Sound scattering from oceanic turbulence

Tetjana Ross
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

Rolf Lueck
Center for Earth and Ocean Research, University of Victoria, Victoria, British Columbia, Canada

Received 6 December 2002; accepted 3 March 2003; published 29 March 2003.

[1] The first near coincident measurements of acoustic backscatter and temperature/velocity microstructure confirm theoretical predictions that oceanic turbulence scatters sound. Not only are acoustic backscatter at 307 kHz and turbulent microstructure unambiguously correlated on a patch-by-patch basis, but measured scattering amplitudes agree with theoretical predictions for scattering from turbulent microstructure. Nearby plankton net-hauls indicate that there were far too few zooplankton in the turbulent regions to account for the scattering intensity. At an acoustic frequency of 307 kHz, backscatter from salinity microstructure can be as strong as - or stronger than - the signal from a zooplankton scattering layer. There are two important consequences of these strong scattering results. First, they suggest the feasibility of using acoustics to remotely sense oceanic turbulence. Second, they could easily confound acoustic zooplankton biomass estimates in turbulent regions.


1. Introduction

[2] Because of the strong attenuation of light in water, acoustics has established itself as a vital tool for exploring the ocean depths. Oceanographers use high-frequency acoustics for everything from tracing oceanic phenomena (e.g., overflows [Farmer and Smith, 1980], internal waves [Haury et al., 1979], or buoyant plumes [Rona et al., 1991]) to measuring currents using Doppler frequency shifts to mapping fine-scale distributions of biomass of different size classes of plankton [Pieper et al., 1990]. As long as scatterers are passively following the flow, knowledge of what is actually scattering the sound is generally overlooked in the former examples, but is critical to making quantitative estimates of plankton or fish abundance.

[3] Strong scatter is often observed in regions of the water column expected to be turbulent, but it has never been clear if this is because turbulence is scattering sound or because there are higher plankton concentrations in turbulent regions. Models and laboratory experiments show zooplankton encounter food more frequently in turbulent regions [Rothschild and Osborn, 1988; Peters and Marrasé, 2000] and therefore they may be seeking out these “high food zones” [Mackas et al., 1993, Dower et al., 1997]. Then again, the elevated scattering in these regions could be due to scattering from turbulence. In which case, acoustic backscatter is potentially a powerful tool for remotely sensing turbulence, possibly replacing the difficult and costly methods currently being used.

[4] Models predict that turbulent velocity fluctuations do not backscatter sound [Batchelor, 1957]. It is small-scale fluctuations in sound speed and density that backscatter sound, so turbulence will backscatter sound only if there is a temperature and/or salinity gradient present. Controlled experiments, with artificially generated turbulence, have shown that temperature fluctuations do scatter sound [Pelech et al., 1983; Thorpe and Brubaker, 1983; Oeschger and Goodman, 1996]. Estimates based on models of oceanic turbulence [Goodman, 1990; Seim et al., 1995; Seim, 1999; Lavery et al., High-frequency acoustic scattering from turbulent oceanic microstructure: the importance of density fluctuations, accepted pending revisions J. Acoust. Soc. Am., 2003] indicate that scatter from in-situ turbulence could be as strong as that from zooplankton. Although there is previous work comparing oceanic microstructure to acoustic backscatter (e.g., [Seim et al., 1995]), the poor coincidence of the acoustic and turbulence measurements rendered model comparisons less than convincing.

2. Results and Discussion

[5] We collected the first near coincident acoustic backscatter and turbulent microstructure measurements with a torpedo-shaped vehicle carrying four shear probes and two thermistors on its nose [Wolk and Lueck, 2001], and a forward-looking 307 kHz echosounder (mounted 20 cm below and 40 cm aft of the turbulence sensors). The vehicle was towed through the stratified turbulence that forms tidally over the lee side of a sill in a British Columbia fjord. Conventional downward-looking echosounder measurements were also made with a 100 kHz sounder mounted in the ship’s hull (experimental setup is illustrated in Figure 1). Populations of amphipods, euphausiids, copepods and gastropods were present in the fjord (sampled with 335 μm mesh vertical net-hauls) and could be seen in the sounder data.

[6] Despite the presence of zooplankton in the fjord, in regions with stratified turbulence (such as over the sill, Figure 1) the backscatter seen with the 307 kHz sounder was predominantly from turbulence. While the source of scatter remains unclear in Figure 1a due to poor matching between 100 kHz ship-board sounder data and microstruc-
ture data collected 200 meters behind the ship, the 307 kHz echogram (Figure 1b) gives a striking visual example of how well acoustic scatter correlates with temperature microstructure. The correlation coefficient between the magnitude of the small scale horizontal temperature gradient and the acoustic scatter at 1 m is .75 for the data shown in Figure 1. Following patches of water from different ranges into the sounder and making the same comparison, we found that this correlation coefficient stays fairly constant up to about 5 m range, then drops slowly down to .45 for scatter at 20 m. At 1 m range, the cross-section of water sampled by the sounder is 1.5 \times 10^{-2} \text{ m}^2 – about an order of magnitude larger than the 1.1 \times 10^{-3} \text{ m}^2 circle enclosed by the shear probes - by 20 m range this cross-section has become 6.1 \text{ m}^2. The larger mismatch of sampling cross-sections at far range may contribute to the decrease in correlation, but evolution of the turbulence is just as important. The time between when the acoustic measurement is made at 20 m and the turbulence measurement is made is 13–20 s, which is a significant fraction of the growth/decay rate of a turbulent patch \tau \sim 1/N (24 s in Figure 1).

Not only is there a strong correlation between temperature microstructure and 307 kHz acoustic scatter, but the scattering amplitudes are in excellent agreement with theory. We modelled the turbulent scattering cross-section (\sigma_{\text{turb}}) as,

$$\sigma_{\text{turb}} = \frac{-k^3}{2} \left( (\alpha_{\eta} - \alpha) \frac{d\phi_T(k)}{dk} + (b_{\eta} + \beta) \frac{d\phi_S(k)}{dk} \right)_{k \approx 2k}$$

(1)

which is Goodman’s “classical turbulence” model [Goodman, 1990], expanded to include salinity microstructure [Seim et al., 1995], but still neglecting the unknown T-S co-spectrum. \alpha_{\eta} and \beta are, respectively, the fractional changes in potential sound speed due to temperature and salinity changes, while \alpha and \beta are the coefficients of thermal expansion and saline contraction. Thus, the two terms in (1) are a combination of the contributions to sound scattering by small-scale changes in sound-speed and in density, which are in turn due to fluctuations in temperature and salinity. k_x is the horizontal wave number, which is evaluated at the Bragg wave number, 2k (for backscatter), where k is the acoustic wave number (k = 2\pi f c = 1300 \text{ rad/m} for 307 kHz). In (2), the salinity spectra (\phi_S) was assumed to have a form

Figure 1. (a) Sketch of experimental setup (not to scale) overlaying an echogram from the 100 kHz ship-board sounder. The pink beams emanating from the ship and the towed vehicle represent the 100 and 307 kHz sounders, respectively. White line is the approximate path of the towed vehicle (ship-board sounder data is lagged to line up with vehicle data) and the colored circles are predicted backscatter at 100 kHz as estimated from microstructure data. (b) Echogram from 307 kHz vehicle-mounted sounder for time and depth of the pink box in a. Each horizontal line shows the echo from one ping. As time progresses downwards and range is distance ahead of the vehicle, parcels of water travel diagonally across the figure, from right to left. Temperature microstructure is shown on the left. Color scale on the right applies to both images.

Figure 2. Scatterplot of predicted versus measured volume scattering strengths. X-axis is \text{Sv} calculated from 10-second averages of \epsilon, \phi_T, \phi_S, and N. Y-axis is measured acoustic scatter at one meter range averaged over 10 seconds (10 pings) and 22.2 cm of range (equivalent to 300 \mu s pulse length). Data is compiled from times when turbulent scatter was strong enough to be seen above the –95 dB noise floor of the sounder. Gray line is one-to-one correspondence, for reference.
analogue to the standard classical temperature spectrum given in Goodman [1990].

$$\phi_S(k_x) = \left[ 0.3 \chi_S \left( \frac{N}{k_x} \right)^{2} + \chi_T \left( \frac{N}{k_x} \right)^{2} \right] e^{-\frac{1}{2} \left( \frac{N}{k_x} \right)^{2}}$$

(2)

$\epsilon$ is the rate of turbulent energy dissipation, $\nu = 1.3 \times 10^{-6}$ m$^2$/s is the coefficient of viscosity, and, $\kappa_S = 1.5 \times 10^{-9}$ m$^2$/s is the coefficient of diffusivity of salt ($\kappa_T = 1.5 \times 10^{-7}$ m$^2$/s for heat). $\chi_S$ and $\chi_T$, the rates of dissipation of salinity and temperature variance, can be modelled using a mixing efficiency $= 0.1$ [Osborn, 1980; Ruddick et al., 1997]:

$$\chi_S = \frac{2 \Gamma \epsilon}{N^2} \left( \frac{dS}{d\zeta} \right)^2 ; \quad \chi_T = \frac{2 \Gamma \epsilon}{N^2} \left( \frac{dT}{d\zeta} \right)^2.$$  

(3)

$[8]$ $N$ is the buoyancy frequency and $\frac{dS}{d\zeta}$ and $\frac{dT}{d\zeta}$ are the average vertical salinity and temperature gradients.

[9] Using ((1)-(3)) with observed values of $\epsilon$ (measured with shear probes), $\frac{dS}{d\zeta}$, $\frac{dT}{d\zeta}$, and, $N$ (measured with conductivity and temperature sensors on either end of the vehicle’s mast), we predict turbulent volume scattering strengths ($\hat{S}_V = 10 \log_{10} \sigma_{turb}$) in excellent agreement with those observed (Figure 2). In over an hour of data compiled from times when turbulence was strong enough to scatter sound above the $-95$ dB noise floor of the echosounder (shown in Figure 2), the predicted volume scattering strength at 307 kHz was on average only $1.2 (\pm 0.2)$ dB higher than what was observed (there is also $0.2$ dB uncertainty in the sounder calibration). Perhaps more important than this average difference (which can vary between $-14$ and $6$ dB depending on which of the large range of measured mixing efficiencies [Ruddick et al., 1997]) we employ), is the fact that the model predicts the correct dependence on $\epsilon$, $\frac{dS}{d\zeta}$, $\frac{dT}{d\zeta}$, and, $N$.
on the density ratio \( R_p = \frac{\rho p}{\rho} \), Figure 3), even with \( R_p \) much higher than in our measurements, salinity is the sole contributor to acoustic backscatter at 307 kHz for the moderate to low rates of energy dissipation commonly observed in the ocean (i.e. \( \epsilon \leq 10^{-7} \) W/kg).

The strong correlation between acoustic scatter and turbulent microstructure, and the good agreement between the measured scattering intensities and those predicted by theory, indicate that we are observing scatter from turbulence. But, there is still the possibility that aggregations of zooplankton (perhaps taking advantage of the turbulence to “concentrate” their food) are coincidentally scattering at levels predicted by turbulence scattering theory. While we do not have zooplankton data coincident with the microstructure and 307 kHz acoustic data, plankton net hauls (collected between tows and while observing similar patterns of scatter with the ship-mounted sounder) indicated that there were far too few zooplankton above 30 meters to cause the level of scatter observed in turbulent regions (Figure 4).

Even if we assume the unlikely scenario that, in the presence of turbulence, all zooplankton found between 0–30 meters aggregate into a 2-meter thick layer (about the thickness of layer seen in Figure 1a), we would still have only 75% of the density needed to scatter at \( S_V = -64.5 \) dB (the maximum level of turbulent scatter in Figure 1b).

The fact that the turbulent scatter we observed was continuous at all ranges introduces another consideration. To mimic turbulent scatter with discrete targets such as zooplankton, the zooplankton would have to have a number density high enough for at least one animal to occupy the sampling volume \( V_s \) at each range (i.e. \( N \geq \frac{\rho}{\rho_p} \sqrt{\frac{a}{g}} \)), Targets that are less abundant than \( 40 \) m\(^{-3}\) are easy to distinguish from turbulent scatter, since at some range they will disappear (no targets in the beam) or will appear distinctly as discrete targets (short blasts of scatter the length of the transmit pulse) with a volume scattering strength increasing inversely proportional to the sampling volume of the sounder. As the turbulent scatter is continuous even for relatively low scattering levels (around 90 dB), only copepods could simulate turbulent scatter (in Figure 4 they are the only taxa that has both the black and gray bars extending out of the light gray \( N = 40 \) m\(^{-3}\) region). Applying the same extreme aggregation scenario to copepods alone, we find only 37% of the necessary target density.

3. Conclusions

As zooplankton could not cause the level of scatter we observed in turbulent regions, we must conclude that turbulent microstructure strongly scatters sound at 307 kHz. While the levels of turbulence we observed are stronger than commonly observed in the open ocean, such levels do occur elsewhere (for instance in the ocean’s surface mixed layer [Denman and Gargett, 1988] and productive coastal waters), and serve to illustrate how turbulent scatter could easily confound zooplankton biomass surveys. On the one hand, if we ignored turbulence at times of strong turbulent scatter, we would overestimate the abundances of animals in Figure 4 from 300% (copepods, gastropods) to 6000% (euphausiids). On the other hand, the fact that turbulent scattering often drowns out zooplankton is promising for using backscatter to remotely sense turbulent microstructure without having to make extensive zooplankton measurements. Promising, but still not practicable, as we need more turbulent scattering data - at different frequencies and in different turbulent regimes - to refine and establish the universality of the model.

References


T. Ross, Department of Physics and Astronomy, University of Victoria, PO Box 3055, Victoria, British Columbia, V8W 3P6, Canada. (tetjana@uvic.ca)

R. Lueck, Center for Earth and Ocean Research, University of Victoria, PO Box 1700, Victoria, British Columbia, V8W 2Y2, Canada. (rueck@uvic.ca)