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Key Points:

- Dissipation rate estimates in low-energy environments are subject to increased uncertainty when stratification is strong
- Shear microstructure measurements may overestimate dissipation rates in low-energy environments
- Resulting biases in geometrically averaged dissipation rates may exceed an order of magnitude

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Measuring the Dissipation Rate of Turbulent Kinetic Energy in Strongly Stratified, Low-Energy Environments: A Case Study From the Arctic Ocean

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Abstract We compare estimates of the turbulent dissipation rate, ϵ , obtained independently from coincident measurements of shear and temperature microstructure in the southeastern Beaufort Sea, a strongly stratified, low-energy environment. The measurements were collected over 10 days in 2015 by an ocean glider equipped with microstructure instrumentation; they yield 28,575 shear-derived and 21,577 temperature-derived ϵ estimates. We find agreement within a factor of 2 from the two types of estimates when ϵ exceeds 3×10^{-11} W/kg, a threshold we identify as the noise floor of the shear-derived estimates. However, the temperature-derived estimates suggest that the dissipation rate is lower than this threshold in 58% of our observations. Further, the noise floor of the shear measurements artificially skews the statistical distribution of ϵ below 10^{-10} W/kg, that is, in 70% of our observations. The shear measurements overestimate portions of the geometric mean vertical profile of ϵ by more than an order of magnitude and underestimate the overall variability of ϵ by at least 2 orders of magnitude. We further discuss uncertainties that arise in both temperature- and shear-derived ϵ estimates in strongly stratified, weakly turbulent conditions, and we demonstrate how turbulence spectra are systematically modified by stratification under these conditions. Using evidence from the temperature-gradient spectral shapes and from the observed ϵ distributions, we suggest that the temperature-derived dissipation rates are reliable to values as small as 2×10^{-12} W/kg, making them preferable for characterizing the turbulent dissipation rates in the weakly turbulent environment of this study.

1. Motivation

The purpose of this study is to examine the agreement between measures of the turbulent kinetic energy dissipation rate, ϵ , derived from measurements of shear and temperature microstructure in a stratified *low-energy* environment, that is, a stratified environment where the amount of turbulent kinetic energy in the flow field is unusually small. It was motivated when, in an attempt to quantify turbulent mixing in the Beaufort Sea thermocline, we discovered that results from the two measurements diverged strongly at low ϵ . Where dissipation rate estimates from shear measurements frequently clustered near a clearly defined lower limit, estimates from temperature measurements distributed to much lower values that were often multiple orders of magnitude smaller. We noted that this may have serious implications for how shear microstructure measurements from the Arctic Ocean are interpreted. This study is therefore dedicated to describing the divergence we observed and discussing its causes with the goal of informing the collection and interpretation of microstructure measurements in the Arctic Ocean or similar stratified low-energy environments.

The western Arctic Ocean, where we collected our measurements, is known to be an exceptionally low-energy, and highly stratified, ocean environment with some of the lowest estimates of oceanic turbulence in the world (e.g., Guthrie et al., 2013; Lincoln et al., 2016). Only a relatively small number of microstructure measurements from this region exist to date (e.g., Bourgault et al., 2011; Padman & Dillon, 1987; Rainville & Winsor, 2008; Rippeth et al., 2015; Shaw & Stanton, 2014; Shroyer, 2012), but this number is certain to increase in the coming years owing to increased interest in constraining oceanic heat budgets in the Arctic (Carmack et al., 2015). Constraining these budgets requires knowledge of turbulent mixing rates in the ocean which are obtained most directly from microstructure measurements; we demonstrate here why this is a challenging endeavor and why special considerations are needed when interpreting those measurements

in stratified low-energy environments. Our present study is therefore timely since turbulent mixing estimates from microstructure measurements have become a key component in estimating heat fluxes through the Beaufort Sea thermocline.

Both shear and temperature microstructure measurements are frequently used to estimate the dissipation rate ϵ , a quantity that characterizes the intensity of turbulent flows and can range over more than 10 orders of magnitude in the ocean (Gregg, 1999; Lueck et al., 2002). Ours is not the first study to compare estimates of ϵ from coincident shear and temperature microstructure measurements: similar comparisons were performed by Oakey (1982), Kocsis et al. (1999), and Peterson and Fer (2014). These three studies all found excellent agreement, generally within a factor of 2, between shear- and temperature-derived estimates. Our study, however, is distinct because we focus on comparing ϵ estimates at the very low end of reported values where shear probes in particular operate at their lower sensitivity limit. The three previous comparative studies examined primarily dissipation rates in excess of 10^{-10} W/kg. We will demonstrate that it is necessary to resolve dissipation rates lower than this in the Beaufort Sea, that ϵ estimates from shear and temperature measurements no longer agree at these small values, and that this disagreement can lead to serious biases in the resulting mixing rate estimates in low-energy environments. In addition, we will demonstrate the way in which turbulence spectra diverge systematically from commonly used reference shapes when turbulence becomes weak and stratification becomes strong. We attribute this divergence to a breakdown of the assumption that turbulence in the flow is stationary, homogeneous, and isotropic.

2. Measurements

2.1. Measurement Platform: Slocum Glider

The platform for our microstructure measurements was the 1,000-m-rated Slocum G2 ocean glider *Comet*, one of the gliders also used by Schultze et al. (2017). The glider samples autonomously in a vertical sawtooth pattern, surfacing at predetermined intervals to establish a satellite link in order to update its position estimate, send low-resolution flight and hydrography data, and receive updated sampling instructions from an onshore pilot. For a detailed review of the operation and utility of gliders, see Rudnick (2016).

The glider's onboard sensors include an SBE-41 (pumped) Seabird CTD measuring in situ conductivity, pressure, and temperature; a three-dimensional compass module measuring heading, pitch, and roll; and an altimeter measuring height-above-bottom. The turbulence measurements are taken with a specialized, externally mounted instrument, described in section 2.2. A moveable weight that controls the pitch of the glider was set to fixed positions and only moved during inflections at the top and bottom of profiles to avoid mechanical vibrations that affect the quality of turbulence measurements midprofile (Fer et al., 2014).

The first published use of gliders as a platform for microstructure measurements is in the proof-of-concept study by Wolk et al. (2009). Gliders have since successfully demonstrated their utility for microstructure measurements in studies by Fer et al. (2014), Peterson and Fer (2014), Palmer et al. (2015), and Schultze et al. (2017). These have shown that gliders are suitable low-noise platforms providing microstructure measurements of comparable quality to those obtained from free-falling profilers.

Gliders are able to provide continuous measurements during a deployment, yielding a spatial and temporal coverage in oceanic microstructure fields that is often unattainable from ship-based profiling, especially in inclement weather. The high density and large number of measurements obtained from *Comet* is an important feature for our study because it allows us to calculate robust statistical measures of turbulence metrics which are critical to interpreting microstructure measurements (Gibson, 1987); these have been largely unavailable from previous studies in the western Arctic Ocean where microstructure measurements are sparse.

2.2. Shear and Temperature Microstructure

Comet is equipped with an externally mounted turbulence package (MicroRider) carrying two airfoil velocity shear (SPM-38) and two fast-response temperature (FP07) probes. The shear probes are of the design by Osborn (1974) and sense transverse forces in a direction perpendicular to the direction of travel (Lueck et al., 2002; Osborn & Crawford, 1980). The probes are oriented such that each measures a distinct shear component, orthogonal to that measured by the other (as in Fer et al., 2014). The temperature probes are sensitive thermistors with response times of ~ 10 ms and sensitivities better than 0.1 mK (Sommer, Carpenter, Schmid, Lueck, & Wüest, 2013). The microstructure probes extend beyond the nose of the glider by ~ 17 cm, outside of

Figure 1. (a) The measurement location at the entrance to the Amundsen Gulf in the southeastern Beaufort Sea. The glider path is shown by the line inside the dashed black rectangle. Bathymetry contours are drawn at 1,000-m intervals beginning at 200 m. (b) Enlarged view of the area inside the dashed rectangle indicated in panel a, showing the glider path and the local bathymetry. Selected waypoints along the path are numbered consecutively and indicated by squares for reference when reading Figures 2 and 3. Contours are drawn at 75-m intervals beginning at 50 m. In both panels, color indicates water depth (m); bathymetry data are from the International Bathymetric Chart of the Arctic Ocean 3.0 (Jakobsson et al., 2012). Mean vertical profiles of (c) conservative temperature, (d) in situ density anomaly, and (e) buoyancy frequency are also shown; these are horizontally averaged over all casts where the glider's maximum dive depth exceeded 325 m.

the radius of flow deformation caused by the glider's motion (Fer et al., 2014). We do not install a probe guard in order to minimize the potential for contamination of the flow in the immediate vicinity of the measurement.

Besides shear and temperature, the MicroRider also measures pressure, pitch, roll, and transverse accelerations. Shear, temperature, and acceleration are sampled at 512 Hz, the other channels at 64 Hz. The MicroRider is produced by Rockland Scientific International (RSI); it is the same model used in the four glider-microstructure studies referenced in the previous section.

2.3. Location, Local Hydrography, and Sampling Strategy

The measurement location was the Amundsen Gulf on the southeastern margin of the Beaufort Sea (Figure 1a). Circulation in the region is complex and highly variable in space and time; it is strongly influenced by surface wind stress, complex local bathymetry, submesoscale frontogenesis, and the intermittent presence of mesoscale eddies (Sévigny et al., 2015; Williams & Carmack, 2008, 2015). Barotropic tidal currents can be regionally strong but are locally weak where the glider was deployed because of the presence of a local amphidrome (Kowalik & Matthews, 1982; Kulikov et al., 2004). The presence of sea ice is seasonal; during our campaign, the southern edge of fragmented sea ice was coincident with the mouth of the Amundsen Gulf, prohibiting us from guiding the glider north toward the central Beaufort Sea as initially planned. The Amundsen Gulf was consequently selected for the measurement locale to mimic as closely as possible the hydrographic characteristics of the wider Beaufort Sea while minimizing the risk of collisions with sea ice floes.

The basin depth in Amundsen Gulf is ~450 m (Figure 1b), well below the typical Beaufort Sea shelf-break depth of ~75 m and deep enough to extend across the entire range of the thermocline separating Atlantic- and Pacific-sourced water masses. As a result, the hydrography of the region largely reflects that of the broader Beaufort Sea (Figures 1c–1e). A 10-m-thick brackish surface lens, resulting from summer sea ice melt and the nearby Mackenzie River's freshwater inflow, caps a near-surface pycnocline that extends to 25-m depth and has a density anomaly σ that ranges between 22 and 24.5 kg/m³. Between ~25 and 200 m, the signatures of cold Pacific-sourced water dominate the mean temperature profile leading to a temperature minimum of -1.4°C at 120-m depth; a complex submesoscale temperature structure is notably visible in this layer and modifies the mean profile between ~40- and 110-m depth. A prominent thermocline characteristic

of the Beaufort Sea extends from 125 m to the temperature maximum associated with the warm core of Atlantic-sourced water (Rudels, 2015; Williams & Carmack, 2015) at 375-m depth. Stratification is strong throughout the water column, with buoyancy frequency N of $O(10^{-2})\text{ s}^{-1}$ in the near-surface pycnocline and $O(10^{-3})\text{ s}^{-1}$ elsewhere.

The glider sampled continuously between 25 August and 4 September 2015, following the path outlined in Figure 1. It measured 348 quasi-vertical profiles over a total path length of 186 km, remaining in the deeper central Amundsen Gulf for the first 4.5 days and partially crossing the continental shelf slope three times during the remainder of the mission. The glider dove to a fixed depth of 300 m during the first 3 days; after this, it dove to within 15 m of the local bottom.

3. Data Processing

Processing microstructure measurements from a glider is similar to processing ones from a free-falling profiler but with added complications. Estimating the speed of the microstructure probes through water requires specialized procedures, as does screening the data for corrupt measurements. Because measuring turbulence from gliders is still a novel technique, we outline here in detail the steps we take to go from microstructure measurement to dissipation rate estimate, including our procedure for estimating the glider's velocity underwater. The quality control criteria we use to flag and discard suspect measurements, a comparison of dissipation rate results from upcasts and downcasts, and a brief description of Nasmyth and Batchelor reference spectra are provided in the Appendix.

Throughout the text, the symbol ϵ is used for the dissipation rate generally, ϵ_U for dissipation rate estimates obtained from velocity shear measurements, and ϵ_T for dissipation rate estimates obtained from temperature measurements. All wavenumbers are defined cyclicly, with units cpm. Note that the cyclic wavenumber, k , is related to the radian wavenumber, $\hat{k}$, which has units m^{-1} , through the relation $k = \hat{k}/2\pi$. The kinematic viscosity, ν , of seawater is evaluated locally using TEOS-10 (McDougall & Barker, 2011) because it varies by more than 20% in our measurements. We use $D_T = 1.44 \times 10^{-7}\text{ m}^2/\text{s}$ for the molecular diffusion coefficient of temperature and $q_B = 3.4$ for the Batchelor constant; the latter is required when evaluating the Batchelor spectrum (section 3.3), and a sensitivity analysis for this parameter is presented in Appendix C. Measurements from the MicroRider's clock, pressure sensor, and temperature probes are prone to low-frequency drift; thus, the low-frequency response from each of these channels is corrected to measurements from the glider. Note that unless otherwise stated, we average quantities that span many orders of magnitude using the geometric mean, and we use the term *trimmed mean* to refer to an average calculated over the central 90% of data.

3.1. Glider Velocity Estimates

The processing of microstructure measurements to obtain dissipation rates is heavily reliant on accurate knowledge of the speed, U , with which the probes travel through water. Unfortunately, there is no direct measurement of the glider's speed underwater: the glider pitch, θ , and rate-of-change of pressure are known, but this is not enough information to directly obtain U because the glider travels with an unknown and variable angle of attack, α , which in our experience is usually in the range $1^\circ < |\alpha| < 10^\circ$.

Studies by Fer et al. (2014), Peterson and Fer (2014), and Palmer et al. (2015) use a hydrodynamic flight model developed by Merckelbach et al. (2010) to estimate U . The model assumes a steady state balance of drag, buoyancy, and lift forces to optimize estimates of U and a drag coefficient C_{D_0} . The angle of attack is then obtained numerically from the implicit relation

$$\alpha = - \left(\frac{C_{D_0} + C_{D_1} \alpha^2}{A \tan \gamma} \right) \quad (1)$$

where $\gamma = \theta - \alpha$ is the glide angle, and C_{D_1} and A are constants optimized for Slocum gliders in Merckelbach et al. (2010).

In contrast to this approach, we follow the method of Schultze et al. (2017) and use the steady state model of Merckelbach et al. (2010) to obtain the angle of attack but then use the measured pitch and pressure to estimate U dynamically using

$$U = \frac{W}{\sin \gamma}, \quad (2)$$

Table 1
Mean $\pm$ 1 Standard Deviation of Glider-Flight Variables From All Upcasts and Downcasts of the Mission

Profile Type	θ ($^{\circ}$)	α ($^{\circ}$)	γ ($^{\circ}$)	U (cm/s)
Upcasts	21.8 ± 1.0	-4.7 ± 0.2	26.4 ± 0.9	41 ± 4
Downcasts	-21.3 ± 0.8	4.8 ± 0.1	-26.0 ± 0.6	25 ± 4

Note. θ is the measured pitch, α the estimated angle of attack, γ the estimated glide angle, and U the estimated speed through water. Only data coincident with at least one viable ϵ estimate (see Appendix A) are included.

where W is the glider's vertical velocity estimated from the measured rate-of-change of pressure. We found that this quasi-dynamic estimate of U leads to more consistent results between profiles of ϵ from upcasts and downcasts. Note that angles are measured positive upward, θ and γ relative to the horizontal, α relative to the glide angle γ .

Mean and standard deviation values of selected glider flight characteristics separated by upcasts and downcasts are summarized in Table 1 to enable comparison with previous studies. For the most part, the values presented are not remarkable and are similar to ones previously reported, albeit with marginally larger angles of attack. One exception is the relatively large discrepancy in U between upcasts and downcasts. The discrepancy arises because of the strong near-surface stratification in the Beaufort Sea, resulting in asymmetric dive and climb rates over most of the water column; however, we do not see a significant systematic effect on the dissipation rate results (see Appendix B), and we do not differentiate between upcasts and downcasts from here on.

3.2. Microstructure Shear

The procedure we use to process the shear measurements uses code provided by RSI and is based on recommendations outlined in their documentation. We provide an overview here; a comprehensive rationale for the algorithm and detailed review of recommended procedures are available in RSI's Technical Note 028 (Lueck, 2016).

We calculate the dissipation rate from the viscosity and the variance of the turbulent velocity shear according to $\epsilon_U = 7.5\nu \langle (\partial u' / \partial x)^2 \rangle$, assuming isotropic flow. Here angled brackets indicate averaging, x represents the glider's along-path coordinate, and u' represents either of the two perpendicular turbulent velocity components. As discussed in section 5.3, the isotropy assumption is problematic when energetics are weak and stratification is strong, and it leads to increased uncertainty in the observed dissipation rates, but it is necessary to make the assumption because we measure only two of the nine strain rate tensor components.

We estimate the variance from the measured shear record in half-overlapping 40-s segments. Each of these is further subdivided into 19 half-overlapping 4-s subsegments which are detrended, cosine windowed (in a variance-preserving manner), and transformed into shear power spectra using a fast Fourier transform (FFT). These 19 spectra are averaged to create one observed shear power spectrum, Φ , for each 40-s segment of shear measurement. Coherent acceleration signals measured by the MicroRider are removed from Φ using the algorithm proposed by Goodman et al. (2006). Frequencies, f , are transformed to wavenumbers, k , using the glider's mean speed, $\bar{U}$, over the 40 s and assuming Taylor's frozen turbulence hypothesis, that is, $\Phi(k) = \bar{U}\Phi(f)$ and $k = f/\bar{U}$.

The 4-s length of the subsegments passed to the FFT sets the scale for the largest wavelengths (smallest wavenumbers) included in the shear spectrum $\Phi(k)$; it is identical to the FFT length chosen by Fer et al. (2014) and Schultze et al. (2017). Given the average glider speeds in Table 1, a typical FFT calculation includes along-path wavelengths as large as 164 cm on upcasts and 100 cm on downcasts, resolving the low-wavenumber transition between the inertial and viscous ranges of the turbulence spectrum (Lueck et al., 2002). The choice of 40 s for the total averaging length, corresponding on average to 16.4 m on upcasts and 10 m on downcasts, is larger than the 12-s averaging length used in the above mentioned studies; it is a heuristic choice and a compromise which trades a decrease in the spatial resolution of the observations in favor of an increase in the statistical confidence of individual ϵ_U estimates (Lueck, 2016).

We numerically integrate each $\Phi(k)$, calculating ϵ_U according to

$$\epsilon_U = 7.5\nu \int_0^{k_u} \Phi(k) dk. \quad (3)$$

Here, k_u is an upper integration limit, chosen to exclude large wavenumbers at which electronic noise dominates the measurement. To choose k_u , we fit a third-order polynomial to $\Phi(k)$ in order to isolate the location of the spectral minimum which typically indicates the onset of noise domination, but we constrain k_u to be at least 7 cpm. Note that in a low-energy environment most of the variance is at low wavenumbers: 90% of the variance lies below 7 cpm when $\epsilon = 10^{-10}$ W/kg (Gregg, 1999).

To account for unresolved variance, we calculate the fraction, P , of the integral of the nondimensionalized empirical Nasmyth spectrum (Nasmyth, 1970; Oakey, 1982) that is resolved below the nondimensionalized integration limit $k_u/(\epsilon_U/\nu^3)^{1/4}$. We then scale up ϵ_U by a factor of $1/P$ and iterate the correction procedure until the change in ϵ_U in successive iterations is less than 2%.

We further correct for a small integration underestimate that occurs between the origin and the first nonzero wavenumber, k_1 . The Nasmyth spectrum rises approximately as $k^{1/3}$, and so its integral to k_1 is proportional to $(3/4)k_1^{4/3}$; trapezoidal integration between $k = 0$ and k_1 , however, is proportional only to $(1/2)k_1^{4/3}$. We correct by adding the term $7.5\nu(1/4)k_1\Phi_N(k_1)$, where $\Phi_N(k_1)$ is the value of the Nasmyth spectrum at k_1 . Note that the two correction procedures described here are both standard features implemented in the provided RSI codes.

There are two distinct shear probes (section 2.2), yielding two independent, simultaneous ϵ_U estimates. When both estimates pass quality control (see Appendix), we average them; when only one passes quality control, we use that single estimate for the analysis presented in section 4. Note that, on average, we do not see a meaningful difference between results from the two shear probes (see Appendix A).

3.3. Microstructure Temperature

The dissipation rate ϵ_T may be estimated from temperature microstructure measurements by determining the Batchelor wavenumber, defined $k_B = (1/2\pi)(\epsilon_T/\nu D_T^2)^{1/4}$, and inverting to yield

$$\epsilon_T = \nu D_T^2 (2\pi k_B)^4. \quad (4)$$

We determine the Batchelor wavenumber by fitting the theoretical Batchelor spectrum (Batchelor, 1959) to observed power spectra of temperature gradients using the procedure outlined below, which is modeled on descriptions by Ruddick et al. (2000), Steinbuck et al. (2009), and Peterson and Fer (2014).

We first calculate a temperature power spectrum, Λ , from the temperature measurements for each of the same half-overlapping 40-s segments that we used to calculate the shear spectra. Each spectrum is again the average of 19 spectra calculated from half-overlapping, detrended and cosine windowed 4-s subsegments. Values of Λ at high frequencies, where the temperature probes' temporal response is inadequate, are corrected using the transfer function proposed by Sommer, Carpenter, Schmid, Lueck, and Wüest (2013). Like shear spectra, temperature spectra are transformed from frequency to wavenumber space using $\bar{U}$ and Taylor's frozen turbulence hypothesis.

From each Λ , we next calculate a *raw* one-dimensional temperature-gradient power spectrum, Ψ_r , using the variance-preserving transformation

$$\Psi_r = (2\pi k)^2 \Lambda. \quad (5)$$

From each of these we then subtract a probe-specific noise spectrum:

$$\Psi = \Psi_r - \Psi_{ns}, \quad (6)$$

where Ψ_{ns} is the noise spectrum, empirically determined for each probe by averaging the 1% of raw spectra with the least observed variance. We refer to Ψ as the *observed* temperature-gradient spectrum. Note that the temperature gradients are defined with respect to the along-glider path coordinate.

We next estimate the rate, χ , of destruction of temperature-gradient variance (Osborn & Cox, 1972) from the observed temperature-gradient spectra. Following Steinbuck et al. (2009), we iteratively calculate

$$\chi = \chi_{lw} + \chi_{obs} + \chi_{hw} = 6D_T \left(\int_0^{k_l} \Psi_B dk + \int_{k_l}^{k_u} \Psi dk + \int_{k_u}^{\infty} \Psi_B dk \right), \quad (7)$$

on each iteration subsequently fitting the Batchelor spectrum, Ψ_B , to the observed spectrum as described below. The term χ_{obs} is the component of χ that comes from integrating the observed spectrum between wavenumbers k_l and k_u . At wavenumbers outside this range, the observed spectrum is not reliable and we instead integrate Ψ_B to obtain the correction terms χ_{lw} and χ_{hw} . Note that the correction terms are unavailable and thus set to zero for the first iteration. The factor of 6 arises from assuming isotropic flow.

We fit the Batchelor spectrum between wavenumbers k_l and k_u on each iteration using the maximum likelihood estimation (MLE) procedure described by Ruddick et al. (2000). This procedure minimizes a cost function to choose the best fit from a family of Batchelor curves which are constructed using constant χ but variable k_B . For the upper limit k_u we choose the intersection between Ψ_r and $2\Psi_{ns}$. The lower limit k_l is the smallest available nonzero wavenumber k_1 on the first iteration, and on subsequent iterations is the greater of k_1 and $3k_*$, where $k_* = 0.04k_B(D_T/\nu)^{1/2}$ represents the top of the convective subrange (Luketina & Imberger, 2001). We implement three iterations, enough for k_B estimates to converge (Steinbuck et al., 2009), and then calculate ϵ_T from equation (4).

There are two distinct thermistors (section 2.2), yielding two independent, simultaneous ϵ_T estimates. As with the shear-derived estimates, when both pass quality control (see Appendix), we average; when only one passes, we use the single estimate for our analysis.

4. Comparison of Results From Temperature and Shear Microstructure

Here we present ϵ estimates derived from our coincident microstructure measurements of shear and temperature, demonstrating how the two estimates agree on average within a factor of 2 when $\epsilon > 3 \times 10^{-11}$ W/kg but diverge for smaller dissipation rates. We demonstrate that this divergence leads to inconsistencies between statistical metrics that describe the two sets of observations. Using evidence presented in sections 4.3 and 4.4, and in anticipation of the discussion presented in section 5.1, we attribute differences between the ϵ_U and ϵ_T data sets to the effects of the ϵ_U noise floor. With this foreknowledge, our description of these differences can be interpreted as a case study that demonstrates the degree by which the ϵ_U noise floor influences the ability of the shear measurements to characterize the dissipation rate in a stratified, low-energy environment.

4.1. Spatial Cross Sections

A qualitative comparison of the dissipation rates derived from shear and temperature microstructure measurements is generally favorable. This can be seen in spatial cross sections of ϵ_U and ϵ_T (Figure 2). Both fields exhibit obvious variability over at least 3 orders of magnitude and indicate the same coherent patches of enhanced turbulence superimposed on a less turbulent background. In both fields, these patches are characterized by dissipation rates $O(10^{-9})$ W/kg. They have a spatial coherence on scales $O(10)$ – $O(100)$ m vertically and $O(10)$ km horizontally. Three easily identifiable examples, seen in both panels, are between approximately (i) 10–20 km at depths 105–305 m, in the central Amundsen Gulf; (ii) 52–81 km at depths 155–400 m, at the edge of the shelf slope; and (iii) 161–183 km within a 75-m band above the sea floor, on the shelf slope. These are indicated in the figure with magenta rectangles. The qualitative similarity between the two independently derived estimates is encouraging and suggests that temperature and shear probes may be used to qualitatively identify the same regions of enhanced turbulence.

Figure 2, however, also reveals an immediate difference between the observed ϵ_U and ϵ_T fields: these indicate markedly different background states, easily seen in the figure because the images in the two panels are drawn with the same color scale. The ϵ_U field from the shear measurements indicates a background of $O(10^{-11})$ W/kg, imaged as a turquoise blue. There appears to be no obvious variability below $\epsilon_U \sim 5 \times 10^{-11}$ W/kg. The ϵ_T field from the temperature measurements, on the other hand, suggests a lower background value of $O(10^{-12})$ W/kg, as indicated by the frequent darker blue colors. Additional structure not seen in the ϵ_U observations is apparent in the ϵ_T field at dissipation rates between 1×10^{-12} and 5×10^{-11} W/kg. An example of this phenomenon may be seen by looking at the dissipation rate signature of what appears to be a mesoscale eddy whose presence can be identified in the temperature and density fields (not shown) at depths 40–100 m between 52–87 km: it carries an obvious signature of enhanced dissipation in the ϵ_T field (Figure 2b, dashed magenta box), but in the ϵ_U field (Figure 2a) no such signature can be identified.

The magnitude of the discrepancy between the two fields is apparent when visualizing a cross section of the ratio ϵ_U/ϵ_T (Figure 3). The discrepancy is largest, at times larger than a factor of 10^3 , in a band approximately at 50- to 150-m depth and between 100–186 km. Comparing with Figure 2, this region tends to coincide

Figure 2. Cross sections of the turbulent dissipation rate, ϵ , in $\log_{10}$ space, derived from microstructure measurements of (a) shear and (b) temperature. The panels are drawn using the same color scale. Gray shading indicates the bathymetry, black shading discarded or unavailable data (see section 2.3 and the Appendix). Small white lines along the horizontal axis indicate the locations of individual profiles. The breaks in the horizontal axis, labeled 1–4, correspond to the waypoints shown in Figure 1b. Magenta rectangles with solid white lines indicate regions of enhanced dissipation discussed in the text. The magenta rectangle with dashed white line in panel (b) indicates the signature of the mesoscale eddy discussed in the text.

with the region where ϵ_T is smallest. The discrepancy is less pronounced, however, in the three patches of enhanced turbulence identified in Figure 2; here the ratio ϵ_U/ϵ_T tends to unity.

4.2. Mean Vertical Profiles

We find, on average, more than an order of magnitude difference between ϵ_U and ϵ_T where dissipation rates are smallest. This can be seen in Figure 4a, in which the observed dissipation rate fields are horizontally averaged in 25-m vertical bins to create mean vertical profiles of ϵ_U and ϵ_T . In both profiles, the lowest dissipation rates are found between 100- and 125-m depth where, on average, $\epsilon_U = 4 \times 10^{-11}$ W/kg while $\epsilon_T = 3 \times 10^{-12}$ W/kg; there is a factor of 13 disagreement between the two. This disagreement is statistically significant: in this depth bin, the respective interquartile range for each data set is $\epsilon_U = 2 \times 10^{-11} - 8 \times 10^{-11}$ W/kg and $\epsilon_T = 3 \times 10^{-13} - 3 \times 10^{-11}$ W/kg, indicating little overlap between the two measurement distributions. The geometric standard deviation factors σ_g are 2.4 for ϵ_U and 13.4 for ϵ_T , reflecting the substantial horizontal variability seen in Figure 2 and the larger range of ϵ_T values. Despite the variability, the estimates of the mean values are robust: the 95% confidence intervals indicated by the geometric standard error (Kirkwood, 1979) are $\epsilon_U = 4 \times 10^{-11} - 5 \times 10^{-11}$ W/kg and $\epsilon_T = 3 \times 10^{-12} - 4 \times 10^{-12}$ W/kg, respectively.

Figure 3. Cross section of the ratio ϵ_U/ϵ_T in $\log_{10}$ space. Shading, panel division, magenta rectangles, and annotations as in Figure 2.

Figure 4. (a) Average vertical profiles of the dissipation rates ϵ_U and ϵ_T , obtained from shear and temperature microstructure and calculated using a trimmed geometric mean in 25-m vertical bins. Shading indicates the 95% confidence interval for the mean as indicated by the geometric standard error. (b) The ratio of the average vertical profiles of ϵ_U and ϵ_T , highlighting disagreement by a factor of 5 or greater between 75- and 175-m depth.

The discrepancy between the depth-binned average profiles is less dramatic in the rest of the water column, and the two profiles qualitatively have a similar shape. Both exhibit small dissipation rates below 10^{-10} W/kg in the shallowest available bin (25–50 m), decreasing further to their distinct minima between 100 and 125 m and then gradually increasing with depth to maximum average values near 10^{-10} W/kg as they approach the seabed. Disagreement between the geometric mean values, imaged in Figure 4b, is a factor of 5 or greater between 75- and 175-m depth and smaller everywhere else. Whenever both geometric mean values are simultaneously at least 3×10^{-11} W/kg, the agreement between them is better than a factor of 2, highlighting that the divergence between ϵ_U and ϵ_T occurs only at very low dissipation rates.

Note that our measurements tend to exhibit small ϵ relative to measurements from other regions of the global ocean, which often exhibit typical averaged values of $O(10^{-9})$ W/kg and higher (Waterhouse et al., 2014). This incongruity, however, is not surprising: small dissipation rates are anticipated in the western Arctic Ocean where turbulence is thought to be exceptionally low because of limited energy input and seasonal sea ice

Figure 5. Histograms showing the distributions of all (a) ϵ_U and (b) ϵ_T observations. The interquartile range is indicated by the darker shading; the mode, arithmetic and geometric means, and median are marked in both panels according to the legend in (a). The labels N and σ_g indicate the total number of observations in each histogram and the geometric standard deviation factor, respectively. Histograms are calculated over 100 logarithmically spaced bins. (c) Quantile-quantile plot demonstrating the goodness of fit of the histograms to idealized lognormal distributions. For each set of data, deciles are marked by gray-shaded circles, and the squared linear correlation coefficient, R^2 , is indicated.

Table 2
Statistical Parameters of the ϵ_U and ϵ_T Distributions Shown in Figure 5

Data Set	N	Mode	G. Mean	Median	P_{25}	P_{75}	A. Mean	σ_g
ϵ_U	28,575	2.7	6.5	4.6	2.5	13	25	3.7
ϵ_T	21,577	1.2	1.6	1.7	0.27	12	61	18.3

Note. Given, from left to right, are the number, N , of observations; mode; geometric mean; median; first and third quartiles, P_{25} and P_{75} ; arithmetic mean; and geometric standard deviation factor, σ_g . The quantities N and σ_g are dimensionless and unscaled. All other quantities are scaled by a factor of 10^{-11} W/kg.

cover (Rainville & Woodgate, 2009). Microstructure measurements from the western Arctic are very sparse but those that do exist (section 1) have so far indicated typical background dissipation rates of $O(10^{-10})$ W/kg.

4.3. Distributions of ϵ_U and ϵ_T

The histograms of all ϵ_U and ϵ_T observations (Figures 5a and 5b) provide further insight into the discrepancies between the two data sets. The histograms have markedly different shapes despite being constructed from coincident sets of measurement. Most notably, the distribution of ϵ_T observations is nearly symmetric with only small negative skew (skewness, $s_g = -0.2$) in $\log_{10}$ space, while the ϵ_U distribution is skewed positive and more heavily ($s_g = 1.2$). Statistical properties that can be used to further compare the distributions are tabulated in Table 2 and indicated in Figures 5a and 5b. Of note are the larger geometric mean and median ϵ_U values, reflecting the relative absence of very small ϵ_U observations; the separation between the median and geometric mean of ϵ_U , reflecting the skewness of that distribution; and the wider interquartile range of ϵ_T , reflecting the larger variability of the ϵ_T observations.

The distributions may be further contrasted using a quantile-quantile (Q-Q) plot (Figure 5c) to quantify how similar each distribution is to an idealized lognormal one—the more linear the plot, the greater the similarity. From this visualization, it is clear that the distribution of ϵ_T observations can be described as lognormal over all ϵ except below the second decile (2×10^{-12} W/kg). In contrast, the distribution of ϵ_U observations may be described as lognormal only above the seventh decile (1×10^{-10} W/kg). The strong positive curvature in the Q-Q plot for ϵ_U below the seventh decile indicates that there is substantially less weight on the left side of the observed distribution relative to an idealized lognormal one. The slight negative curvature in the Q-Q plot for ϵ_T below the second decile indicates a small trend in the opposite direction, that is, a marginally heavier tail on left side relative to an idealized lognormal distribution. The squared linear correlation coefficients of the Q-Q plots are $R^2 = 0.917$ for ϵ_U and $R^2 = 0.995$ for ϵ_T , confirming the qualitative impression that the ϵ_U observations deviate more strongly from an idealized lognormal distribution.

We attribute the discrepancy in the shapes of the ϵ_U and ϵ_T histograms primarily to the sensitivity limit of the shear probes, which imposes an artificial lower limit (or *noise floor*) on the ϵ_U observations. This noise floor will skew the histogram of ϵ_U observations positive by distributing samples that would otherwise be recorded as smaller values within a narrow range around the lower limit. Given the distinctive peak in the ϵ_U histogram and the extremely rapid roll-off to the left of the peak, we simply use the mode to approximate the noise floor as 3×10^{-11} W/kg. The ϵ_U observations that fall below this estimate of the noise floor are in the range $(1 \leq \epsilon_U < 3) \times 10^{-11}$ W/kg (Figure 5a); we attribute this statistical scatter to errors in the data processing which may, in part, arise because of uncertainty surrounding the characteristics of weakly turbulent, strongly stratified flows (section 5.2). The range of values below the noise floor suggests uncertainty here within a factor of 3, implying that the effects of the noise floor begin to skew the ϵ_U distribution at $\sim 9 \times 10^{-11}$ W/kg. This is consistent with the trend in the Q-Q plot (Figure 5c) where the shape of the ϵ_U histogram begins to diverge from that of the ϵ_T histogram at dissipation rates below $\sim 1 \times 10^{-10}$ W/kg.

Previous studies using loosely tethered profilers often cite a noise floor of $O(10^{-10})$ W/kg for shear-derived observations (e.g., Fer, 2014; Gregg, 1999; Lincoln et al., 2016; Shroyer, 2012; Wolk et al., 2002), though two glider-based studies that incorporated microstructure shear measurements both quote 5×10^{-11} W/kg for the noise floor (Fer et al., 2014; Wolk et al., 2009). The presence of an ϵ_U noise floor has practical ramifications for the interpretation of microstructure shear measurements; these are particularly important to consider in low-energy environments, and we discuss them further in section 5.4.

Figure 6. Scatter plot comparison of the two coincident dissipation rate estimates ϵ_U and ϵ_T . Identical agreement and agreement within factors of 2 and 5 are indicated as labeled. Bin averages are calculated perpendicular to the one-to-one line (see text). Our empirical estimate of the ϵ_U noise floor (3×10^{-11} W/kg) is indicated by the horizontal dotted line. Purple shading indicates where both estimates of ϵ simultaneously lie above 3×10^{-11} W/kg and also delineates the region where bin averages agree within a factor of 2.

4.4. One-to-One Comparison of ϵ_U and ϵ_T

A simple scatter plot of the coincident ϵ_U and ϵ_T observations (Figure 6) elucidates how the agreement between the two varies over the range of the observed dissipation rates. If one considers only observations where the two ϵ estimates are simultaneously greater than our empirical estimate of the ϵ_U noise floor (3×10^{-11} W/kg, section 4.3), the agreement between the two sets of observations is encouraging. This subset of data is indicated in Figure 6 by the purple-shaded region. Here the cloud of individual measurements largely scatters around the one-to-one line: 88% of these 8,064 observation pairs agree within a factor of 5, and 53% agree within a factor of 2. More importantly, the bin averages that are shown (defined below) always agree within a factor of 2. This level of agreement is consistent with the factor of 2 agreement in the mean vertical profiles (Figure 4) whenever those averages indicate $\epsilon > 3 \times 10^{-11}$ W/kg in both estimates. Statistical agreement within a factor of 2 is comparable to the best agreement seen in other studies (e.g., Kocsis et al., 1999; Peterson & Fer, 2014).

When at least one of the ϵ estimates is less than 3×10^{-11} W/kg, statistical disagreement between the shear- and temperature-derived dissipation rates becomes concerning. Here only 22% of the 16,842 observation pairs agree within a factor of 5, and only 6% agree within a factor of 2. The data diverge systematically from the one-to-one line: as the ϵ_T estimates continue to decrease, the ϵ_U estimates asymptote to a lower limit of approximately 2×10^{-11} W/kg, marginally below but still consistent with our estimate of the ϵ_U noise floor. The bin averages indicate the same pat-

tern as the individual measurements: below $\epsilon_T = 1 \times 10^{-11}$ W/kg they exhibit disagreement greater than a factor of 5 and, even in this averaged sense, suggest disagreement greater than 2 orders of magnitude when ϵ_T is less than 2×10^{-13} W/kg.

Note that averaged measures like bin averages are more appropriate than individual measurements when evaluating the agreement between ϵ estimates because we expect substantial statistical scatter (within about an order of magnitude) in these estimates. This scatter is, in part, attributed to uncertainties surrounding the validity of the isotropy, homogeneity, and stationarity assumptions inherent in the data processing (see section 5.2). The bin averages shown in Figure 6 are averages calculated from the trimmed mean in logarithmically spaced bins that lie perpendicular to the one-to-one line, that is, in a coordinate system rotated 45° clockwise from that shown. Defining the bins in this manner helps minimize biases in the average by assuming roughly equal uncertainty in both variables, similar in principle to a bivariate least squares minimization (Ricker, 1973).

5. Discussion

Measuring turbulence parameters to estimate the turbulent dissipation rate comes with unique challenges in low-energy environments like the Beaufort Sea, and our results in section 4 demonstrate that the two most common means of directly estimating the dissipation rate can yield divergent results that disagree by multiple orders of magnitude at low ϵ . Our results suggest that most of this discrepancy can be attributed to the noise floor of the shear-derived estimates, but fundamental questions about the nature of marginally turbulent, strongly stratified flows also introduce uncertainty into the observations. And, more pragmatically, our results highlight questions about how to correctly process and interpret shear microstructure measurements in such environments since it appears that the majority (about 70%, Figure 5c) of ϵ_U estimates are skewed by the effects of the noise floor. We address these topics in the following discussion: in section 5.1, we look more closely at the effect of sensor limitations on the measurements and the observed spectra; in section 5.2 we discuss averaged observed spectral shapes; in section 5.3 we examine uncertainties that arise from the (potentially unjustified) assumptions needed for the processing of microstructure measurements; and in section 5.4 we discuss practical implications, that is, in which circumstances the difference between ϵ_U and ϵ_T matters and in which circumstances it can be safely ignored.

Figure 7. Sample coincident shear (a–f: Φ) and temperature-gradient (g–l: Ψ) spectra (black) for 6 orders of magnitude of ϵ , as determined by the temperature measurements. Bold indicates the wavenumbers explicitly included for integration; the remaining variance is estimated as described in sections 3.2 and 3.3. For Ψ , bold also indicates the wavenumber range used for the MLE Batchelor fit (see section 3.3). Shear spectra have the accelerometer signal removed (section 3.2) and temperature gradient spectra have the empirically determined noise spectra removed (section 3.3). Nasmith (a–f) and Batchelor (g–l) reference spectra (gray) are also drawn. Batchelor spectra are those determined by the MLE fitting algorithm which are used to estimate k_B (section 3.3).

5.1. The Effect of Sensor Limitations

We propose that the systematic divergence between ϵ_U and ϵ_T that is obvious in Figures 5 and 6 at small dissipation rates is primarily a result of the effects of the noise floor of the ϵ_U estimates. This low-end divergence is then responsible for the large discrepancies seen in the spatial cross sections (Figures 2 and 3) and mean vertical profiles (Figure 4) of ϵ_U and ϵ_T . This interpretation is consistent with the known sensitivity limitations of microstructure shear probes (Osborn & Crawford, 1980) and previous empirical estimates of the ϵ_U noise floor (section 4.3).

Assuming vibrations from the measurement platform do not contaminate the measured signal, the noise floor of an ϵ_U estimate is set by the lower limit of a shear probe's ability to detect hydrodynamic transverse forces and distinguish these from electronic measurement noise. Hydrodynamic forces from small-scale velocity shear below this detection limit may still act on the probe, but the signal is either not recorded or is masked by the instrument's electronic noise. As a result (section 3.2), any variance $\langle (\partial u' / \partial x)^2 \rangle$ that exists below the probe's detection limit will yield an ϵ_U estimate at (or near) the level of the noise floor, irrespective of what the true dissipation rate at the instant of the measurement may be. If the true dissipation rate is below the level of the noise floor in a large proportion of the measurement realizations, this behavior will lead to an artificially skewed measurement distribution and a pile-up of observations against a lower limit, that is, a distinct peak in the distribution near the noise floor and a rapid roll-off toward smaller—unresolved—values, as can be seen in the distribution of our ϵ_U observations (Figure 5a).

The manifestation of the noise floor can also be seen in the observed shear spectra when these are compared to the simultaneously observed temperature-gradient spectra. Figure 7 depicts six representative pairs of observed shear and temperature-gradient spectra, distributed over 6 consecutive orders of magnitude of ϵ (as suggested by the temperature-derived estimates). Each column of panels shows the two coincidently observed spectra $\Phi(k)$ and $\Psi(k)$, defined in sections 3.2 and 3.3. Following panels g–l from right to left, the Batchelor fit to the temperature-gradient spectra (section 3.3) indicates continually decreasing ϵ_T , as labeled in each panel. The shear spectra indicate a similar ϵ -trend over the 4 larger orders of magnitude (panels c–f): as anticipated, the peak of the observed shear spectrum moves downward and to the left as ϵ decreases, and the integral of the spectrum (section 3.2) indicates decreasing ϵ_U , as labeled. However, below $O(10^{-11})$ W/kg (panels a–b) the spectrum runs into a spectral floor and does not decrease any further. Here the integral of $\Phi(k)$ no longer reflects the shear variance or any true physical quantity; instead, it saturates at a lower limit that indicates the available precision of ϵ_U , which, as anticipated, is in the vicinity of our empirical estimate of the noise floor 3×10^{-11} W/kg (section 4.3).

So far, we have focused our discussion on limitations of the shear measurements. Of course limitations also exist on the measurement of temperature microstructure, but these are of a different nature than those

which affect the shear measurements, and they tend to be less problematic in our study. Sensitivity limitations are not a concern for microstructure thermistors in the way they are for shear probes since the FP07 thermistors easily respond to within better than 0.1 mK (Sommer, Carpenter, Schmid, Lueck, & Wüest, 2013), which is approximately the smallest temperature scale we need observe (e.g., Figure 7g). The relatively slow time response of thermistors is generally a concern (Gregg, 1999), but at small dissipation rates it is possible to adequately account for the slow response using the transfer function proposed by Sommer, Carpenter, Schmid, Lueck, and Wüest (2013) or a similar correction method. At rates greater than $\sim 1 \times 10^{-7}$ W/kg, the effects of the slow response time can no longer be adequately corrected and temperature-derived estimates will tend to systematically underestimate the true dissipation rate (Peterson & Fer, 2014), but this limitation is not a concern in our observations since fewer than 0.1% of our ϵ_T estimates are above this cutoff value. A more relevant concern for our temperature-derived estimates is the potential uncertainty that surrounds the characteristics of turbulent eddies and the resulting turbulence spectra when turbulent energetics are weak and stratification is strong, as is the case in the setting for our measurements. This is the topic of the following two sections.

5.2. Turbulence Spectra in Stratified Low-Energy Flows

Our observations suggest that the shape of shear and temperature-gradient spectra deviate systematically from Nasmyth and Batchelor reference spectra in stratified low energy flows. Fitted Nasmyth and Batchelor spectra are drawn with the selected observed spectra in Figure 7 for reference, exemplifying varying levels of agreement; however, individual observed spectra have limited utility for providing broader physical insight because we anticipate naturally occurring variability in the shapes of individual spectra (e.g., Fer et al., 2014). In order to identify systematic trends in the shapes of turbulence spectra, we bin all observed spectra by buoyancy Reynolds number, $Re_B = \epsilon/\nu N^2$, and calculate median temperature-gradient and shear spectra in each bin (Figure 8). The Re_B parameter quantifies the destabilizing effects of turbulent kinetics relative to the stabilizing effects of stratification and viscosity. It is proportional to the ratio of the largest vertical (Ozmidov) scale to the smallest isotropic (Kolmogorov) scale of turbulent eddies, so when $Re_B < 1$ we anticipate that turbulent eddies of all sizes, including the smallest ones on dissipative scales, are modified by stratification and exhibit a degree of anisotropy. Further, modeling results suggest that the characteristics of turbulent structures undergo regime shifts in the vicinity of $Re_B \sim 10$ and $Re_B \sim 100$ (Ivey et al., 2008; Shih et al., 2005), and so combining with the above scaling argument, we use 1, 10, and 100 to delineate the boundaries of our Re_B bins.

To calculate median spectra, individual spectra must first be normalized identically so that the shapes of spectra over varying ϵ and χ may be compared. To do this, we nondimensionalize shear spectra using

$$\Phi^* = \Phi/(\epsilon_U^3/\nu)^{1/4} \quad (8)$$

and temperature-gradient spectra using

$$\Psi^* = \Psi/\left(\frac{\chi \sqrt{q_B/2}}{k_B D_T}\right), \quad (9)$$

consistent with schemes used by Oakey (1982) and Dillon and Caldwell (1980). We nondimensionalize wavenumbers using k/k_v for shear spectra and k/k_B for temperature-gradient spectra. The scaling factor k_v is the Kolmogorov wavenumber defined $(1/2\pi)(\epsilon_U/\nu^3)^{1/4}$; the remaining variable definitions for equations (8) and 9 are given in section 3. For each Re_B bin, we then calculate the median spectral height at each nondimensional wavenumber using all spectra within the bin, creating the median spectra shown in Figure 8; we also calculate the interquartile range at each nondimensional wavenumber as a measure of the variability around the median. To exclude artificial effects that may arise because of the ϵ_U noise floor (section 5.1), we exclude from the calculations any shear spectra where $\epsilon_U < 1 \times 10^{-10}$ W/kg.

The systematic modification of the temperature-gradient spectra with decreasing Re_B is clearly visible if one follows panels e–h from right to left: there is a clear trend toward less curvature and greater low-wavenumber deviation from the theoretical curve as Re_B decreases. None of the median temperature-gradient spectra exhibit a curvature as strong as that predicted by the Batchelor spectrum, but the discrepancy increases with decreasing Re_B , and for the two lowest Re_B bins there is no longer a peak and roll-off delineating distinctive

Figure 8. Median nondimensionalized shear (a–d) and temperature-gradient (e–h) spectra in bold, for regimes of Re_B as indicated. Also shown are the 25th and 75 percentile of data (thin solid line) as well as nondimensionalized reference spectra (dashed line): Nasmyth for shear and Batchelor for temperature gradient. The total number of spectra used in each calculation is indicated by N . Shear spectra with $\epsilon_U < 10^{-10}$ W/kg are excluded.

subranges of the spectrum. This behavior is similar to that seen in measurements taken by Dillon and Caldwell (1980) who, as we do, observed decreasing curvature with smaller turbulence intensities.

The median shear spectra likewise vary systematically with Re_B , indicating increasing deviations from the Nasmyth spectrum as Re_B becomes small (following panels a–d from right to left). The dissipative subrange, to the right of the peak, is not as steep in any of the median spectra as predicted by the Nasmyth shape, and it becomes increasingly more shallow with decreasing Re_B . In addition, the amplitude of the spectrum in the inertial subrange, left of the peak, is overestimated by the Nasmyth spectrum in all median spectra and no longer appears to be well described by a simple power law when $Re_B < 1$. This behavior is reminiscent of that seen in measurements by Gargett et al. (1984) who found that inertial subranges of shear spectra gradually disappeared when turbulence became weak and stratification strong.

5.3. Understanding Uncertainty for Small ϵ

The above discussion (section 5.2) highlights the manner in which turbulence spectra are systematically modified away from their reference shapes as Re_B becomes small. We propose that the systematic modification with decreasing Re_B occurs as the characteristics of turbulent eddies in strong stratification increasingly depart from the idealized framework of steady, isotropic turbulence. Evidence for this behavior can be seen in the distribution of the Re_B parameter which is below unity in 76% of our observations, suggesting that turbulent eddies are frequently anisotropic and modified by the effects of stratification. Further, the Ozmidov scale, $L_O = (1/2\pi)(\epsilon/N^3)^{1/2}$, has a median value of 0.1 cm, which is exceptionally small and again suggests that even viscous-scale eddies are squashed by the stratification.

These characteristics signal that there is increased uncertainty in the dissipation rate estimates when ϵ is small and N^2 is large. This is especially true for ϵ_T estimates where the data processing depends on the ability to determine k_B from Batchelor spectrum fits (section 3.3). One way to characterize the increased uncertainty is to quantify the degree by which observed turbulence spectra and idealized reference spectra diverge. We do this here for the temperature measurements and compare temperature-gradient spectra to Batchelor spectra

Figure 9. Root-mean-square error between Ψ and Ψ_B , as defined in the text, visualized as a function of (a) buoyancy Reynolds number, and (b) dissipation rate. This metric quantifies the degree of divergence between observed temperature-gradient and theoretical Batchelor spectra. Large open faced markers are bin averages. Regressions to subsets of the bin averages are shown in each panel; the subsets are those on either side of the datum marked by the circle (inclusive).

by calculating for each spectrum the root-mean-square error, ξ_{rms} , of $\log_{10}(\Psi/\Psi_B)$, defined:

$$\xi_{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^n \log_{10}^2 \left(\frac{\Psi_i}{\Psi_{Bi}} \right)} = \sqrt{\frac{1}{n} \sum_{i=1}^n [\log_{10}(\Psi_i) - \log_{10}(\Psi_{Bi})]^2}. \quad (10)$$

The summation index, i , runs over all wavenumbers included in the Batchelor fitting procedure; n is the number of spectral points included in the fit (section 3.3). We find that averages of ξ_{rms} increase gradually from 0.3 to 0.5 as Re_B estimates decrease from $O(10^1)$ to $O(10^{-2})$; at smaller Re_B , mean ξ_{rms} increases rapidly to a maximum value of 0.7 (Figure 9). A similar, but more pronounced, pattern is visible when ξ_{rms} is visualized as a function of ϵ_T . The increase in ξ_{rms} is gradual and modest, from 0.3 to 0.45, as ϵ_T decreases from $O(10^{-7})$ to $O(10^{-12})$ W/kg; this behavior is followed by a sharp increase in ξ_{rms} at smaller ϵ_T .

Further insight into the confidence of the ϵ_T values can be gained empirically if we make the assumption that dissipation rates distribute lognormally in the ocean (Baker & Gibson, 1987; Gregg, 1987). Under this assumption, we can use the observed distribution of ϵ_T (Figure 5b) to estimate a lower cutoff below which the application of the steady, isotropic turbulence model becomes problematic and ϵ_T estimates become unreliable. The distribution of ϵ_T observations follows the lognormal shape closely over the entire range of data except below the second decile (Figure 5c), where the observed distribution is disproportionately heavy. The distortion in the distribution indicates that uncertainties in the data processing statistically skew the ϵ_T estimates below the second decile; our simple statistical model therefore suggests that the ϵ_T estimates are reliable and physically meaningful to values as small as $\epsilon_T \approx 2 \times 10^{-12}$ W/kg. Below this cutoff, ϵ_T estimates are unreliable and perhaps not meaningful. Note that a lower cutoff of 2×10^{-12} is consistent with the sudden increase in ξ_{rms} that occurs in Figure 9b below $\epsilon_T = O(10^{-12})$ W/kg.

5.4. Implications for Interpreting Microstructure Measurements

In section 4 we demonstrated that there can be a significant difference between dissipation rate estimates derived from coincident measurements of shear and temperature microstructure. The ϵ_T estimates suggest that the true dissipation rate is below the ϵ_U noise floor of 3×10^{-11} W/kg in 58% of our observations. A histogram of the ratio ϵ_U/ϵ_T (Figure 10) demonstrates the severity and the frequency with which the shear probes may overestimate the dissipation rate in low-energy environments like the Beaufort Sea. Using ϵ_T as a reference (and acknowledging the associated uncertainties described in section 5.3), the shear measurements overestimate the dissipation rate by a factor of at least 5 in 44% of our measurements, by at least 1 order of magnitude in 31% of our measurements, and by at least 2 orders of magnitude in 9% of our measurements. This is a level of error that has the potential to alter the interpretation of the shear measurements, as described in the following paragraph. In contrast, the temperature measurements overestimate the

Figure 10. Histogram of the ratio ϵ_U/ϵ_T , highlighting the large number of coincident measurements where the shear-derived values overestimated the temperature-derived ones in our data set. Agreement by factors of 5, 10, and 100 is indicated by dashed lines. The histogram is calculated over 50 logarithmically spaced bins.

dissipation rate relative to ϵ_U by a factor of at least 5 in less than 3% of measurements, a degree of mismatch that could safely be neglected in many applications.

The severity with which the bias we found in the shear measurements may alter the interpretation of ϵ_U estimates depends on the specific goals of a study. If, as in section 4, the utility of the measurements is to characterize the variability and the statistical distribution of dissipation rates, then the potential for biases greater than an order of magnitude cannot be ignored. Without the coincident ϵ_T estimates to which to compare, the ϵ_U estimates would lead us to misrepresent the degree of spatial variability (Figures 2 and 3), the geometric averages representing typical values (Figure 4), and the observed distribution and related statistics (Figure 5 and Table 2) of the turbulent dissipation rate here in the Amundsen Gulf. These misrepresentations may then be further propagated into calculations of the mixing rate coefficient K_p , which typically rely on the Osborn (1980) model $K_p = 0.2\epsilon/N^2$, leading to similar misrepresentations of the variability, the geometric averages representing typical values, and the distribution and related statistics of K_p .

Arithmetic mean values of ϵ_U , however, are much less sensitive to the bias we describe. This is fortunate, because arithmetic mean values are arguably the appropriate measure to use when estimating bulk buoyancy fluxes and characterizing net water mass transformation from mixing rate estimates (Baker & Gibson, 1987). As noted in section 4, in this study we

have tended to use the geometric mean to average dissipation rates. We do this because the geometric mean effectively characterizes the central tendency of lognormally distributed data and more fairly represents typical ϵ realizations (Kirkwood, 1979). In contrast, the arithmetic mean is ineffective at representing typical values of a lognormal-like distribution because it is dominated by a small number of very large values at the high end of the distribution. Further, the arithmetic mean tends to be very sensitive to individual outliers that may exist on the far right-hand side of the distribution, which may be problematic because of the large uncertainty in individual ϵ realizations. However, the disproportionate importance of large values in setting the arithmetic mean also makes it mostly insensitive to errors in small ϵ estimates. The effect can be seen, for example, when comparing the arithmetic mean of the ϵ_U and ϵ_T distributions (Figure 5 and Table 2): in contrast to the geometric mean, the median, and the 25th and 75th percentiles, the arithmetic mean of the ϵ_T distribution is *greater* than that of the ϵ_U distribution because of a marginally thicker tail on the right-hand side of its distribution which more strongly influences its arithmetic mean.

A final subtle point remains to be discussed. When carrying out an analysis using microstructure measurements of shear, it is tempting to simply remove observed ϵ_U values that sit at or near the estimated noise floor, discarding these as untrustworthy. This approach is viable when only a small number of the observations are near the noise floor; however, in the present study, simply removing data likely to be corrupted by the effects of the noise floor would only exacerbate the bias evident in the ϵ_U observations. For example, if we remove from the data set the shear-derived estimates where $\epsilon_U < 5 \times 10^{-11}$ W/kg, we increase the positive bias in our sample by removing 53% of the measurements and the entire left half of the ϵ_U histogram (Figure 5). Rather than helping to correct biased averages of ϵ_U , this change shifts the median from 4.6×10^{-11} to 1.4×10^{-10} W/kg and the geometric mean from 6.5×10^{-11} to 1.9×10^{-10} W/kg, in both cases increasing the error in these averaging metrics.

The best practical way to account for the effects of the noise floor in microstructure shear measurements will depend on the goals of each individual study and on the proportion of the observations that are in the vicinity of the noise floor. One approach is to set dissipation rates that appear to be near the noise floor to zero (e.g., see Gregg et al., 2012); this approach is probably justifiable for arithmetic mean calculations since the averaging is dominated by the large ϵ values, but it is problematic when describing the variability or when calculating a geometric mean to characterize typical ϵ values. In these situations, it may be more appropriate to fit a lognormal distribution to the part of the observed distribution that resides above the noise floor, but care is required here also since the theoretical conditions for expecting lognormality are strict and often not

satisfied in a set of field measurements (Yamazaki & Lueck, 1990). In any case, it is clear that the interpretation of microstructure shear-derived dissipation rate estimates should proceed with caution if the measurements are from a very low energy environment and it appears that a large proportion of the data cluster around a well-defined noise floor.

6. Conclusions

Care must be taken to understand how measurement limitations may bias microstructure measurements in low-energy environments like the Beaufort Sea: this is the central theme of our study. The results we have presented here suggest that microstructure measurements of velocity shear, in particular, are prone to misrepresenting averaged dissipation rates—and, consequently, mixing rates—in such environments because the noise floor of the ϵ_U estimates artificially biases the majority of the observations. In addition, our measurements suggest that both shear- and temperature-derived dissipation rate estimates may be complicated by further uncertainty when strong stratification modifies the characteristics of turbulence in a weakly energetic, strongly stratified flow; this change in the characteristics can be seen in the systematic modification of the shapes of shear and temperature-gradient spectra at low Re_B .

We have documented the discrepancy between the two distinct dissipation rate estimates ϵ_U and ϵ_T because we find disagreement large enough to lead to substantial differences in how the two sets of data would be interpreted independently. The temperature-derived estimates were able to resolve smaller dissipation rates than the shear-derived estimates: averages of ϵ_U began to exhibit biased behavior below 10^{-10} W/kg and were not able to resolve rates below 3×10^{-11} W/kg, while averages of ϵ_T were reliable to values as low as 2×10^{-12} W/kg and were characterized by unacceptably large uncertainty below this. Our experience suggests that caution interpreting shear-derived dissipation rate estimates is warranted if a large number of observations cluster at or near an identifiable ϵ_U noise floor, in our case 3×10^{-11} W/kg. In the measurements presented here, the temperature-derived estimates suggest that the true dissipation rate lies below this noise floor often enough to fundamentally alter the scientific interpretation of the measurements. Other low-energy environments in which the special measurement considerations outlined in this study may be applicable include the wider Canada Basin (Rainville & Winsor, 2008), stratified lakes (Scheifele et al., 2014; Sommer, Carpenter, Schmid, Lueck, Schurter, & Wüest, 2013), the central Baltic Sea (Holtermann et al., 2017), and the abyssal global ocean over smooth topography (Waterhouse et al., 2014).

Appendix A: Quality Control Measures for Dissipation Rate Estimates

Here we describe the quality control procedures we apply to the measurements to identify dissipation rate estimates deemed untrustworthy. These are removed before the analysis described in section 4.

Before implementing quantitative quality control measures, we remove any obviously contaminated measurements by hand. These include all measurements after 27 August from one of the two shear probes because the probe appears to have been damaged at this point and thereafter no longer measured a sensible

Table A1
Quality Control Parameters, as Defined in the Text

Parameter	ϵ_U	ϵ_T
<i>N</i> before QC	45,571	63,507
QC1	9.8%	10.3%
QC2	13.6%	13.2%
QC3	2.7%	17.0%
QC4	3.5%	4.1%
QC5-U	13.2%	—
QC6-T	—	5.6%
QC7-T	—	4.6%
One or more	22.3%	33.9%
<i>N</i> after QC	35,395	41,955

Note. Percentages are the fraction of measurements flagged by each condition.

Figure A1. Comparison of results from individual (a,b) shear probes and (c,d) temperature probes. Bin averages are calculated as in Figure 6. Agreement within a factor of 5 is indicated in all panels by the dashed lines.

signal. We then begin systematic quality control measures with 45,571 independent ϵ_U estimates and 63,507 independent ϵ_T estimates. Note that the estimates from the two distinct shear or two distinct temperature probes are not yet averaged at this stage (see sections 3.2 and 3.3).

Individual estimates of ϵ_U and ϵ_T are flagged untrustworthy and removed if they satisfy one or more of the following conditions:

- QC1. The magnitude of the glider's acceleration $|dU/dt|$ is above the tenth percentile ($|dU/dt| > 4.6 \times 10^{-4} \text{ m/s}^2$). This is a heuristic measure, but it satisfactorily isolates measurements where the glider appears to be changing speed over the span of one ϵ estimate. The data processing assumes that U is constant over the span of an ϵ estimate.
- QC2. The glider is within 15 m of an inflection point. When the glider inflects, the angle of attack and the estimate of U are uncertain and mechanical vibrations from the glider contaminate the measurements.
- QC3. Estimates from two identical probes differ by greater than a factor of 10. For shear, the higher estimate is removed. For temperature, both estimates are removed.
- QC4. The ratio $U/(\epsilon/N)^{1/2}$ is less than 5. This is the ratio between the glider's velocity and an estimate of the turbulent flow velocities (Fer et al., 2014) and may indicate when Taylor's frozen turbulence hypothesis is violated.

In addition, ϵ_U measurements are flagged and removed if

- QC5- U . The maximum of the nondimensionalized shear spectrum Φ^* , defined in section 5.2, is greater than twice the peak of the nondimensionalized Nasmyth spectrum. This isolates shear spectra obviously contaminated at low wavenumbers.

In addition, ϵ_T measurements are flagged and removed if

- QC6- T . The sum of the correction terms χ_{lw} and χ_{hw} (see equation (7)) is greater than the *observed* term χ_{obs} .

QC7-T. There are fewer than six distinct wavenumbers available in the closed interval $[k_l, k_u]$. This ensures a reasonable minimum number of spectral points to which to fit a Batchelor spectrum.

Cumulatively, quality assessment conditions flag and remove 22.3% of individual ϵ_U measurements and 33.9% of individual ϵ_T measurements. The percentage of measurements flagged by each individual condition is given in Table A1.

Beyond these conditions, confidence in the measurements may be indicated by the level of agreement between duplicate measurements of ϵ_U and ϵ_T . This comparison is favorable: after the quality assessment procedures, 96% of 6,820 coincident sets of ϵ_U measurements agree within a factor of 5, and the agreement is comparable over the full range of ϵ_U . Note that a factor of 5 is typically considered reasonable agreement for individual microstructure measurements which often scatter within an order of magnitude and can vary by more than 10 decades in the ocean. The comparison is slightly more variable but still favorable for ϵ_T , where 87.3% of 20,378 coincident sets agree within a factor of 5 and there is likewise no trend with ϵ_T .

The comparisons are imaged in Figure A1, where subscripts 1 and 2 are arbitrarily designated to measurements from distinct probes. Bin averages are calculated as in Figure 6.

Following the quality control procedures described here, we average (using an arithmetic mean) results for each of the two distinct sets of measurements, as described in sections 3.2 and 3.3. This leaves 28,575 ϵ_U and 21,577 ϵ_T estimates for analysis.

Appendix B: Comparison of Results from Upcasts and Downcasts

The stratification conditions in the Amundsen Gulf resulted in much faster glider speeds on upcasts than on downcasts (Table 1). Because dissipation rate calculations are very sensitive to the estimated glider speed U (Gregg, 1999; Lueck, 2016; Osborn & Crawford, 1980), this discrepancy can be leveraged to further inform our confidence in the measurements and data processing methods. In the absence of systematic errors in the data processing, we would expect to see no systematic difference in the results derived separately from upcasts and downcasts despite the nearly factor of 2 difference in U .

We observe little to no difference between dissipation rate estimates when the results are separated by upcasts and downcasts. Figure B1 presents an overview of the ϵ_U and ϵ_T results separated in this manner. The two histograms of ϵ_U (panel a) have nearly indistinguishable characteristics: for example, the medians are

Figure B1. Overview of select results, separated by upcasts and downcasts. For each of ϵ_U and ϵ_T , we show the histograms (a,e), averaged vertical profiles (b,f), and selected spectra (c–d,g–h) separated in this manner. The spectra shown are those corresponding to dissipation rates within a factor of 1.1 of 10^{-9} W/kg. Thick black lines depict the median of the selected spectra at each wavenumber.

5×10^{-11} and 4×10^{-11} W/kg for upcasts and downcasts, respectively, and the respective geometric standard deviation factors are 3.5 and 3.7. Similarly, the two averaged vertical profiles of ϵ_U (panel b) are nearly identical in magnitude everywhere; they typically agree within a factor of 1.2 and always within a factor of 1.8. Shear spectra are likewise similar between upcasts and downcasts, as highlighted in the selected spectra shown in panels c and d. Median spectra are generally alike in shape with a marginally wider spectral peak for the upcast median spectrum.

There is slightly more discrepancy between upcasts and downcasts in the ϵ_T results, though the overall agreement is still encouraging and the discrepancy does not impact the results or conclusions of the study. The histogram comparison (panel e) is generally favorable: the median is 2×10^{-11} W/kg for both distributions, and the geometric standard deviation factors are 23.4 and 16.2 for upcasts and downcasts, respectively. The upcast distribution is wider because of a small unexpected increase in the number of ϵ_T values below 1×10^{-13} W/kg. As discussed in section 5.3, there is extensive uncertainty associated with values of ϵ_T smaller than 2×10^{-12} W/kg, and so it is unclear how much meaning can be assigned to this feature of the distribution. The mean profiles (panel f) demonstrate adequate agreement, typically within a factor of 2 and always within a factor of 3.5, in line with typical uncertainties from microstructure measurements. The shape of the two median temperature gradient spectra (panels g and h) compares favorably with only a slightly less rounded roll-off to the Batchelor scale for the upcast spectrum.

Appendix C: Nasmyth and Batchelor Spectra

The Nasmyth spectrum, Φ_N , is an empirically derived form for the one-dimensional power spectrum of velocity shear in an unstratified turbulent flow and is based on measurements collected in a strongly turbulent tidal channel in coastal British Columbia (Nasmyth, 1970). It describes both the inertial subrange of the shear spectrum, predicted by Kolmogorov (1941), and the viscous subrange where viscosity begins to influence the motion of turbulent eddies. The results of Nasmyth were tabulated by Oakey (1982), and a mathematical fit was later proposed by Wolk et al. (2002). We use a modified form of that expression, described by Lueck (2016), which can be written nondimensionally as $\Phi_N^* = 8.05x^{1/3} / (1 + (20.6x)^{3.715})$, where $x = k(v^3/\epsilon)^{1/4}$ and the spectrum is nondimensionalized using $\Phi_N^* = \Phi_N/(\epsilon_U^3/\nu)^{1/4}$.

The Batchelor spectrum is a theoretical one-dimensional power spectrum describing the wavenumber distribution of a passive tracer's gradients in an unstratified turbulent flow (Batchelor, 1959); its integral is proportional to the rate, χ , at which the tracer gradients are smoothed by molecular diffusion. The spectrum is an analytic solution to the advection-diffusion equation driven by turbulent strain and the large-scale tracer gradient. In one dimension, it may be written as follows:

$$\Psi_B = \frac{\chi \sqrt{q_B/2}}{k_B D_T} \left(\alpha \exp\left(\frac{\alpha^2}{2}\right) - \alpha^2 \sqrt{\frac{\pi}{2}} \operatorname{erfc}\left(\frac{\alpha}{\sqrt{2}}\right) \right) \quad (C1)$$

where

$$\alpha = (k/k_B) \sqrt{2q_B}. \quad (C2)$$

The factor q_B is a dimensionless constant related to the average least principal rate of strain; it represents the time scale by which compressive strain sharpens scalar gradients (Smyth, 1999). The value of q_B is uncertain, and experiments by Oakey (1982) suggest that the range 2.2–5.2, though typically $q_B = 3.4$ (e.g., Ruddick et al., 2000) or $q_B = 3.7$ (e.g., Peterson & Fer, 2014), are used. A percentage error in q_B is expected to lead to twice the percentage error in ϵ_T (Dillon & Caldwell, 1980). We used $q_B = 3.4$ in our analysis but also processed all the temperature measurements using $q_B = 3.7$, and the difference in results was small: using $q_B = 3.7$, we found for ϵ_T a mode of 1.5×10^{-11} W/kg, a geometric mean of 1.9×10^{-11} W/kg, and a geometric standard deviation factor of 18.3 (compare with Table 2).

Note that the Kraichnan spectrum (Kraichnan, 1968) would be an adequate alternative for the fitting procedure described in section 3.3. Peterson and Fer (2014) compared the results of fitting observed temperature gradient spectra to Batchelor and Kraichnan spectra and found no significant difference in the final ϵ_T results.

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