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Spectra of poorly resolved ocean data

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Abstract Standard temperature and pressure sensors on Aanderaa RCM8 current meters have a resolution of ~0.024 °C and ~0.6 bar, each equal to 1 digital number (value) over a range of 1024. It is shown that an 11-month deep-ocean temperature record using only four values can contain useful spectral information on internal wave motions. This is partially due to the modulation of high-frequency data by non-zero low-frequency (subinertial) variations. This result follows from the comparison of this record with artificial three- and four-value data constructed from temperature records observed in stronger stratified waters nearby. These artificial records show main features of the internal wave band similar to those observed in the original data spectra. Peaks at tidal harmonic frequencies and enhancements at sum-tidal-inertial interaction frequencies are preserved in the artificial data, but overall noise level (and thus the continuum spectral slope) is enhanced with respect to the properly resolved records (using 15 and 100 values). As a demonstration of the stable accuracy of the temperature sensors, the poorly resolved records provided an estimate of mean stratification to within 5% of the estimate using Seabird CTD data.

Keywords Bay of Biscay · Temperature and current observations · Poor resolution · Internal wave spectra

1 Introduction

Ideally, internal gravity waves supported by stratification in the ocean are measured by pressure (*P*) variations. This is impossible in practice, because a pressure sensor cannot be moored at a fixed location in space. As a result, its data reflect mooring motions, being a measure of current rather than pressure. Alternatively, internal waves can be monitored using horizontal current (*u*, *v*) measurements, but more unambiguously using vertical current (*w*) or temperature (*T*) measurements. A problem in (*u*, *v*) measurements is that internal wave motions may be indistinguishable from barotropic motions, which are not related to stratification. A problem in deep-ocean (*w*, *T*) measurements is their poor signal-to-noise ratio.

In this paper, internal wave frequency spectra are presented using data from poorly resolving (*T* and, for comparison, *P*) sensors mounted on standard current meters and moored above the abyssal plain and the continental slope in the Bay of Biscay (Fig. 1). At the deepest mooring, with instruments at ~4000 m depth, temperature (Fig. 2a) did not vary by more than 0.07 °C over the entire 11-month record. This variation was not due to mooring motions, as the pressure record (Fig. 2b) showed vertical excursions < 20 m, whilst a vertical excursion of 150 m was required through the observed stratification to achieve the above temperature variation with time. As will be shown by comparison with temperature data from moorings higher up the slope and with current data, such deep-ocean temperature data can provide useful internal wave (spectral) information, despite the extremely poor resolution as only four digital numbers (henceforth values) are used. The usefulness of such information depends partially on the low-frequency motions being relatively strong. Such motions are not observed in the (three-value) pressure record.

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2 Data

Spectra were evaluated using 11 months of Aanderaa RCM-8 current meter data from 3810 m at mooring BB8 (45°48′N, 06°50′W; water depth H = 4810 m; local inertial frequency f = 1.437 cpd) in the Bay of Biscay

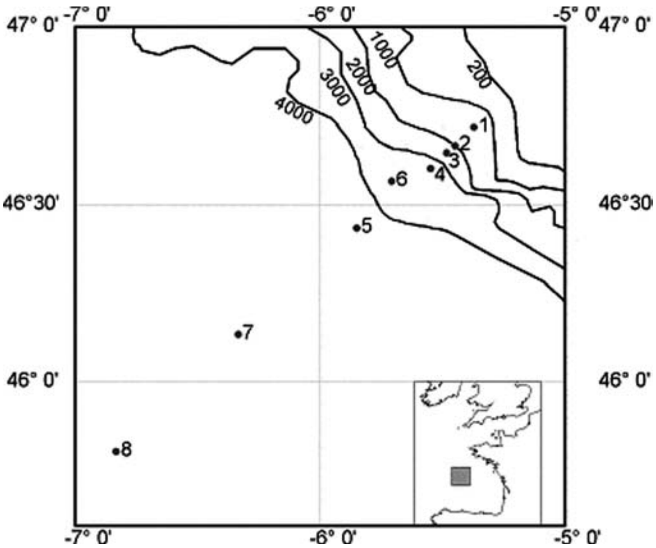


Fig. 1 Site of moorings 1–8 in the Bay of Biscay (named BB1-8 in the text) with depth contours (m)

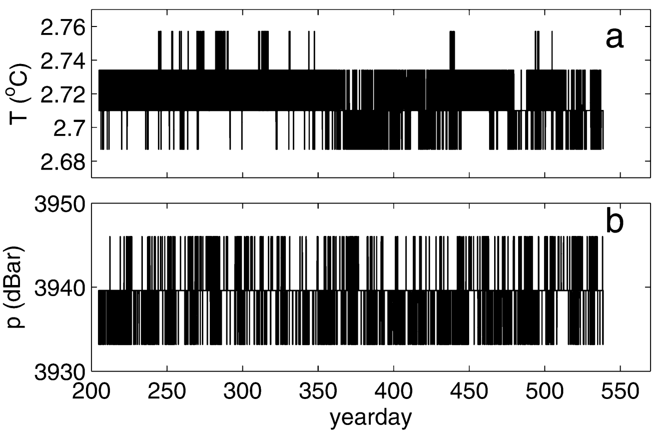


Fig. 2a, b Original time series **a** Temperature **b** Pressure, P (dbar) observed at 3810 m (BB8). Time is in yeardays (=days of the year) according to the convention that 12.00 UTC at January 1 = yearday 0.5, and yearday 365.5 in the second year of observations

(Fig. 1). For reference, current meter records were also used from 4210 and 4510 m at BB8, and from moorings higher up the continental slope: 3700 and 4100 m (BB7; H = 4700 m), 2700 m (BB6; H = 3700 m) and 1450 m (BB3; H = 2450 m). At the latter depths, stratification and temperature variations with time were (much) larger than at BB8. All instruments stored data every 20 min.

The temperature and pressure sensors were standard sensors on RCM-8 current meters, in which all samples were digitally stored in 10-bit binary words (1024 values). The temperature sensor had a calibrated temperature accuracy of ± 0.05 °C and it was set to have a resolution of (1 value step =) 0.024 °C, using the standard low range between −2.5 and 21.5 °C. In retrospect, the smaller resolution option arctic range could have been chosen, yielding a resolution of 0.005° C. As will be shown in this paper, this better resolution would have only marginally improved dominant spectral observations. The pressure sensor had a range of ~600 bar (1 bar = 10^5 Pa), a calibrated pressure accuracy of ± 3 bar and a resolution of 0.6 bar. Maximum current speeds were typically ~0.3 m s^{-1} above the continental slope and about half that value above the abyssal plain. These speeds corresponded to 50 and 100 values, so that, in general, current speeds were well resolved. The time series records of these data were fast Fourier transformed to compute spectra.

The frequency (σ) spectra of kinetic energy $P_{KE}(\sigma)$, temperature $P_T(\sigma)$ and pressure $P_P(\sigma)$ were usually moderately smoothed, using a Kaiser (~cosine-bell) taper window over half-overlapping data segments so that $\nu \approx 30$ degrees of freedom (df). As a result, individual frequencies like tidal constituents M_2 (semidiurnal lunar) and S_2 (semidiurnal solar) were indistinguishable, but their peaks and those of higher harmonics up to third order extended well above background noise at the 95% statistical significance level. Commonly, such frequencies are indicated by a band rather than by their individual names. For example D_2 denotes the band between N_2−0.1 cpd $< \sigma < S_2$+0.1 cpd, and similarly for D_4, etcetera. Combined bands, like the inertial–tidal band, are indicated by their main constituents. For example, M_2+f denotes a band between N_2+f-0.1 cpd $< \sigma < S_2+f$+ 0.1 cpd.

Stratification was inferred from Seabird 911 CTD observations just after deployment and just before recovery of the moorings, at positions less than 2 km away from the moorings along the same isobaths. A 50-m smoothed vertical density gradient provided a background buoyancy frequency (N) that varied linearly with depth over most of the depth range of interest, $N_{CTD}(z) = (1 \pm 0.5)(20 + 0.0034z)$ cpd, $-4480 < z < -2740$ m (frequency was calculated in cycles day^{-1}, 1 cpd = $2\pi/86400\ s^{-1}$). In order to test the (relative) accuracy of the temperature sensors, stratification was also computed using data from the upper two current meters at BB7 and BB8, separated by 400 m, for an estimate of $N_{RCM}(4000)$. Using a thermal expansion coefficient following the T–σ_θ relationship in local CTD observations, thereby compensating for the adiabatic lapse rate (Gill 1982; Pond and Pickard 1984), the N_{RCM} (4000) = 6.7^{+3}_{-1} cpd, whilst $N_{CTD}(4000) = 6.4 \pm 3$ cpd. This suggests that the similar standard 11-month mean deviations predominantly indicate natural fluctuations, with the means a true year long climatic mean (estimated to within 5% certainty).

3 Observed spectra

Despite the extremely poor resolution of T (and P) data at BB8, their amplitude spectra showed considerable detail (Fig. 3). The three-value P-data showed a nearly white noise spectrum with peaks at tidal (higher) harmonic frequencies up to D_4 rising significantly above the noise. The four-values T data showed similar spec-

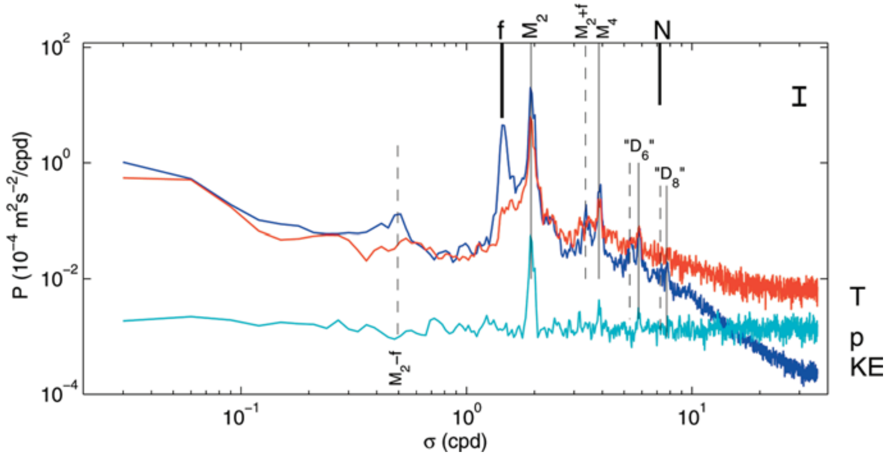


Fig. 3 Moderately smoothed ($\nu \approx 30$ df, degrees of freedom; 95% significance level in *upper right corner*) spectra of temperature, pressure and horizontal kinetic energy from original current meter record at 3810 m (BB8). The *vertical scale* is for P_{KE}, which is arbitrary for the other two spectra. Further explanations of symbols are *in the text*

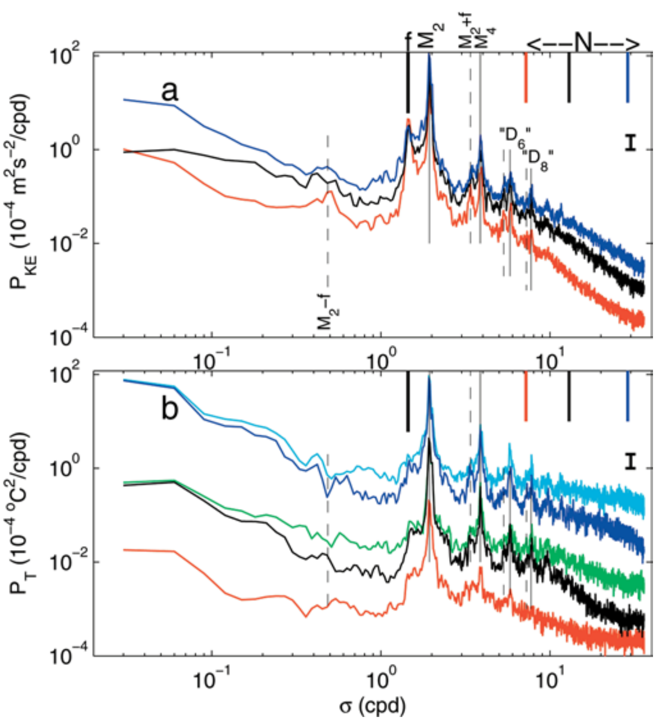


Fig. 4 a Moderately smoothed ($\nu \approx 30$ df) kinetic energy spectra from observations at 1450 m (BB3 *dark blue*), 2700 m (BB6 *black*) and at 3810 m (BB8 *red*). **b** Moderately smoothed ($\nu \approx 30$ df) temperature variance spectra from observations at 1450 m (BB3 *dark blue*), 2700 m (BB6 *black*) and at 3810 m (BB8 *red*). From the former two records 3- and 4-value artificial records are constructed (Fig. 5) of which the spectra are shown in *light blue* (BB3) and *green* (BB6), respectively. In both panels, none of the spectra has been offset vertically. *Symbols* as in Fig. 3

tral peaks extending above a spectral continuum that rose significantly above white noise level up to frequencies $\sigma \leq 10$ cpd. In addition, the $P_T(\sigma)$ showed elevated shoulders at non-linear tidal–inertial interaction frequencies like M_2+f. The difference between the P_T and P_P confirmed that the T data were not contaminated due to mooring motions.

In comparison with P_{KE}, a few other differences were observed in P_T apart from the higher noise level in the latter (Fig. 3). Firstly, in the P_T a weak shoulder was observed near the inertial frequency f, where a significant peak was found in the P_{KE}. Secondly, variations at higher tidal harmonic and inertial–tidal interaction frequencies appeared more peaked in the P_{KE} than in the P_T. This was partially due to the poor resolution of the T data and partially due to natural differences in current and temperature internal wave observations, as will be demonstrated after comparison with well-resolved T data observed higher up the continental slope at BB3 ($N \approx 28$ cpd) and BB6 ($N \approx 12$ pcd) (Figs. 4, 5).

In the observed P_{KE} (Fig. 4a) the energy levels of the spectral continuum increased with increasing stratification. Similarly, the number of higher tidal harmonics increased with N (at BB8 up to D_6, at BB3 up to D_{14}), whilst the levels of inertial and non-linear inertial–tidal (e.g. M_2+f, M_4+f) peaks decreased in absolute value and relative to the background continuum, respectively (van Haren et al. 2002). The observed P_T (Fig. 4b) showed the same increase of number of peaks with increasing N from BB8 (red), BB6 (black) to BB3 (dark blue). The P_T showed comparable higher harmonics as in P_{KE}. In contrast with P_{KE}, the P_T showed peaks at D_4 and D_6 that increased relative to the background continuum with increasing N, and enhanced, but not peaked, values at inertial and sum-inertial–tidal interaction frequencies. At M_2+f, temperature variance (slightly) increased relative to the background continuum with increasing N, despite decreasing $P_{\mathrm{KE}}(f)$ and, relative to the background continuum, decreasing $P_{\mathrm{KE}}(M_2+f)$. This contrast between P_{KE} and P_T was probably due to the progressively better resolution of the T data with N, as investigated below in a comparison with artificial data.

Artificial spectra

In order to adequately study poorly resolved time series, well-resolved T data observed higher up the continental slope at BB3 and BB6 were resampled artificially (Fig. 5). These data were chosen because the natural

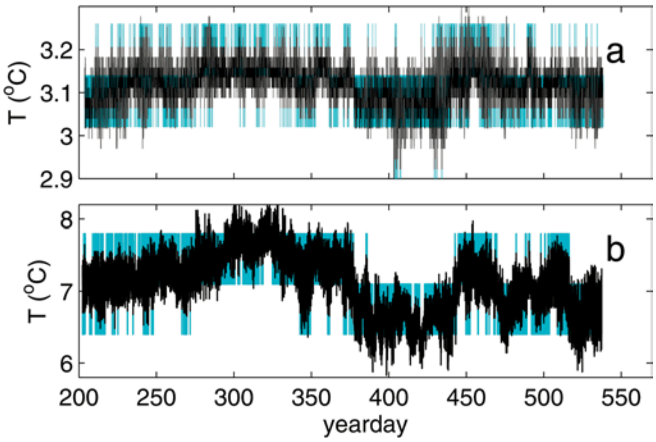


Fig. 5 a Original temperature time series observed at 2700 m (BB6 *black*) and corresponding 4-value artificial data (*light blue*). **b** As **a**, but for 1450 m (BB3) and corresponding 3-value artificial data. *Time* as in Fig. 2

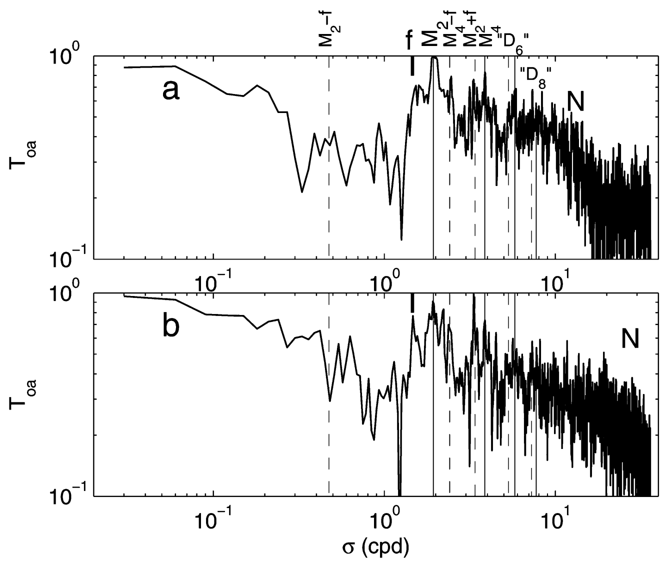


Fig. 6a, b Transfer function between observed and artificial spectra for: **a** data as in Fig. 5a (2700 m, BB6; 4-value artificial data) and **b** data as in Fig. 5b (1450 m, BB3; 3-value artificial data). *Symbols* as in Fig. 3

low-frequency variations were (spectrally) similar to those at BB8 (Fig. 4b). The original 100- (BB3) and 15-value (BB6) data were resampled to 3- and 4-value data, respectively (Fig. 5). Although the chosen values were arbitrary, the variance of the artificial series was adapted to exactly match the variances of the original time series.

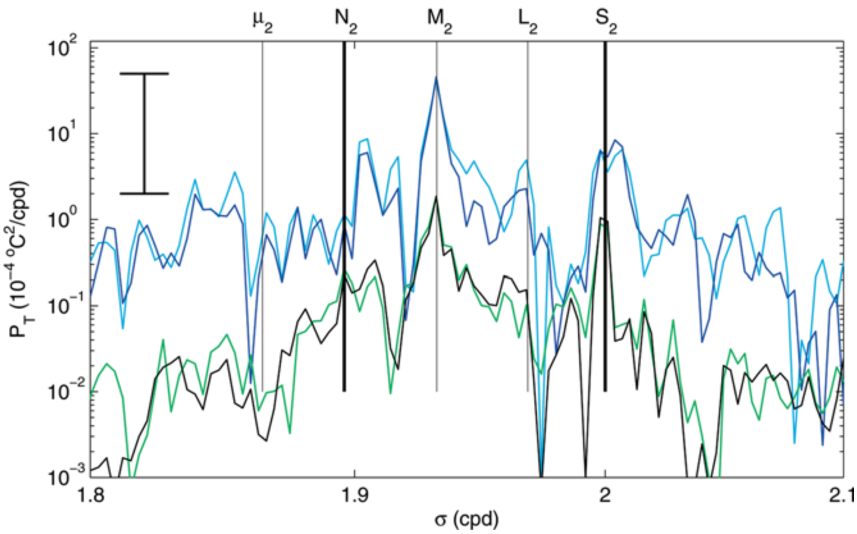
The resulting spectra (included in Fig. 4b) showed almost the same spectral features of enhanced variance at tidal higher harmonic and tidal–inertial interaction frequencies as for the original series. This was somewhat more clearly seen in the transfer functions T_{oa} between observed (*o*) and artificial (*a*) spectra (Fig. 6; before variance adaptation, using a factor by which the artificial spectra had to be multiplied amounting to 83 and 77% for Fig. 6a and b, respectively). Note the good correspondence at subinertial frequencies $\sigma < 0.05$ cpd, at *f*, M_2, and at interaction frequencies like M_4–*f*, M_2+f and M_4. At higher interaction frequencies $\sigma > M_8$ in Fig. 6a and $\sigma > M_6$ in Fig. 6b, the amplitude correspondence became less than 50%. The main difference between the artificial and the original series was an enhanced (continuum) noise level in the former, which showed the largest discrepancy with the original series at frequencies where relatively low variance was found: in between groups of tidal–tidal and sum-tidal–inertial frequencies (e.g. between the bands D_4 and D_6) and at $\sigma > N$. At these continuum noise frequencies the horizontal current ellipse polarization was not (at all) internal wave-like, in contrast with that at tidal–inertial interaction frequencies (van Haren 2003). The noise increased with decreasing number of values used. Note that the spectral fall-off near *N* was retained in the artificial spectra, albeit to a weaker extent than in the original series. In contrast, the general slope of a heavily smoothed spectrum changed with varying digitization. It became less steep with reduced digitization, whilst individual peaks were recovered, albeit perhaps with slightly enhanced peak height due to noise level increase. Individual peaks were not recovered only for tidal harmonic frequencies, but also for non-tidal harmonic frequencies, as was inferred from the D_2 band (Fig. 7).

In this detail of D_2, nearly raw temperature spectra from BB3 and BB6 were shown together with their artificial spectra, using the same colours as in Fig. 4b. In the original data, peaks were observed at familiar tidal constituent frequencies (e.g. M_2, S_2, L_2), but also at non-tidal constituent frequencies (for example between M_2 and N_2, and shoulders around M_2 and S_2). The relatively large peaks at non-tidal constituents were not due to noise, but were evidence of internal wave motions resulting from interactions between subinertial (~0.01 cpd) and tidal motions (van Haren, unpublished results). This suggestion was supported by the artificial data, in which elevations at the same non-tidal frequencies were retained just as at tidal harmonic frequencies for varying artificial digitization, rather than changing randomly as in proper noise.

4 Discussion

An artificial, single harmonic, pure sinusoidal signal represented by only three values extends as a single spectral peak about a decade above many higher harmonics noise. However, the poor-resolution data presented in this paper owe their presentation of natural (not artificial) higher harmonics to the existence of low-frequency currents. Except perhaps very near a source, open-ocean internal (tidal) waves do not manifest themselves at single harmonic frequencies, but as finite frequency bands due to interactions with the varying (current and stratification) background. As a result, the

Fig. 7 Semidiurnal tidal band of nearly unsmoothed ($\nu \approx 3$ df, using a single taper window over the entire time series) kinetic energy spectra from 11 months of current meter observations at 1450 m (BB3 *dark blue*) and 2700 m (BB6 *black*). In *light blue* (BB3) and *green* (BB6) the artificial spectra are shown. At $\nu \approx 3$ df spectra have a frequency resolution of 0.007 cpd ≈ 2 data points. *Vertical solid lines* indicate tidal constituents



varying background has direct influence on the spectral shape of the internal wave band, as the height and width of these interaction bands may vary in space and over short time scales. This causes poorly resolved T data to be spectrally more interesting than poorly resolved P data, as the latter are less affected by background variations as they also contain, perhaps predominantly, surface gradient (barotropic) information.

The comparison between artificial data with original, digitally well-resolved T data showed that the variance at interaction frequencies like M_4 and M_2+f may be influenced by (digitizer) noise, but that their peaking above the spectral environment remains unchanged. The overall noise continuum level (and the continuum slope) dropped rapidly with increasing digitization, as could be inferred from the closer correspondence between four-value artificial and original data than between the three-value artificial and original data in Fig. 4b. From the changes in spectral slope upon digitization it is suggested that for the original four-value T data at BB8 having nearly the same spectral slope as original BB3 and BB6 T data for $f < \sigma < N(3800 \text{ m}) = 7$ cpd, the actual spectral slope should be (only slightly) steeper when properly resolved. A decreasing mean spectral slope p with increasing N, from $p = -2$ at BB3 to $p = -3$ at BB8 was observed for P_{KE} (van Haren et al. 2002). It is noted that peaks at higher harmonics dominate the spectral slopes in P_{KE} and P_T. These slopes may be different at the same depth as P_{KE} can be different from P_T, because of different spatial scales of the different (non-linear) advective motions.

The above implies the necessity for better-resolution temperature sensors. They are not so much needed for resolution of spectral peaks up to reasonable high frequencies (~10 cpd, until reaching noise levels), that dominate the internal wave band spectra. Instead, they are needed for the resolution of spectral gaps, which are part of the (sloping) internal wave band continuum, extending to frequencies $\sigma > N$, well into the turbulence range. The present observations show that when high-resolution temperature data are not available, spectral analysis can be more informative than time-series analysis for specific purposes, provided the sensors are stable with time in their accuracy.

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