A methodology for Thorpe scaling 512 Hz fast thermistor data from buoyancy-driven gliders to estimate turbulent kinetic energy dissipation rate in the ocean

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***Abstract*—A Kongsberg Seaglider with a microstructure package was deployed in the Faroe-Shetland Channel in 2017 as part of the 4th Marine Autonomous Systems in Support of Marine Observations (MASSMO4). Using the FP07 fast thermistor (512 Hz), the standard Seaglider thermistor (0.2 Hz) and potential density calculated from Seaglider conductivity-temperature sail (0.2 Hz) a comparison of the Thorpe Scale method has been made. Through this method turbulent kinetic energy (TKE) dissipation rates are inferred from the length-scale of a turbulent overturn. Comparison of the three physical quantities show that overturns with a comparable length-scale also have a comparable TKE dissipation rate. The range of estimated TKE dissipation rates from the 0.2 Hz data is also comparable to those inferred using the same method applied to potential density calculated from a ship mounted CTD.**

***Index Terms*—Seaglider, Thorpe scale, Ocean mixing, Autonomous Vehicles**

I. INTRODUCTION

Turbulent mixing influences the distribution of physical, chemical and biological properties of the ocean [1], but is poorly mapped on a global scale. Turbulence measurements in the ocean are typically limited both spatially and temporally [2] so the intermittent nature and space-time variability of turbulence is rarely captured in its entirety. In the last 10 years, there have been efforts to increase the archive of turbulence measurements by fitting microstructure sensor systems to mechanically quiet autonomous platforms, including buoyancy-driven gliders equipped with shear probes and fast thermistors [3], [4]. Although shear data is more commonly used to calculate turbulent kinetic energy (TKE) dissipation rate (ε), values can also be inferred from temperature data by fitting the temperature gradient spectrum to a theoretical curve [5]. Here we discuss an alternative, and complimentary, approach in which ε is empirically related to the physical size of observed turbulent overturns.

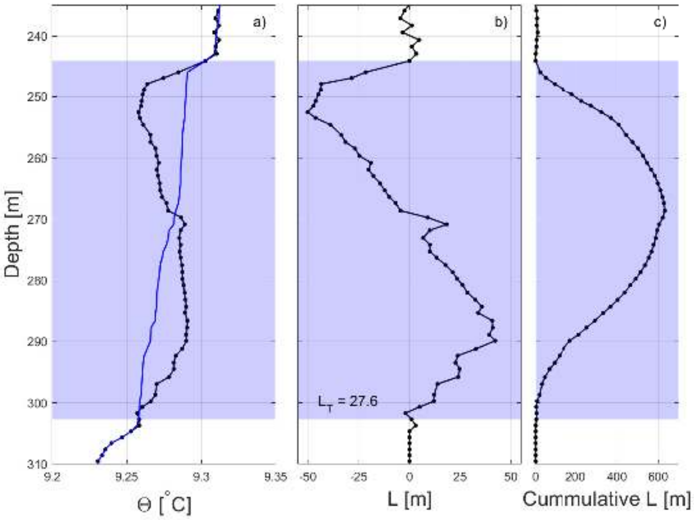

Fig. 1. a) Measured (black) and reordered (blue) conservative temperatures profiles. b) Associated Thorpe displacements c) Cumulative Thorpe displacements. Shaded blue areas mark the vertical extent of the complete overturn.

II. THE THORPE SCALE

TKE dissipation rate can be inferred from the length-scale of a turbulent overturn (the Thorpe length-scale, L_T) [6]. The Thorpe length-scale is usually calculated from profiles of potential density (ρ), but in regions where temperature is the dominant control on density it is possible to achieve a reasonable approximation using conservative temperature (Θ) profiles. A high-resolution conservative temperature profile (either up or downcast) is reordered so that it monotonically decreases from the surface to the deepest point (Fig. 1, a). The vertical distance that a water parcel is moved during

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Fig. 2. MicroPods mounted either side of the CT sail on a Kongsberg Seaglider. Note the metal dummy probes that are inserted when the Seaglider is in storage or transit.

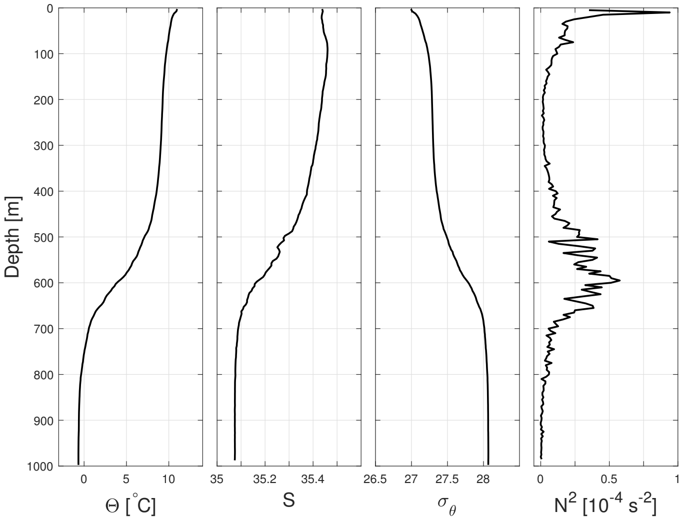

Fig. 3. Time-averaged conservative temperature, absolute salinity, potential density and buoyancy frequency squared for the 17 profiles presented.

the reordering process is its Thorpe displacement (L, Fig. 1, b). The difference in temperature between the original and reordered profile is the Thorpe fluctuation (T_f). L_T is the r.m.s. of L over a section of the water column identified as an overturn (a vertical section of the water column where non-zero values of L cumulatively sum to zero [7]). For consistency the sign of cumulative L on down casts (up casts) has been switched for temperature (density) so that all profiles have a positive L value. TKE dissipation rate is then estimated using

$$\varepsilon = 0.64 L_T^2 N^3, \tag{1}$$

where N is the average buoyancy frequency across the overturn.

III. DATA COLLECTION

In 2017 a Kongsberg Seaglider (SG613) with a Rockland Scientific MicroPod system, consisting of a FP07 faster thermistor and shear probe, was deployed for three days as part of the 4th Marine Autonomous Systems in Support of Marine Observations (MASSMO4) in the Faroe-Shetland Channel (North Atlantic, typical physical properties for the region can be seen in Fig. 3.) to the north east of the Wyville Thomson Ridge (Fig. 4). In the first 36 hours 25 up and downcast profiles where recorded by the microstructure system, 17 of these being 500 m deep or greater. These profiles and the associated conductivity-temperature (CT) data collected by the Seaglider will be the focus of the work presented here.

Unlike the self contained MicroRider system mounted on the Slocum glider [3] the Seaglider microstructure package comprises of two MicroPods and a separate pressure casing. The pair of MicroPods are mounted either side of the Seaglider CT sail (Fig. 2) and can be configured to house either a FP07 fast thermistor or shear probe (more recently a new pod has been developed to house an electromagnetic current meter). The pressure casing, which houses the electronics and data logger, is mounted in the aft fairing of the glider. More information can be found in *Creed et al.* 2017 [4] .

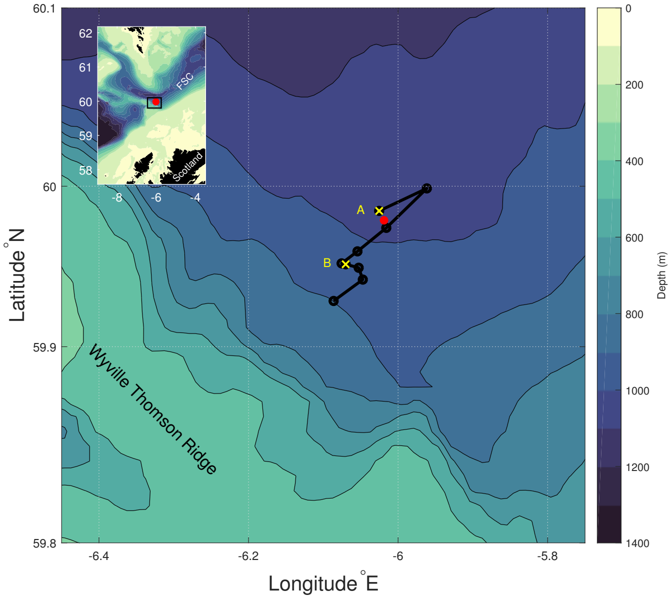

Fig. 4. Dive locations during the MASSMO4 deployment. The inset map shows the dive locations in relation to the wider area. The red dot represents glider deployment location. Crosses A and B are the starting locations of dive 5 and 10 respectively

IV. RESULTS

A. Comparison of Physical Quantities

The Thorpe scale method is applied to temperature data from both the FP07 fast thermistor (512 Hz) and the CT sail thermistor (0.2 Hz) as well as potential density (calculated from the temperature and conductivity from the Seaglider's CT sail, 0.2 Hz) to provide comparison of the impact resolution

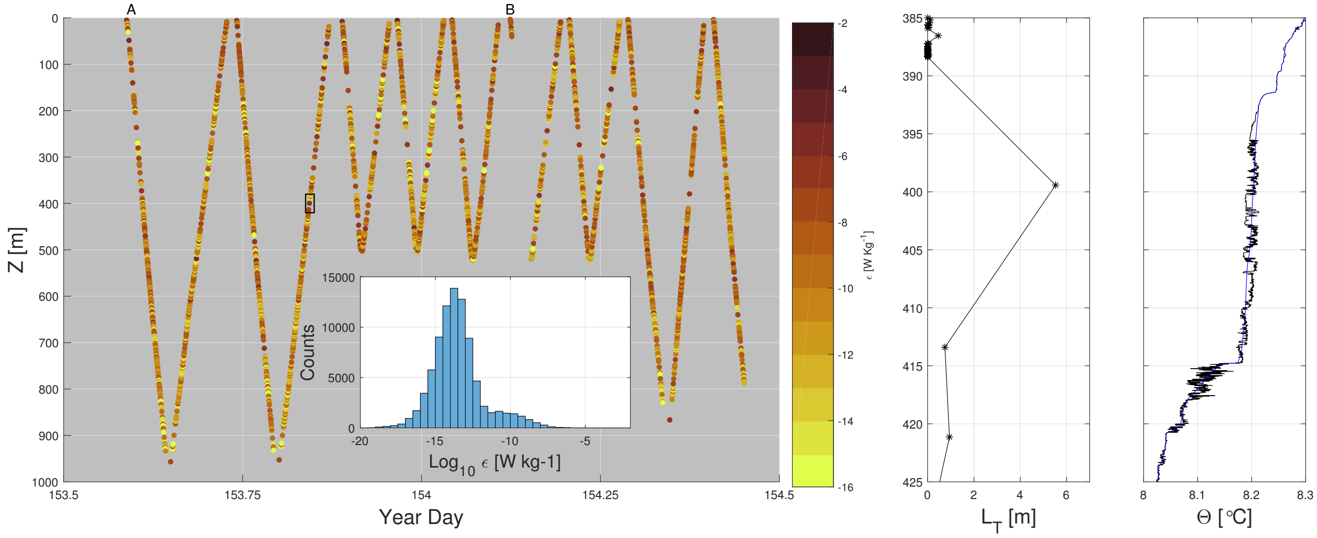

Fig. 5. TKE dissipation rate calculated from 512 Hz conservative temperature data from 17 profiles. Inset histogram shows the spread of ε. A and B represent the start of dives 5 and 10 respectively as in Fig. 4. L_T, observed and reordered temperature for an overturn in dive 6 up cast (located by the black rectangle) are also shown.

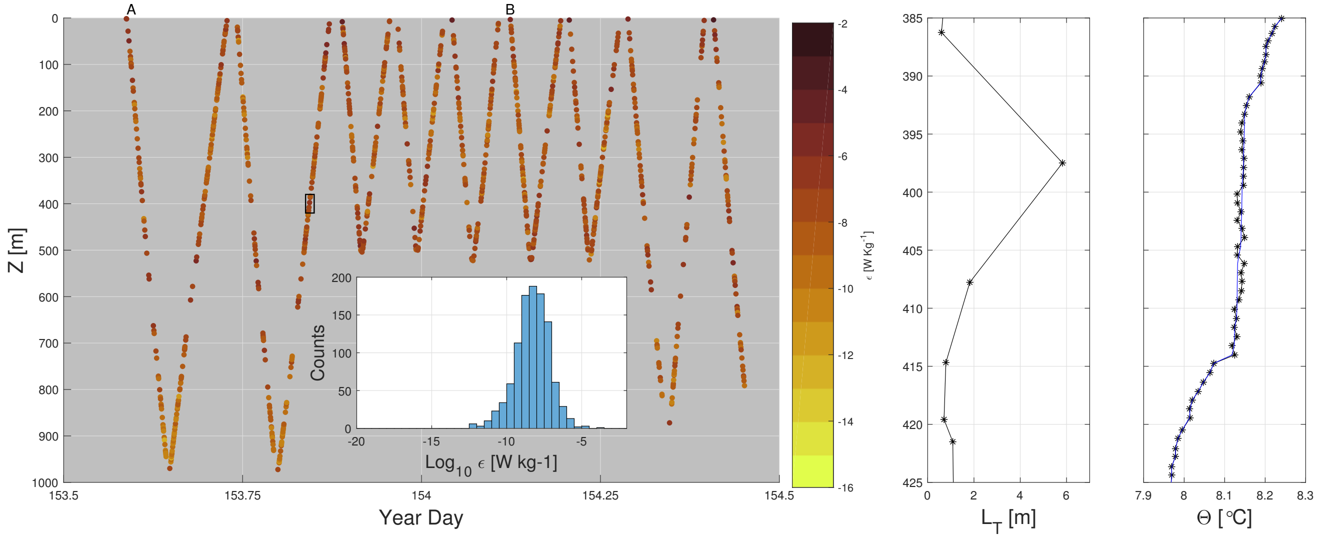

Fig. 6. TKE dissipation calculated from 0.2 Hz conservative temperature data from 17 profiles. Inset histogram shows the spread of ε. A and B represent the start of dives 5 and 10 respectively as in Fig. 4. L_T, observed and reordered temperature for an overturn in dive 6 up cast (located by the black rectangle) are also shown.

and physical quantity has on estimated TKE dissipation rates (ε). In Fig. 4,5 and 6 the ε values from all 17 profiles are displayed. Alongside each is the L_T for an overturn on dive 6 up cast as well as the observed (black) and reordered (blue) temperature or density. This overturn was selected as an example due to a comparable depth and L_T in each dataset.

Fig. 5 shows the TKE dissipation rates (ε) calculated from the 512 Hz temperature data. Compared to Fig. 6 (0.2 Hz temperature) and Fig. 7 (0.2 Hz potential density) a greater range of ε have been identified from L_T extending from order 10^{-4} to an average minimum 10^{-14}, a range greater than previous estimates in the region using the same method applied to medium resolution (24 Hz) CTD data [8]. ε calculated from the 0.2 Hz temperature and 0.2 Hz potential density both show an average minimum of 10^{-8}, as well as upper estimated values of ε of order 10^{-4}.

A higher density of smaller overturns can be seen in the top $\sim$ 150 m and again between $\sim$ 400 m and $\sim$ 700 m across all three data sets with the this being most pronounced in the 0.2 Hz potential density data (Fig. 7) that exhibits fewer identified overturns between $\sim$ 200 m and $\sim$ 350 m than either temperature data set. This is discussed in more detail in the next section.

Overturns of similar L_T in temperature (Fig. 5 and 6, $\sim$ 6 m, overturns highlighted in the black rectangle) show the same order of magnitude for the calculated ε ($\sim 2 \times 10^{-7}$) as well

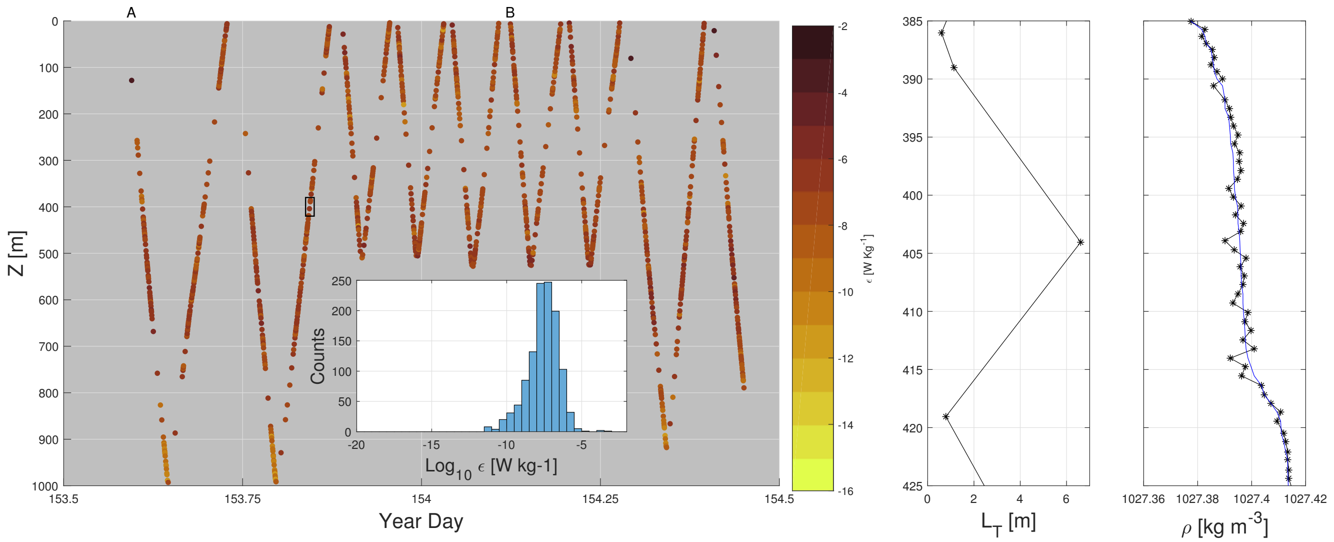

Fig. 7. TKE dissipation calculated from 0.2 Hz potential density data from 17 profiles. Inset histogram shows the spread of ε. A and B represent the start of dives 5 and 10 respectively as in Fig. 4. L_T, observed and reordered density for an overturn in dive 6 up cast (located by the black rectangle) are also shown.

as when compared with potential density with a similar L_T.

B. *Considerations*

1) Calculating Buoyancy Frequency : A buoyancy frequency (N) is required for the calculation of ε (Eq. 1), where $N = \sqrt{-g/\rho \ \partial\rho/\partial z}$. when the Thorpe scale method is applied to potential density N is calculated from the gradient of the reordered density ($\partial\rho/\partial z$) associated with a given overturn. Buoyancy frequency cannot be directly calculated from temperature. However a value for N is still required when applying the Thorpe scale method to temperature. The initial approach of providing a value of N involved creating a pseudo-density profile. This used a mean salinity profile taken from the Seaglider data to calculate a density profile based on the reordered temperature. This pseudo-density profile was then used to calculate N in the same manner as when Thorpe scaling potential density. However this approach led to a two order of magnitude difference between estimates of ε for temperature and density when similar sized and located overturns where compared.
Due to these issues, in this study N was instead calculated using reordered density from the matching density profile. To match the resolution of the FP07 data the reordered density was up sampled using a linear interpolation. By using this method all three physical parameters show comparable values of ε for overturns of a similar size and location.

2) Temperature Dominance: Unlike reordering density to be monotonically increasing with depth, a monotonically decreasing temperature does not equate to a statically stable water column. Using temperature as proxy for density will then only work at points in the water column where the stratification is temperature dominated [7]. This is the likely cause of variation in locations of overturns between the temperature based overturns and the density based overturns. Work is currently ongoing to determine which parts of the water column are suitable for temperature Thorpe scaling.

V. DATA SPREAD AND LOWER DETECTIONS LIMITS

3) Lower Limits: Calculated ε values are based on the raw L_T data and do not take into account that the smallest overturns that can be sampled are dictated by the Seaglider's vertical speed through the water and the sampling speed of the instruments. The glider travels diagonally through the water at $\sim$ 0.2 m s^{-1} which equates to roughly one metre vertical change every 5 seconds. The CT sail (and calculated potential density) are recorded at 0.2 Hz leading to 1 data point approximately every meter, and a minimum L_T of 0.5 m. In comparison the as the FP07 records at 512 Hz leading to a data point approximately every 4×10^{-4} m, and a minimum L_T of 2×10^{-4} m.

4) Data Spread: Fig. 8 shows the spread of L_T and ε values. L_T for the 512 Hz temperature data (Fig. 8 ai) shows two peaks, one at $\sim 2.5 \times 10^{-2}$ m (two orders of magnitude smaller than either 0.2 Hz data) and a second, larger, peak at $\sim 7 \times 10^{-4}$ m. Both 0.2 Hz L_T data sets (bi and ci) show a single peak at $\sim 2 \times 10^{0}$. A similar spread is also seen in the ε data. The 512 Hz temperature shows peaks at $\sim 5 \times 10^{-10}$ and $\sim$ 5×10^{-15} with the peaks of the 0.2 Hz data both occurring at $\sim$ 1×10^{-8}. As stated in the previous section the smallest possible overturn that can be detected in the 512 Hz data is 2×10^{-4} m, a value that is of the same order of magnitude of the larger peak seen in Fig. 8 ai. A study in 2018 [9] suggest that a lower limit for reliable values derived from temperature is no smaller than 2×10^{-12} W kg^{-1} (in weakly turbulent envirnoments), nearly three orders greater than the second peak seen in Fig. 8 aii. This peak is potentially linked to noise floor of the instrument rather than being a true observed

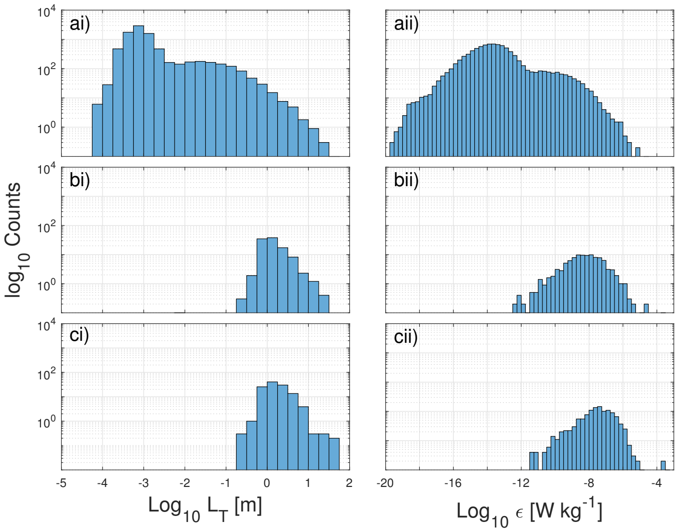

Fig. 8. Histograms showing L_T and ε for 512 Hz conservative temperature (ai and aii), 0.2 Hz conservative temperature (bi and bii) and 0.2 Hz potential. density (ci and cii).

phenomena. Further work is required to determine the exact cause of this.

VI. CONCLUSIONS AND FURTHER WORK

Here we show that the Thorpe scale method can be used successfully used on three different data sets provided by a single ocean glider. Using this method ε values estimated from 0.2 Hz potential density and conservative temperature are consistent with previous estimations from other works carried out in the Faroe-Shetland Channel. Further work is still required to determine the lower limits of ε that can be estimated by this technique when using 512 Hz temperature data. Buoyancy-driven glider deployments are becoming a more routine way of sampling the ocean leading to a constantly growing archive of thermistor data. This comparison of Thorpe scaling methodology increases the value of existing data in addition to improving global estimates of TKE dissipation rate and our understanding of turbulent mixing in the ocean.

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The Seaglider data were processed using the UEA Seaglider Toolbox (https://bitbucket.org/bastienqueste/ueaseaglider-toolbox) and are available from the UEA Glider Group. Data analysis code is available on request from the corresponding author.

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