulence intensity  $Re_b$ , defined as the ratio of the destabilising effect of turbulence to the stabilising effect of stratification and viscosity

$$Re_b = \frac{\varepsilon}{\nu N^2}, \quad (10)$$

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86 where  $\nu$  is kinematic viscosity and  $N$  buoyancy frequency. Bouffard and Boegman (2013) re-  
87 fined the Shih et al. (2005) parameterisation with a validation against in-situ measurements,  
88 distinguishing between distinct turbulent regimes (with  $\Gamma$  increasing with increasing  $Re_b$  in the  
89 buoyancy controlled regime up to  $Re_b = 8.5$ , where it reaches a plateau at 0.2 in the transitional  
90 regime, before decreasing at  $Re_b = 400$  in the energetic regime). A dependency on the turbulence  
91 intensity was also revealed by a variety of mixing efficiency estimates from field measurements,  
92 direct numerical simulations and laboratory experiments alike (e.g. Monismith et al., 2018), and  
93 from measurements collected in the Sicily Channel (Vladoiu et al., 2019). Nevertheless, the mix-  
94 ing efficiency does not depend solely on  $Re_b$ . Gregg et al. (2018) suggest that mixing efficiency  
95 is likely driven by more than one non-dimensional parameter, but also advocate that the vari-  
96 ety of methods used to assess mixing efficiency and the associated uncertainties do not allow a  
97 compelling characterisation of this dependence, hence recommend to keep the conventional 0.2  
98 hypothesis.

99 This study builds on the results presented in Vladoiu et al. (2019) and addresses the  
100 variability of the dissipation flux coefficient  $\Gamma_d$  as a proxy for the mixing efficiency with 134  
101 microstructure profiles collected in the Western Mediterranean basin east of  $5^\circ E$ . The same  
102 methods are employed for the entire dataset, allowing for a consistent analysis over a wider  
103 range of turbulence levels and dynamical regimes than previously reported, thus proving that  
104 the observed variability is not due to computation or sampling discrepancies. The dependency  
105 of the dissipation flux coefficient on turbulence intensity and other parameters suggested in  
106 the literature is explored, and the consequences of the observed variability on the large scale  
107 circulation is discussed with respect to quantifying turbulent fluxes and changes in water mass  
108 properties.

## 109 2 Data and Methods

### 110 2.1 Data

111 The analysis is based on the first full-depth microstructure profiles sampled in the  
112 Western Mediterranean Sea with a Vertical Microstructure Profiler (VMP6000), described in  
113 Ferron et al. (2017). The microstructure dataset used in this study comprises 118 profiles sampled  
114 during 5 cruises (14 profiles during Venus2 in June 2013, 24 during Ichnussa13 in October 2013,  
115 28 during Medocc2014 in March-April 2014, 12 during Ems01 in June-July 2014, and 40 during  
116 Ichnussa14 in November 2014) including the 16 profiles from the Sicily Channel described in  
117 Vladoiu et al. (2019). An additional 16 profiles sampled in the Sicily Channel during DYNAS  
118 (15 of which between May 22<sup>nd</sup>-25<sup>th</sup> 2018 and 1 of which on September 23<sup>rd</sup> 2018) with the  
119 same instrument were also included. The profiles locations are shown in Figure 1. Collocated  
120 current data from LADCP (Lowered Acoustic Doppler Current Profiler, RDI WH 300 kHz, bin  
121 size 4 m) were also available for 85 of the 134 VMP profiles. The dissipation rates of turbulent  
122 kinetic energy ( $\varepsilon$ ) and of thermal variance ( $\chi$ ) were inferred from the VMP measurements with  
123 1 m and 2 m vertical resolution, as described in Ferron et al. (2017) and Vladoiu et al. (2019),  
124 respectively.

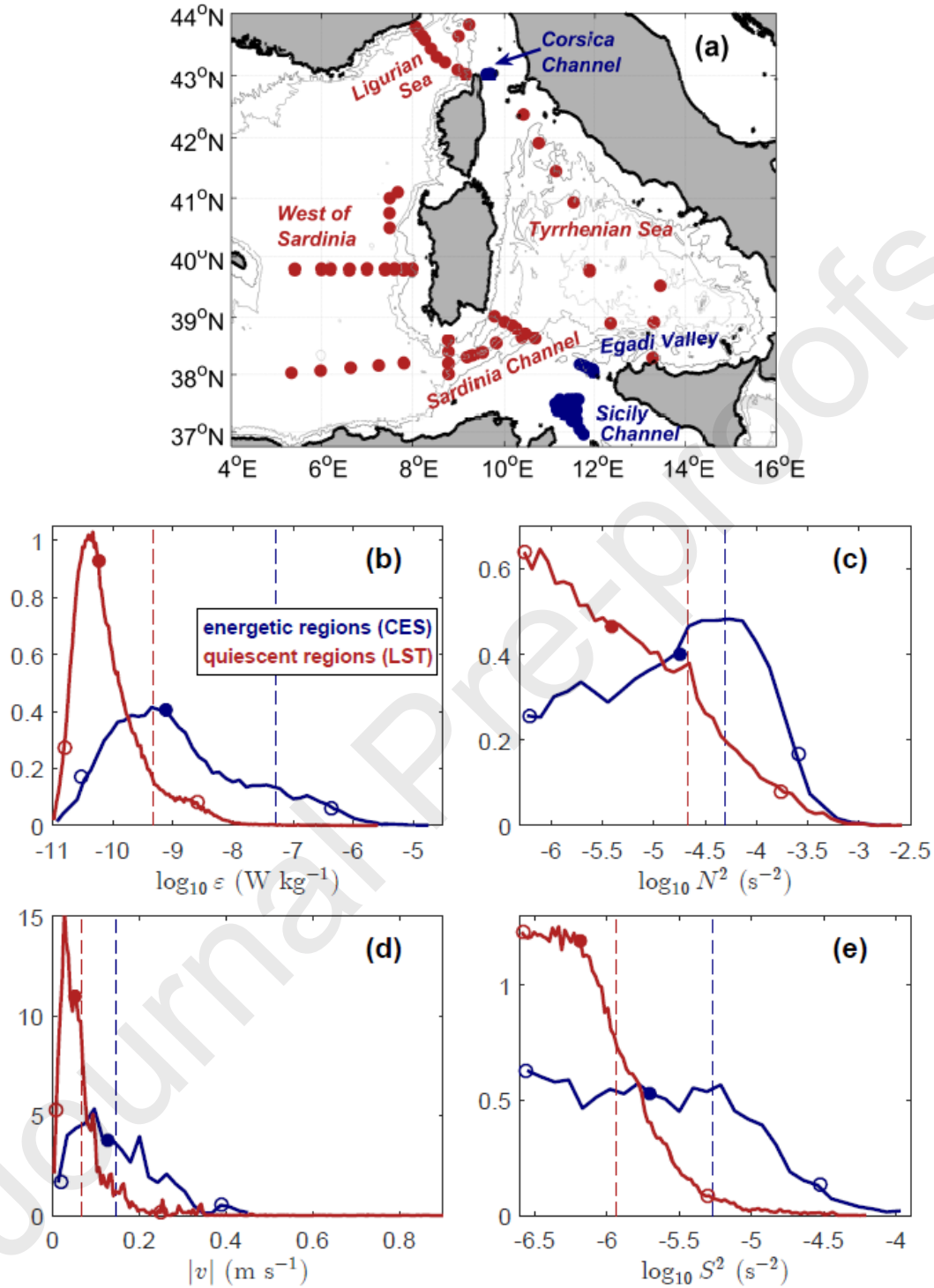


Figure 1: Stations locations (a) colour coded for the two types of regions: energetic regions (blue) - Corsica Channel, Egadi Valley and Sicily Channel (CES), and quiescent regions (red) - Ligurian Sea, West of Sardinia, Sardinia Channel, and Tyrrhenian Sea (LST). Probability density function of dissipation rate (b), buoyancy frequency squared (c), current velocity (d) and velocity vertical shear (e), for the Corsica Channel, Egadi Valley and Sicily Channel energetic regions (CES, blue) and for the Ligurian Sea, West of Sardinia, Sardinia Channel, and Tyrrhenian Sea quiescent regions (LST, red); the dashed lines indicate the mean, the filled circles indicate the median, and the empty circles indicate the 2.5 and 97.5 percentiles.

## 125 2.2 Dissipation flux coefficient as an estimate of the mixing efficiency 126 for mechanically driven turbulent mixing

127 The dissipation flux coefficient was computed from the microstructure measurements  
128 based on Equation (8). Vertical averaging was performed over varying length segments, corre-  
129 sponding to the turbulent patches extensions and as a function of the Ozmidov scale, as described  
130 in Vladoiu et al. 2019 (58% equal to 2 m, 41% between 2 and 10 m, and 1% greater than 10  
131 m). The dissipation flux coefficient variability was assessed by employing the same methods as  
132 in Vladoiu et al. (2019). The vertical shear squared  $S^2 = (\partial u/\partial z)^2 + (\partial v/\partial z)^2$  was computed  
133 from LADCP profiles sampled from the CTD rosette and collocated with the VMP profiles, and  
134 the buoyancy frequency  $N^2$  was computed from the VMP Seabird CTD using sorted density  
135 profiles. The Richardson number  $Ri$  was calculated as  $Ri = N^2/S^2$ , from  $N$  and  $S$  lowpass  
136 first-order Butterworth filtered over 20 m. Shear instabilities at smaller vertical scales are likely  
137 not resolved due to resolution limitations. Noise levels of  $5 \times 10^{-7} \text{ s}^{-2}$ ,  $2.5 \times 10^{-7} \text{ s}^{-2}$ , and  
138  $10^{-11} \text{ W kg}^{-1}$  were applied to  $N^2$ ,  $S^2$  and  $\varepsilon$ , respectively. The imposed noise limit on buoyancy  
139 frequency restricts the analysis roughly to the upper 1000 m, 95 (99) % of the  $\Gamma_d$  estimates being  
140 at depths shallower than 606 (758) m and just 0.3% below 1000 m.

141 Regions where double diffusive instabilities may develop in conditions of weak turbu-  
142 lence and favourable temperature and salinity gradients were excluded from the analysis. In  
143 the Mediterranean Sea, structures indicative of double diffusion such as temperature or salinity  
144 “steps” are common (e.g. Onken and Brambilla, 2003; Carniel et al., 2008). In particular, the  
145 very saline and warm intermediate waters (comprised mostly of Levantine Intermediate Water)  
146 relative to the deep and surface waters may satisfy the stability conditions required for the de-  
147 velopment of salt fingers and diffusive convection, respectively: if warm and salty waters overlay  
148 cool and fresh waters, double diffusive salt fingers may develop, while in the case of cool and  
149 fresh waters overlaying warm and salty waters, double diffusive convection may develop (Schmitt,  
150 1994). The water column stability to double diffusion was assessed depending on the temperature  
151 and salinity vertical gradients using the Turner angle  $Tu$  (Ruddick, 1983)

$$152 \quad Tu = \tan^{-1} \frac{-\alpha \partial_z T - \beta \partial_z S}{-\alpha \partial_z T + \beta \partial_z S}, \quad (11)$$

153 where  $\alpha$  and  $\beta$  are the thermal expansion and saline contraction coefficients, respectively.  $Tu$   
154 indicates the relative contribution of salinity and temperature to the stability of a layer with



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4 155 respect to double diffusion processes, allowing a classification in four regimes (Ruddick, 1983):  
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6 156 favourable for double diffusion - salt finger ( $45^\circ < Tu < 90^\circ$ ) and diffusive convection ( $-90^\circ <$   
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8 157  $Tu < -45^\circ$ ) regimes, and unfavourable for double diffusion - stable ( $|Tu| < 45^\circ$ ) and overturn  
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10 158 ( $|Tu| > 90^\circ$ ) regimes. If the preconditioning for double diffusive processes is satisfied in this  
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12 159 respect, it does not necessarily imply that double diffusion occurs. In the following, “salt finger  
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14 160 regime” and “double diffusive regime” are used only in reference to the Turner angle and the sign  
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16 161 of the temperature and salinity vertical gradients (positive temperature and salinity gradients in  
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18 162 the case of salt fingers, and negative in the case of diffusive convection), and do not imply that  
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20 163 double diffusive processes dominate. Double diffusion was assumed to prevail over mechanically  
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22 164 driven turbulence only if:  $Re_b < 25$  (Stillinger et al., 1983; Padman and Dillon, 1987; Gregg, 1988),  
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24 165  $\chi/\varepsilon > 1$  (Alford and Pinkel, 2000), and  $-90^\circ < Tu < -45^\circ$  or  $45^\circ < Tu < 90^\circ$ . This occurred for  
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26 166 4% of the vertical segments (or 6% of the sub-sample restricted to  $Re_b < 25$ ), equivalent to 467  
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28 167 instances of diffusive convection and 337 of salt fingers. These occurrences were excluded from  
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30 168 the analysis on  $\Gamma_d$  variability. Double diffusive mixing relative to mechanically driven mixing  
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32 169 was highest at the least turbulent stations in the Tyrrhenian Sea and West of Sardinia (5-6% of  
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34 170 the total number of vertical segments).

### 3 Results

The profiles were classified into two types of regions where similar dynamical regimes are expected to prevail (Figure 1):

- energetic regions - Corsica Channel, Egadi Valley and Sicily Channel (CES), which are shallow regions where the flow is constricted by the bathymetry, with mean  $\varepsilon = 5.2 \times 10^{-8}$  W kg<sup>-1</sup>, mean  $N^2 = 4.9 \times 10^{-5}$  s<sup>-2</sup>, mean current velocities of 0.15 m s<sup>-1</sup>, mean  $S^2 = 5.3 \times 10^{-6}$  s<sup>-2</sup>.
- quiescent regions - Ligurian Sea, West of Sardinia, Sardinia Channel, and Tyrrhenian Sea (LST), which are comparatively more offshore and less prone to flow-topography interactions, with mean  $\varepsilon = 4.7 \times 10^{-10}$  W kg<sup>-1</sup>, mean  $N^2 = 2.2 \times 10^{-5}$  s<sup>-2</sup>, mean current velocities of 7 cm s<sup>-1</sup>, mean  $S^2 = 1.2 \times 10^{-6}$  s<sup>-2</sup>.

A contrast was observed between CES and LST, with larger mean and median dissipation rate, buoyancy frequency, current velocity and vertical shear at CES than at LST (Figure 1). Moreover, Ferron et al. (2017) reported a higher range of dissipation rate variability between cruises below 100 m at CES than at LST. The energetic regions comprise 44 profiles and 28% of the total 18469 segments over which  $\Gamma_d$  was computed, and the quiescent regions 90 profiles and 72% of the segments (see Table 1 for numbers of profiles and percentages for each region).

	Region	Number of profiles	% of total number of segments
Energetic regions (CES)	Corsica Channel	6	3
	Sicily Channel	32	20
	Egadi Valley	6	5
Quiescent regions (LST)	Ligurian Sea	11	9
	Sardinia Channel	35	29
	West of Sardinia	32	23
	Tyrrhenian Sea	12	11

Table 1: Number of microstructure profiles in each region shown in Figure 1; percentage of segments over which  $\Gamma_d$  was computed in each region relative to total number of segments in all regions.

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188 The dependency of  $\Gamma_d$  on  $Re_b$  was investigated (in  $\log_{10}$  space) and compared to the  
189 Bouffard and Boegman (2013) parameterisation ( $\Gamma_{BB13}$ ), for the two types of regions (Figure  
190 2). At LST, only 1.7% of the observations occur at  $Re_b > 1000$ , compared to 16% at CES.  
191 At CES, and consistently with the parameterisation,  $\Gamma_d$  showed distinct linear dependencies  
192 on  $Re_b$  subject to the  $Re_b$  range.  $\Gamma_d$  was on average systematically larger than  $\Gamma_{BB13}$ .  $\Gamma_d$   
193 exhibits a plateau for the mean values in the transitional  $Re_b$  regime with  $8.5 \leq Re_b < 400$   
194 defined by Bouffard and Boegman (2013) that here extends up to  $Re_b = 10^4$ , consistent with  
195 the behaviour observed in the Sicily Channel and described in Vladoiu et al. 2019 (this plateau  
196 is still observed when disregarding the profiles from the Sicily Channel). Around  $Re_b = 10^4$ , a  
197 transition to a dependency described by  $Re_b^{-1/2}$  occurs, which is consistent with Monismith et al.  
198 (2018). This transition therefore appears far after the end of the Bouffard and Boegman (2013)  
199 transitional regime. Conversely, at LST  $\Gamma_d$  decreased on average continuously and almost linearly  
200 with increasing  $Re_b$ , a behaviour that differs markedly from the 4 distinct regimes predicted by  
201 the Bouffard and Boegman (2013) parameterisation (Figure 2). In the energetic regime with  
202  $Re_b \geq 400$ ,  $\Gamma_d$  is on average half an order of magnitude larger than  $\Gamma_{BB13}$ .

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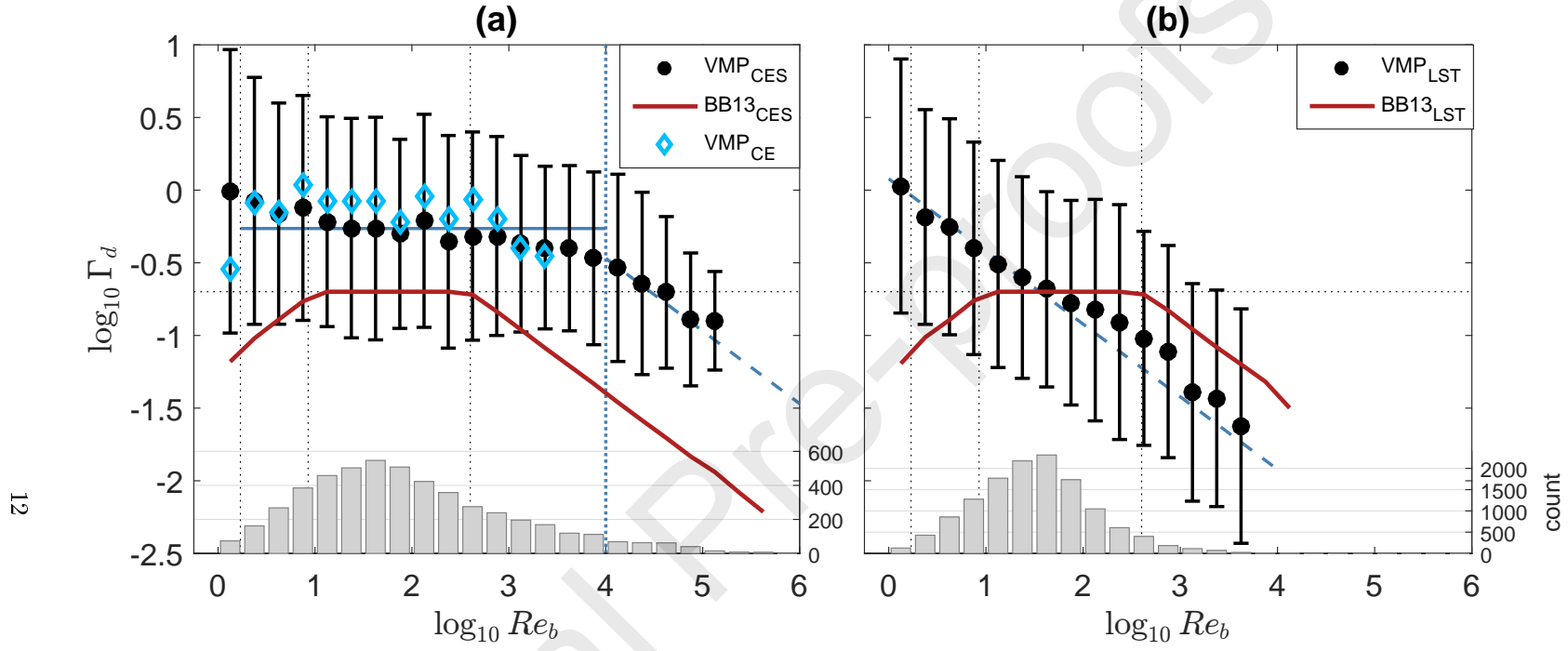


Figure 2:  $\log_{10} \Gamma_d$  (black circles) averaged in bins of  $\log_{10} Re_b$ , for the Corsica Channel, Egadi Valley and Sicily Channel energetic regions (CES, a), only for the Corsica Channel and Egadi Valley regions (CE, a, blue diamonds), and for the Ligurian Sea, West of Sardinia, Sardinia Channel, and Tyrrhenian Sea quiescent regions (LST, b);  $\Gamma_{BB13}$  (red curves);  $\Delta Re_b = 0.25$  in  $\log_{10}$  space; delimitations of the Bouffard and Boegman (2013) turbulent regimes: molecular for  $Re_b < 1.7$ , buoyancy controlled for  $1.7 \leq Re_b < 8.5$ , transitional for  $8.5 \leq Re_b < 400$ , energetic for  $Re_b \geq 400$  (dotted black lines); black bars show the standard deviation; grey bars show the number of occurrences in each  $Re_b$  bin (only bins with at least 10 occurrences are shown);  $\log_{10} \Gamma_d$  averaged over  $1.7 \leq Re_b < 10^4$  (solid blue line, a),  $Re_b = 10^4$  (vertical dotted blue line) at which the transition from a plateau to a slope proportional to  $Re_b^{-1/2}$  occurs (Monismith et al. 2018, dashed blue line, a and b).

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203 Monismith et al. (2018) reviewed a collection of datasets that revealed different be-  
204 haviours of the Richardson flux number (directly related to the dissipation flux coefficient, Equa-  
205 tion (6)) as a function of turbulence intensity (Figure 3). Many datasets exhibit a saturation  
206 of  $R_f$ , illustrated by a plateau such as that of the Bouffard and Boegman (2013) transitional  
207 turbulence intensity regime, followed by a decrease in  $R_f$  with increasing  $Re_b$ . However, the  
208 critical  $Re_b$  at which  $R_f$  starts to decrease differs between studies. In particular, the strongly  
209 sheared, strongly stratified estuarine case presented in Holleman et al. (2016) and characterised  
210 by high dissipation rates resembles the energetic regions (CES), in that  $R_f$  starts to decrease  
211 with increasing  $Re_b$  far after the Bouffard and Boegman (2013) limit of 400 (Figure 3). On  
212 the other hand, the almost linear decrease in  $R_f$  with increasing  $Re_b$  in the transitional regime  
213 illustrated by the quiescent regions (LST) was consistent between field measurements, direct  
214 numerical simulations and laboratory experiments alike. Interestingly, the  $R_f$  curves from the  
215 two types of regions in the Western Mediterranean roughly frame the upper and lower bounds of  
216 the different datasets in the composite plot. Therefore, Figure 3 further suggests that the mixing  
217 efficiency variability is likely not governed only by the turbulence intensity.

218 The distribution of  $\Gamma_d$  in  $(\varepsilon, N^2)$  space is also contrasting between CES and LST  
219 (Figure 4). The bulk of the values at CES is restricted to a smaller parameter space than at  
220 LST, and corresponds to mean  $N^2$  and  $\varepsilon$  roughly one order of magnitude larger. There is some  
221 variability in  $\Gamma_d$  along  $Re_b$  isolines at both CES and LST, but no clear consistent pattern emerges  
222 between CES and LST, suggesting either lacking statistical significance or that the  $(\varepsilon, N^2)$  space  
223 is insufficient to fully describe the mixing efficiency variability and that further parameters are  
224 involved.

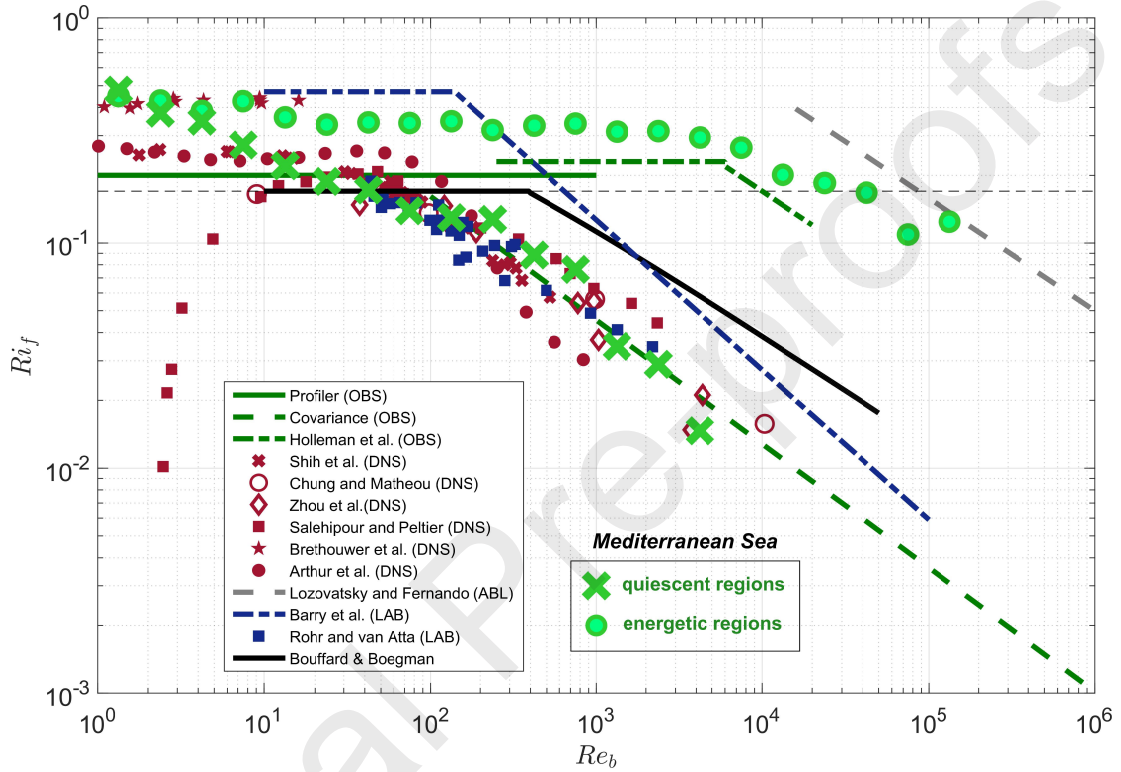


Figure 3: Composite plot of the median Richardson flux number as a function of turbulence intensity from several studies (after Monismith et al. 2018, incorporating an additional dataset by Brethouwer et al. 2007; data courtesy of Stephen Monismith) based on: field measurements (green lines - OBS), direct numerical simulations (red symbols - DNS), laboratory experiments (blue line and squares - LAB), atmospheric boundary layer measurements (grey line - ABL). The Bouffard and Boegman (2013) parameterisation is also shown (black line), and the binned medians from the Western Mediterranean Sea corresponding to Figure 2 are superimposed (green circles - energetic regions and green crosses - quiescent regions).

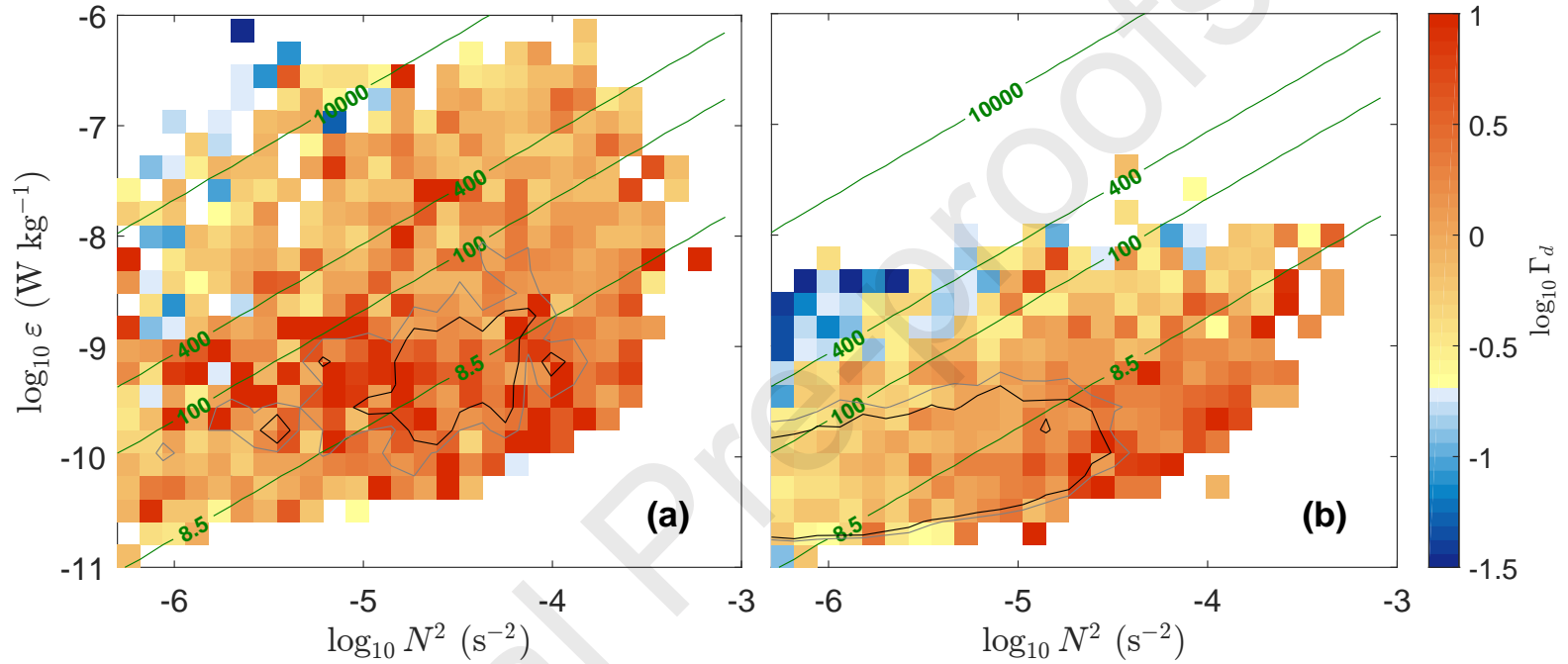


Figure 4: Bin averaged  $\Gamma_d(N^2, \varepsilon)$  for the Corsica Channel, Egadi Valley and Sicily Channel energetic regions (CES, a) and for the Ligurian Sea, West of Sardinia, Sardinia Channel, and Tyrrhenian Sea quiescent regions (LST, b);  $Re_b$  (green contours); 0.2 and 0.15 contours of the probability density function (black and gray, respectively);  $\Delta \log_{10} N^2 = 0.12$ ,  $\Delta \log_{10} \varepsilon = 0.21$ ; note the colour map transition from blue to yellow at  $\Gamma_d = 0.2$ ; only bins with at least 3 occurrences are shown.

225 The dependency of  $\Gamma_d$ ,  $\varepsilon$ ,  $N^2$ ,  $S^2$ ,  $Ri$ , and  $K_\theta$  on  $Re_b$  was investigated for the four  
 226 water column stability regimes with respect to the Turner angle. As explained in Section 2.2,  
 227 the following disregards segments with prevailing double diffusion (indicated for reference in  
 228  $(Tu, Re_b)$  space in Figures 5 a and 6 a) and refers to the diffusive convection and salt finger  
 229 regimes only in terms of the temperature and salinity gradients; moreover, the segments are  
 230 mostly restricted to the upper 1000 m.  $\Gamma_d$  varied significantly not only as a function of  $Re_b$ ,  
 231 but also depending on the  $Tu$  regime. At both CES and LST,  $\Gamma_d$  was highest in the stable and  
 232 diffusive convection regimes, and significantly lower in the salt finger regime (Figures 5 a and  
 233 6 a), consistent with Inoue et al. (2007). At CES, median  $\Gamma_d$  at  $Re_b < 400$  was 0.62 in the  
 234 stable regime, 0.75 in the diffusive convection regime and 0.3 in the salt finger regime, while at  
 235  $Re_b \geq 400$  median values were 0.43, 0.55 and 0.29, respectively. Conversely, at LST, median  $\Gamma_d$   
 236 at  $Re_b < 400$  was 0.3 in the stable regime, 0.31 in the diffusive convection regime and 0.13 in the  
 237 salt finger regime, while at  $Re_b \geq 400$  median values were 0.11, 0.11 and 0.03, respectively. This  
 238 may be related to the variability of  $K_\theta$ , which shows a consistent pattern between CES and LST:  
 239  $K_\theta$  increases on average with increasing  $Re_b$  but is larger in the diffusive convective regime than  
 240 in the salt finger regime (Figures 5 f and 6 f). This asymmetry is likely not due to the criterion  
 241  $Re_b < 25$  used to distinguish double diffusion (a bias induced by prevailing double diffusion  
 242 would imply  $K_\theta \neq K_\rho$ ), as it extends well beyond this value. The  $S^2$  and  $N^2$  variability in  $(Tu,$   
 243  $Re_b)$  space differed greatly between CES and LST, suggesting the presence of water masses with  
 244 different properties and dynamics as outlined previously.  $S^2$  was overall higher for CES (Figure  
 245 5 d) than for LST (Figure 6 d), and strong shear occurred mostly in the stable and diffusive  
 246 convection regimes and at all  $Re_b$  at CES. Conversely, at LST the strongest shear occurred in  
 247 the stable regime at low  $Re_b$ , and  $S^2$  decreased uniformly with increasing  $Re_b$  for all the regimes.  
 248 This indicates that at LST the increase in  $Re_b$  is mainly due to the decrease in stratification at  
 249 low dissipation rate, rather than to the strong production of turbulence by the mean shear. At  
 250  $Re_b$  between 8.5 and 400,  $N^2$  was much larger at CES (Figure 5 c) than at LST (Figure 6 c),  
 251 especially in the diffusive convection regime but also in the stable regime. There was a contrast  
 252 between the water column stability regimes also for  $Ri$ , at both CES and LST:  $Ri$  was larger in  
 253 the diffusive convective regime than in the salt finger regime (Figures 5 e and 6 e).  $Ri$  was larger  
 254 at LST than at CES in the transitional  $Re_b$  regime for all  $Tu$  regimes due to the dominance of  
 255 weaker stratification at LST and despite larger shear at CES. A contrast in the transitional  $Re_b$   
 256 regime between CES and LST was also observed for  $S^2$  and  $K_\theta$ , with higher values at CES than  
 257 at LST.



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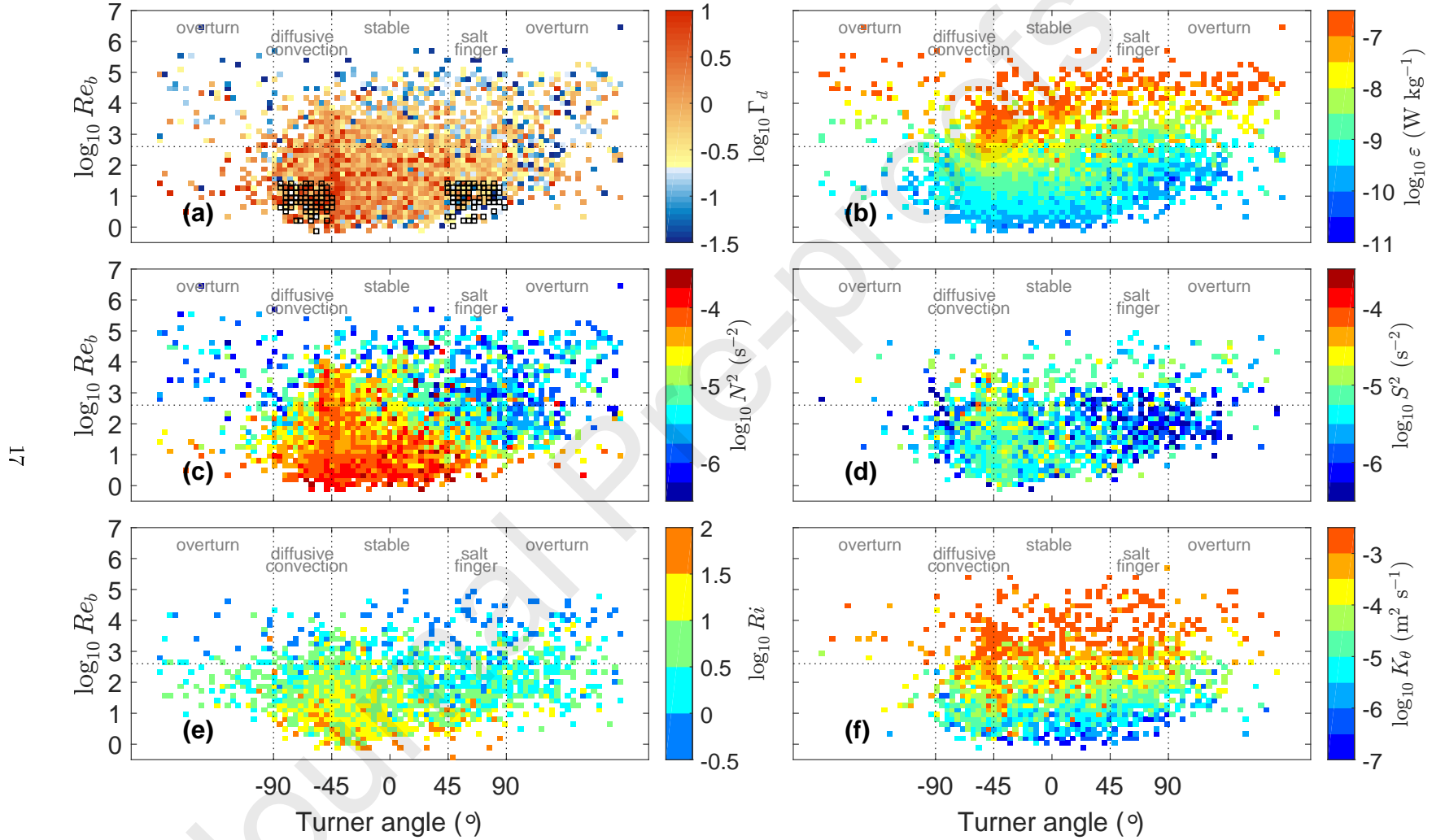


Figure 5: Bin averages in  $(Tu, Re_b)$  space for the Corsica Channel, Egadi Valley and Sicily Channel energetic regions (CES) ( $\Delta Tu=4^\circ$ ,  $\Delta \log_{10} Re_b=0.17$ ) of:  $\Gamma_d$  (a),  $\varepsilon$  (b),  $N^2$  (c),  $S^2$  (d),  $Ri$  (e), and  $K_\theta$  (f). Note same  $y$  axis for (a)-(f). The  $Tu$  water column stability regimes refer to the  $T$  and  $S$  vertical gradients (negative  $T$  and  $S$  gradients for the diffusive convection regime, and positive  $T$  and  $S$  gradients for the salt finger regime), and do not necessarily imply that double diffusion occurs. The  $(Tu, Re_b)$  bins where double diffusion is potentially prevalent relative to mechanically-driven mixing are restricted to  $Re_b < 25$ ,  $\chi/\varepsilon > 1$ , and  $-90^\circ < Tu < -45^\circ$  or  $45^\circ < Tu < 90^\circ$ , and are indicated in (a) by the black squares. The horizontal dashed black line indicates  $Re_b=400$ .

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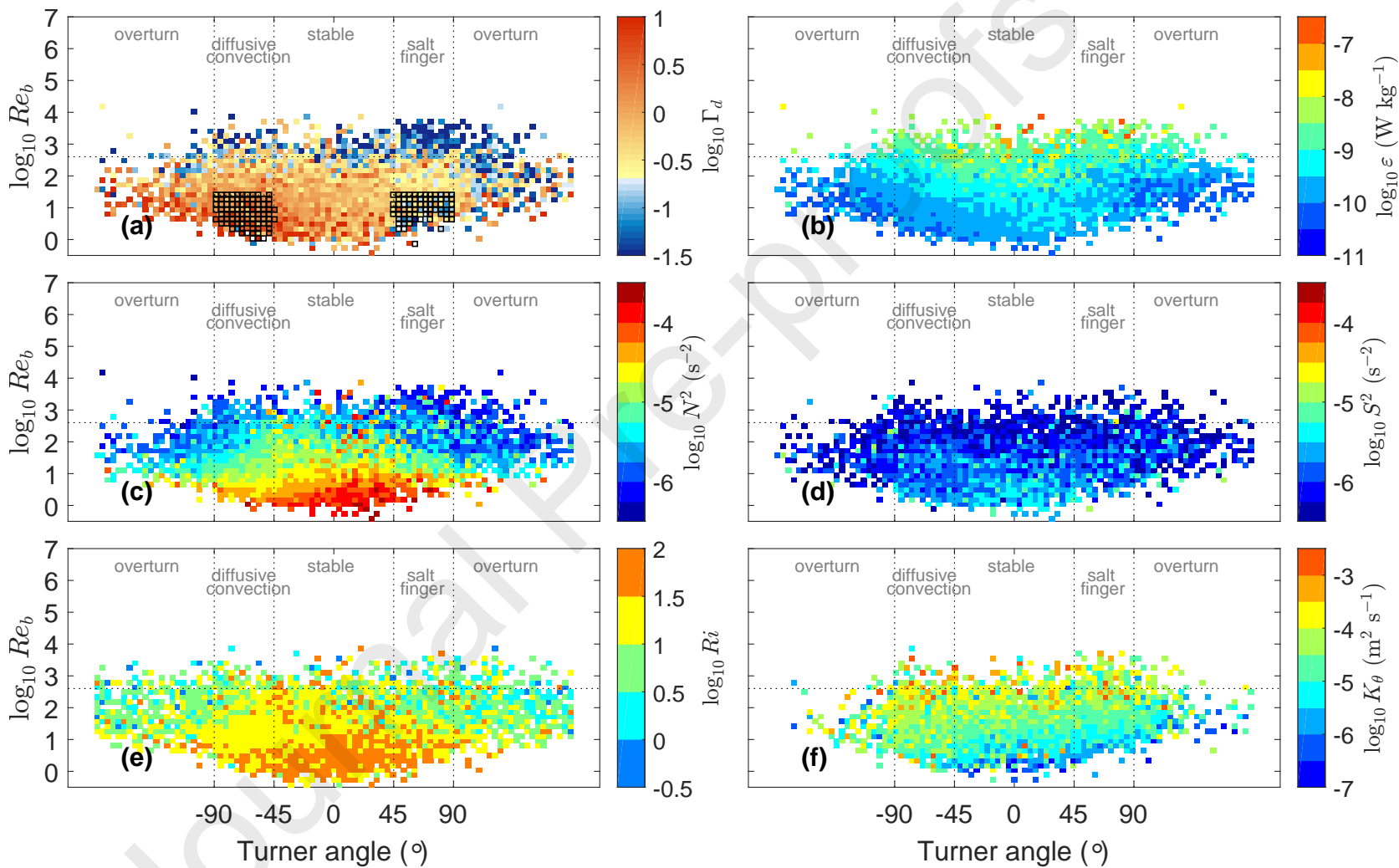


Figure 6: Same as Figure 5, but for the Ligurian Sea, West of Sardinia, Sardinia Channel, and Tyrrhenian Sea quiescent regions (LST).

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3 258 The behaviour of  $\Gamma_d$  as a function of  $Ri$  in the Sicily Channel (Vladoiu et al., 2019)  
4 259 was found to be relatively well described on average by the parameterisation suggested by Ve-  
5 260 nayagamoorthy and Koseff (2016), based on the direct numerical simulations of Shih et al. (2005)  
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7 261 which predicts a constant value at  $Ri > 1$ . Moreover, the  $\Gamma_d$  dependency for  $Ri$  up to  $\approx 1$  was  
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9 262 in agreement with predictions by several numerical simulations and laboratory experiments of  
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11 263 shear instability (Stretch et al., 2010; Schaad and Venayagamoorthy, 2017; Zhou et al., 2017).  
12 264 However, for the complete Western Mediterranean dataset, no clear dependency of  $\Gamma_d$  on  $Ri$  was  
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14 265 observed for either CES or LST (Figure 7). This inconclusive dependency is consistent with the  
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16 266 results of Monismith et al. (2018) based on a combination of datasets. It is possible that  $Ri$  is  
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18 267 not computed at small enough scales from the measurements, or that shear instability is not a  
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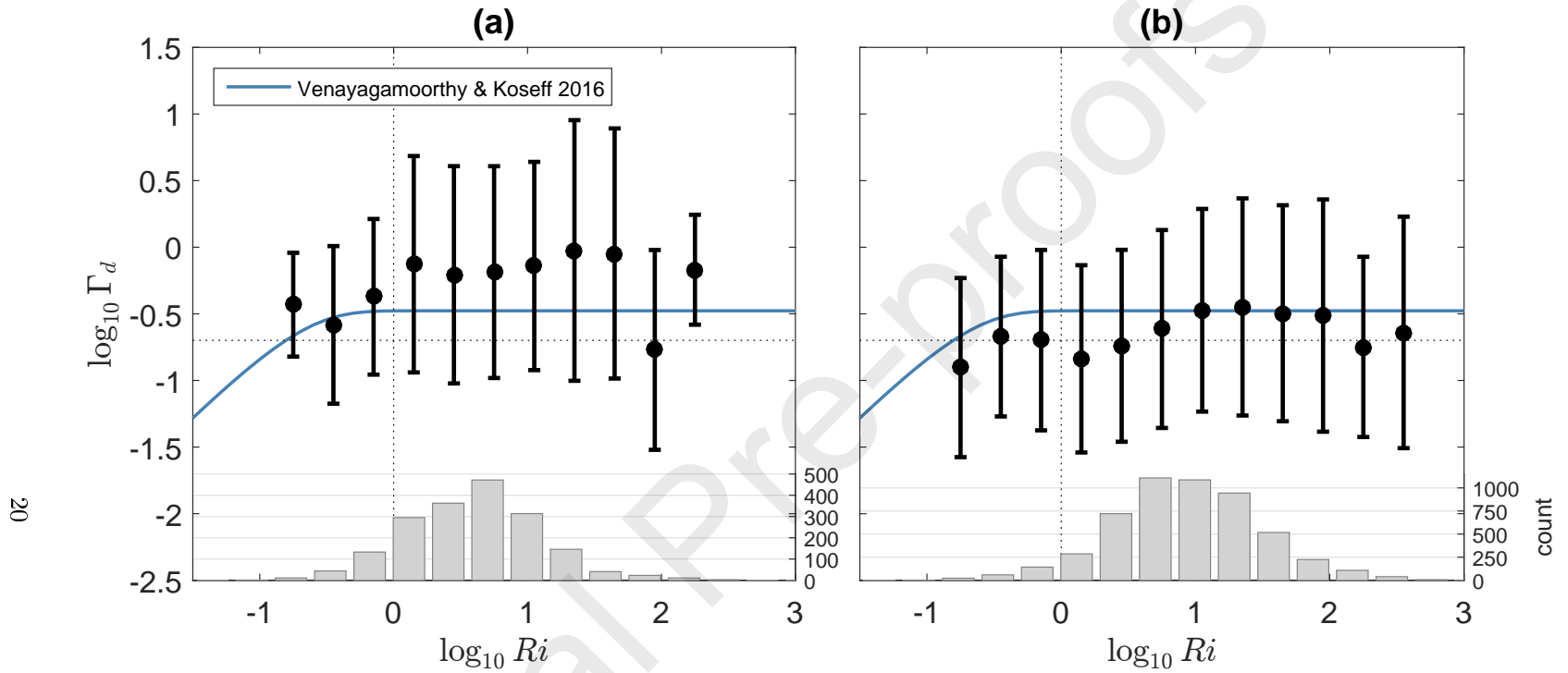


Figure 7:  $\Gamma_d$  (black circles) averaged in bins of  $Ri$ , for the Corsica Channel, Egadi Valley and Sicily Channel energetic regions (CES, a), and for the Ligurian Sea, West of Sardinia, Sardinia Channel, and Tyrrhenian Sea quiescent regions (LST, b); standard deviation for each bin (error bars); grey bars show the number of occurrences in each  $Ri$  bin (only bins with at least 10 occurrences are shown);  $\Delta Ri = 0.3$  in  $\log_{10}$  space; the parameterisation suggested by Venayagamoorthy and Koseff (2016) is shown for comparison (blue line).

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269 A dependency of the mixing efficiency on the ratio between the Ozmidov scale ( $L_O$ ) and  
 270 the Thorpe scale ( $L_T$ ) has been suggested based on scaling analysis and laboratory experiments  
 271 (Ivey and Imberger, 1991), direct numerical simulations (Smyth et al., 2001; Garanaik and Ve-  
 272 nayagamorthy, 2019), and oceanic measurements (Smyth et al., 2001; Ijichi and Hibiya, 2018;  
 273 Ijichi et al., 2020). The Thorpe scale quantifies the extent of a turbulent patch  $L_T = \langle \delta_T^2 \rangle^{1/2}$ ,  
 274 where  $\delta_T$  is the vertical displacement from a depth sorted density profile, and the Ozmidov length  
 275 scale  $L_O = \langle \varepsilon \rangle^{1/2} \langle N \rangle^{-3/2}$  represents the maximum vertical extent of a turbulent overturn in the  
 276 presence of buoyancy forces (angle brackets denote averages over a turbulent patch). The ratio  
 277  $L_O/L_T$  was computed for each turbulent patch with  $L_O$  and  $L_T$  greater than 1 m. A ratio close  
 278 to one is expected for shear driven mixing (Scotti, 2015) and was only found at CES concurrently  
 279 with large  $Re_b$ . At LST  $L_O \ll L_T$ , consistent with previous results in the ocean interior and  
 280 suggesting that convective mixing may occur (Mater et al., 2015).  $\Gamma_d$  decreased on average with  
 281 increasing  $L_O/L_T$ , with a redder slope at LST than at CES (Figure 8). However, the low number  
 282 of resolved turbulent patches due to the noise threshold imposed on  $N$  and to the restriction  
 283  $L_O > 1$  m does not allow a robust comparison with the previously suggested scalings in the same  
 284 parameter space.

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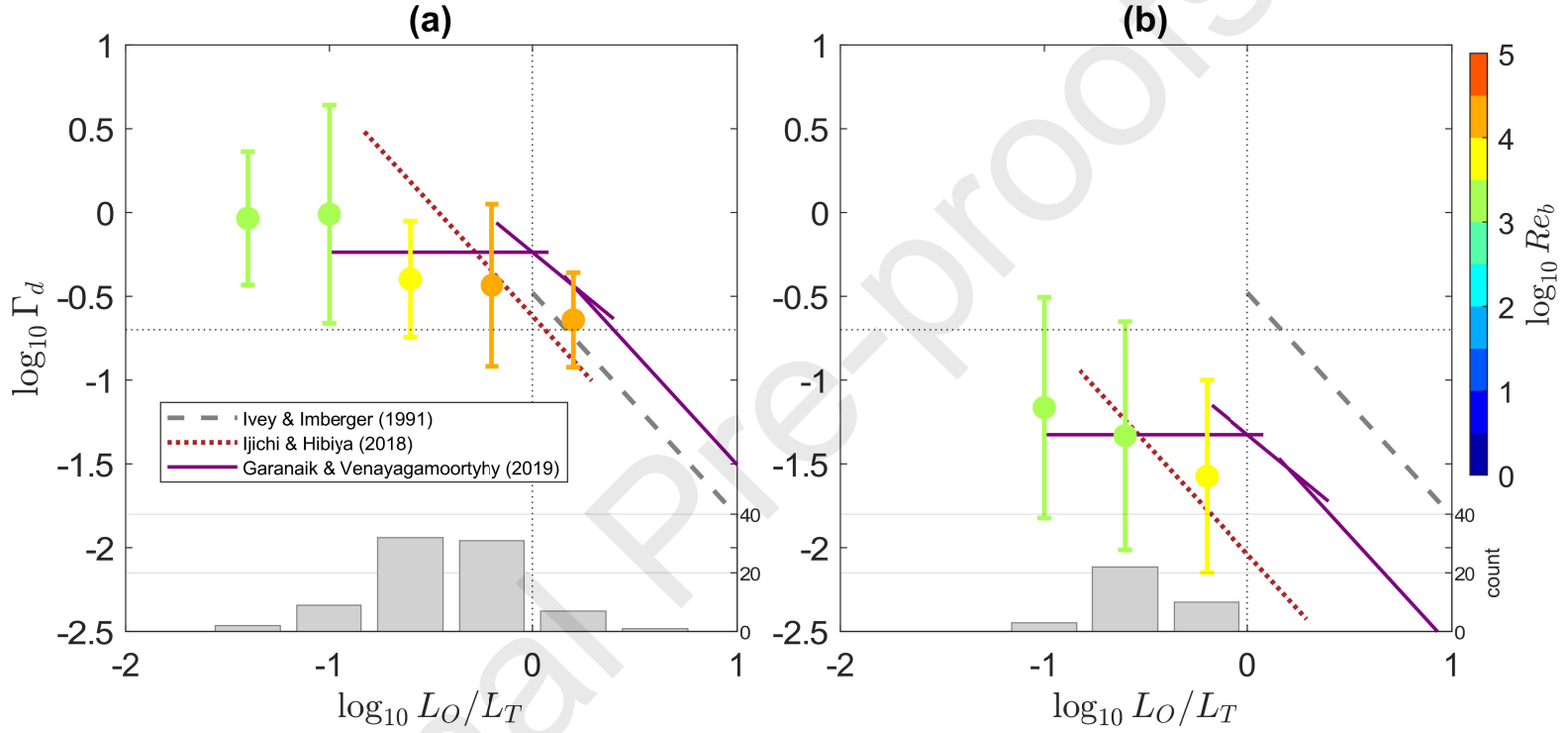


Figure 8:  $\Gamma_d$  (circles) averaged in bins of  $L_O/L_T$ , for the Corsica Channel, Egadi Valley and Sicily Channel energetic regions (CES, a), and for the Ligurian Sea, West of Sardinia, Sardinia Channel, and Tyrrhenian Sea quiescent regions (LST, b); averaged  $Re_b$  in bins of  $L_O/L_T$  (colour); standard deviation for each bin (error bars); grey bars show the number of turbulent patches considered in each  $L_O/L_T$  bin; the scalings suggested by Ivey and Imberger (1991); Ijichi and Hibiya (2018); Garanaik and Venayagamoorthy (2019) are shown for comparison (dashed gray, dotted red, and solid purple curves, respectively).

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285           The contrasting dissipation flux coefficient between CES and LST, with smaller  $\Gamma_d$  in  
286 the quiescent compared to energetic regions, implies significant differences in vertical turbulent  
287 diffusive fluxes and water mass transformations between the two types of regions. Moreover, large  
288  $\varepsilon$  concurrent with large  $\Gamma_d$  in the energetic regions result in a larger buoyancy flux  $J_b = \varepsilon\Gamma_d$   
289 than in the quiescent regions, suggesting that most of the diapycnal mixing occurs at CES.  
290 Intermediate waters were identified based on vertical profiles and  $T$ - $S$  diagrams between  $28.8 \leq$   
291  $\sigma_0 \leq 29.1 \text{ kg m}^{-3}$ , corresponding to 59% of the total observations at CES and 89% at LST,  
292 and with 90% of the occurrences between roughly 175 and 526 m depth at CES and between  
293 130 and 640 m depth at LST. Diapycnal diffusivity  $K_\rho$  estimated from  $\Gamma_d$  (Equation (5)) for  
294  $28.8 \leq \sigma_0 \leq 29.1 \text{ kg m}^{-3}$  has a mean (median) of  $3.7 \times 10^{-3}$  ( $8.2 \times 10^{-5}$ )  $\text{m}^2 \text{ s}^{-1}$  at CES and  
295  $5.8 \times 10^{-5}$  ( $9 \times 10^{-6}$ )  $\text{m}^2 \text{ s}^{-1}$  at LST. Moreover, the mean  $K_\rho$  parameterised as a function of  $Re_b$   
296 following Bouffard and Boegman (2013) is smaller by a factor of 24 and 3 for the mean value at  
297 CES and LST, respectively, than  $K_\rho$  inferred from  $\Gamma_d$ . This further underlines the importance of  
298 microstructure measurements for more accurate estimates of vertical turbulent diffusive fluxes.

## 299 4 Conclusions and discussion

300 Microstructure profiles sampled in the Western Mediterranean basin east of  $5^\circ E$  were  
301 classified into two types of dynamical regions: energetic (Corsica Channel, Egadi Valley and Sicily  
302 Channel) and quiescent (Ligurian Sea, around Sardinia, and Tyrrhenian Sea). The currents,  
303 vertical shear, stratification and dissipation were stronger in the energetic than in the quiescent  
304 regions.

305 The dissipation flux coefficient variability as a function of turbulence intensity also  
306 differed greatly between the two types of regions, especially at  $Re_b$  between 10 and  $10^4$ : while on  
307 average  $\Gamma_d$  exhibits a plateau in the energetic regions, in the quiescent regions  $\Gamma_d$  decreases almost  
308 linearly (in  $\log_{10}$  space) with increasing  $Re_b$ . The Bouffard and Boegman (2013) prediction lies  
309 in between these two curves. A plateau was also found in some previous studies but its extension  
310 is variable (e.g. Holleman et al., 2016). The decrease in  $\Gamma_d$  with increasing  $Re_b$  was suggested to  
311 be induced by boundary effects, however this dependency is exhibited precisely in the offshore  
312 quiescent regions, away from coastal boundaries and bathymetric features. The Bouffard and  
313 Boegman (2013) parameterisation is based on numerical simulations (Shih et al., 2005) and  
314 laboratory experiments (Barry et al., 2001), and was validated with in-situ measurements from  
315 Lake Erie. The range of parameters reproduced in these simulations and experiments may be  
316 more similar to those found in the energetic, well stratified regions. The in-situ data from Lake  
317 Erie and from other studies that showed a similar  $\Gamma_d$  behaviour may also be more representative  
318 of the conditions in the energetic regions. For instance in Lake Erie high dissipation rates occur  
319 in a sharp thermocline as a result of strong internal Poincaré waves (Bouffard et al., 2012).  
320 The Western Mediterranean dataset covers a wide spectrum of dynamical conditions and a large  
321 range of turbulence intensities, comparable with the Monismith et al. (2018) compilation but  
322 with the advantage of a uniform method being employed, thus removing the possibility that the  
323 different observed dependencies would be attributed to different processing methods. As noted  
324 by Monismith et al. (2018), a dependency of the mixing efficiency on  $Re_b$  does exist but it is  
325 most probably not the only parameter governing its variability. The Richardson number, at least  
326 computed at the large vertical scales imposed by the current measurement limitations, does not  
327 seem to govern the variability of  $\Gamma_d$ .

328 An apparent dependence of  $\Gamma_d$  on the water column stability regime was observed,  
329 with higher dissipation flux coefficient for mechanically driven mixing in the case of the diffusive



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3 330 convection favourable regime than in the case of the salt finger favourable regime. A similar  
4 331 contrast was also evidenced by Inoue et al. (2007). This may indicate a bias in the Osborn-Cox  
5 332 method in the case of the regimes favourable for double diffusion, but where mechanical mixing  
6 333 is assumed to prevail. More specifically, when the background stratification is favourable for  
7 334 diffusive convection, the transition between diffusive convective mixing and mechanical mixing  
8 335 for increasing turbulence intensity is likely not abrupt, and there may remain a signature of  
9 336 diffusive convection in the temperature variance of the turbulent regime, resulting in a bias in  
10 337 the Osborn-Cox estimation. However, this contrast persists even at  $Re_b \gg 25$ , and these stability  
11 338 regimes also identify water masses subjected to contrasted shear and stratification conditions.  
12 339 This point could be addressed with the use of process oriented direct numerical simulations or  
13 340 laboratory experiments. In addition, studies based on microconductivity measurements could be  
14 341 conducted in parallel, to assess the Osborn-Cox method in regimes favourable to double diffusion,  
15 342 especially in regions where the stratification is highly influenced by salinity as is the case in  
16 343 the Mediterranean Sea. This method is much less frequently used (e.g. Nash and Moum, 2002;  
17 344 Walter et al., 2014; Holleman et al., 2016) due to sensor resolution and noise issues.

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27 345         Based on the Buckingham  $\pi$  theorem for dimensional analysis and considering the vari-  
28 346 ables turbulent kinetic energy, turbulent kinetic energy dissipation rate, buoyancy frequency,  
29 347 vertical velocity shear, viscosity, and thermal and saline molecular diffusivity, described by their  
30 348 respective length and time scales, Gregg et al. (2018) estimated that the mixing efficiency could  
31 349 be characterised by 5 dimensionless parameters. Numerical simulations suggest that the mixing  
32 350 efficiency variability depends at least on a quantity describing the stratification and on one de-  
33 351 scribing the level of turbulence (Gregg et al., 2018). A caveat of numerical simulations as those  
34 352 performed by Shih et al. (2005) is that large  $Re_b$  concurs with weak stratification, which is not  
35 353 the case everywhere in the ocean, therefore  $N^2$  should be considered as an independent factor  
36 354 (Gregg et al., 2018). A collapse of the dissipation flux coefficient was indeed observed for low  $N^2$   
37 355 in the Western Mediterranean dataset. Moreover, numerical simulations generally only reproduce  
38 356 one idealised mixing mechanism (most often Kelvin-Helmholtz sheared turbulence), which is not  
39 357 necessarily representative of the complex assortment of interacting processes at different stages of  
40 358 development in the ocean. While  $\Gamma_t = 0.2$  is a good approximation for steady state shear-driven  
41 359 mixing with no initial overturning (e.g. Caulfield, 2020), pre-existent turbulence strongly affects  
42 360 the mixing efficiency of a shear instability (Kaminski and Smyth, 2019). In DNS, the age of a  
43 361 turbulent mixing event induced by shear instability was shown to be equivalent to the ratio of  
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3 362 the Ozmidov to the Thorpe scales (e.g. Smyth et al., 2001). Based on estimates inferred from  
4 363 observations, Mashayek et al. (2017) found a behaviour of the mixing efficiency as a function of  
5 364 the turbulence intensity that is similar to that exhibited by the Mediterranean quiescent regions  
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7 365 for young turbulence, while the case of older turbulence rather resembles the behaviour observed  
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9 366 in the energetic regions. Similarly, Cyr and Van Haren (2016) found higher mixing efficiency esti-  
10 367 mated from finescale density (mean 0.36) during energetic periods associated with the collapse of  
11 368 internal bores and younger turbulence, than during less energetic periods of decaying turbulence  
12 369 (mean 0.2). As for ocean measurements, little consistency exists between observational datasets.  
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14 370 This is likely partly due to measurement and method related limitations and uncertainties (e.g.  
15 371 Gregg et al., 2018). Consistent with Monismith et al. (2018), no clear dependence on  $Ri$  was  
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17 372 evident for the Western Mediterranean dataset, possibly due to the inadequate vertical resolution  
18 373 of classical CTD/LADCP measurements used to infer  $Ri$ ; this question could be addressed by  
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20 374 employing more accurate current meters with a high vertical resolution of the order of 1 m.  
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24 375         Mixing efficiency is generally parameterised in order to estimate diapycnal diffusivity  
25 376 from microstructure measurements and subsequently compute vertical turbulent diffusive fluxes.  
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27 377 The diapycnal diffusivity estimates based on the dissipation flux coefficient confirmed that the  
28 378 localised Western Mediterranean energetic regions with a strong bathymetry constricted flow  
29 379 are hotspots for vertical turbulent mixing of intermediate water mass properties. Advection in  
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31 380 particular helps sustain the strong stratification in the energetic regions and thus contributes  
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33 381 to maintain a high mixing efficiency, in contrast to the quiescent, less stratified regions. The  
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35 382 average diapycnal eddy diffusivity on the global oceanic scale was estimated from energy and  
36 383 transport budgets at  $10^{-4} \text{ m}^2 \text{ s}^{-1}$  (Munk, 1966; Munk and Wunsch, 1998). However, mixing is  
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38 384 strongly heterogeneous and local values differ by orders of magnitude (Wunsch and Ferrari, 2004;  
39 385 Waterhouse et al., 2014). Ocean global circulation models are very sensitive to the way mixing  
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41 386 efficiency and diapycnal diffusivity are represented, and more accurate parameterisations need  
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43 387 to be developed and implemented (De Lavergne et al., 2016; Mashayek et al., 2017; Cimoli et al.,  
44 388 2019). This study further suggests that models should employ a non-constant mixing efficiency  
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46 389 and should distinguish between quiescent regions where the mixing efficiency is significantly  
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48 390 below 0.2, and energetic regions with mixing efficiency well above 0.2. Considering that most of  
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50 391 the ocean volume has similar characteristics to the quiescent regions, this difference may cancel  
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52 392 out on a large scale but be locally important. The relative significance of the localised mixing  
53 393 hot spots should therefore be more thoroughly addressed. To this end, the mixing efficiency  
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3 394 variability depending on the mechanisms that drive mixing needs to be further investigated.  
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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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