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Shear at the critical diurnal latitude

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[1] Around latitudes $|\varphi| \approx 30°$ where diurnal D_1 equals the local inertial frequency $f = 2\Omega\sin\varphi$, Ω denoting the Earth's rotational vector, several mechanisms can enhance shear at f due to a reduction in vertical scales. This would imply locally enhanced deep-ocean mixing. Here, recent 1.5 years of acoustic Doppler current profiler (ADCP) observations from the Canary Basin demonstrate largest kinetic energy at semidiurnal tides (D_2), but a complete absence of D_2-shear. Instead, shear is peaking at subinertial 0.97 ± 0.01f and terdiurnal $3f(\approx D_2 + f \approx D_3$ here), and vertical scales $\Delta z(f) < 0.1\Delta z(D_2)$. However, the f-band is broader than deterministic tidal frequencies and the smallest vertical scales, organizing shear in thin layers, are found at the lower inertio-gravity wave limit, which equals 0.97f for the weakest stratification observed (N = 6f, using Δz = 10 m). Hence, besides possibly subharmonic resonance, other mechanisms must be involved in enhancing f-shear, including non-linear harmonic interactions and wave trapping at the critical latitude's poleward shift. **Citation:** van Haren, H. (2007), Shear at the critical diurnal latitude, *Geophys. Res. Lett.*, *34*, L06601, doi:10.1029/2006GL028716.

1. Introduction

[2] The importance of internal waves for mixing in the deep-ocean, with likely implications for the meridional overturning circulation and distribution of suspended material, has led to renewed investigations in ocean shear. As linear waves do not mix, somehow a transition is required to non-linearity, so that large-scale internal waves' induced vertical (z) current shear $\mathbf{S} = (\partial u/\partial z, \partial v/\partial z)$, for horizontal current components (u, v), may cause small-scale waves to break resulting in irreversible mixing. In this paper, the primary question is the transfer of energy from large to small scales and the possible associated change in dominant frequency σ. The question is addressed analyzing open ocean moored current and shear observations at latitude $\varphi = 30.0012 \pm 0.0009°$N, at which $f = K_1$, a diurnal tidal harmonic constituent, $\approx S_2/2$, half the semidiurnal tidal solar constituent.

[3] One of the reasons for choosing this site is that one of the main candidates for an energy transfer from large to small scales, at $\sigma/2$, is parametric sub-harmonic instability or, in other words, sub-harmonic resonance (SR), besides direct K_1-forcing and a more general mechanism of non-linear interaction [*Xing and Davies*, 2002]. A similar mooring at $f = M_2/2$, half the semidiurnal lunar constituent, was lost. Although suggestions have been made for SR's possible relevance in the ocean, time scales seemed far too long O(100 days) [*Olbers*, 1976; *McComas and Bretherton*, 1977], until renewed modeling demonstrated much smaller scales O(5 days) [*Hibiya et al.*, 2002; *MacKinnon and Winters*, 2005; *Gerkema et al.*, 2006]. Observations using microstructure profiler suggested enhanced mixing around the critical diurnal latitude [*Hibiya and Nagasawa*, 2004]. Historic half-year long moored current meter data demonstrated greatly enhanced (factor of 10) kinetic energy at f in a relatively broad band $\varphi \approx 28 - 30°$, although without diurnal harmonic peaks at M_1, N_1 or S_1 and extending poleward of the critical latitudes, besides 50%-decreased levels at M_2 [*van Haren*, 2005]. The spatial extent seems small when SR is associated with internal wave beams near their topographic source. After the first bottom reflection of the M_2-beam into the interior, the M_1- and M_3-signals are lost in the model by *Gerkema et al.* [2006].

[4] In the present paper, long open-ocean acoustic Doppler current profiler (ADCP-) data are analyzed focusing on 30-m shear and spectral variations with a view to examining the role of SR and other non-linear effects in determining the energy distribution in the internal wave spectrum.

2. Data and Background Conditions

[5] An upward looking 75 kHz RDI-Longranger ADCP was mounted at 1450 m in the large elliptically shaped top-buoy of a 3700 m long mooring in the Canary Basin, North-Atlantic Ocean (Table 1). Nearest topography was 450 km away. The mooring showed <1.5° tilt angle implying very small mooring motions across <100 m in horizontal and <1.2 m in vertical directions. Currents are estimated as averages over the beam spread, which varies between 30–440 m depending on the range from the ADCP. The fairly large triangularly weighted transmission length of nearly 40 m ensures relatively accurate ensemble averaged u, v ($\pm 5 \cdot 10^{-3}$ m s^{-1}) at the expense of loss of vertical resolution. However, this length corresponds well with the vertical scale $\Delta z \sim 25$ m, which represents dominant ocean shear scales [*Orlanski and Bryan*, 1969; *Gregg*, 1989; *Hibiya et al.*, 2002] to within ~30%.

[6] The present data quality is generally high, especially further from the ADCP, due to the larger amounts of scattering material associated with layers of larger density stratification. From SeaBird-911 CTD-data around times of mooring deployment and recovery it is observed that the ADCP ranges through the lower parts of Mediterranean outflow water, as evidenced from occasional passages of a Mediterranean eddy ('meddy'). The buoyancy frequency is not small, N > 20 ± 10f using Δz = 25 m, $f = 0.7292 \cdot 10^{-4}$ s^{-1} (1.0027 cpd, cycles per day).

3. Observations

[7] The 1.5 years mean kinetic energy (E_k) spectra show the familiar harmonically sharp M_2, N_2 and S_2, with the first containing the largest energy in the spectrum. The second

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Table 1. Upward Looking ADCP Mooring Details

Property	Value
Latitude	30°00.070′N
Longitude	023°08.250′W
Water depth, m	5137
Deployment	17/10/2004
Recovery	19/05/2006
Beam slant angle, deg	20
Transmission length, m	39
Instrument depth, m	1450
First bin, m	1404
# bins x bin size, m	60 × 10
Ensemble period, s	3600

largest value, nearly at σ = K_1 = f for this φ, is in a moderately broad f-band that, naturally, coincides with the diurnal band D_1 without sharp peaks at harmonics (Figure 1). Henceforth, an (over-)harmonic diurnal band will be indicated as 'D_x', x = 1,2,3,4 etcetera, when no specific tidal constituent is indicated. Two minor energetic bands are observed in the spectrum, D_4, a familiar first harmonic of D_2 and attributed to non-linear advection, and D_3, an unfamiliar harmonic frequency but including a familiar inertial-tidal interaction frequency [*Xing and Davies*, 2002]. D_3's direct (tidal potential) forcing is commonly quite weak [*Cartwright and Taylor*, 1971] and only rare occasions have been reported of resonance-enhanced amplitudes [*Huthnance*, 1980]. However, it may represent here a non-linear inertial-tidal coupling as $D_3 = f + D_2 \approx D_1 + D_2$.

[8] In contrast, the 30-m shear spectrum consists of only two peaks: at f/D_1 and D_3 (Figure 1). Possible peaks at D_2 and D_4 do not significantly extend above the background, non-white 'noise', which is a most dramatic comparison with E_k of up to 2 decades in variance for the tidal D_2-constituents. As a result, the vertical scales $\Delta z(D_2) > 10\Delta z(f)$. This is observed throughout the ADCP's range, although details of peak heights vary slightly. Over time, never a significant D_2-peak is observed in the 30-m shear, in any of the monthly sub-spectra (not shown).

[9] The shear spectrum does not show peaks as narrow as $E_k(M_2, N_2, S_2)$, although weak sub-peaks are discernable within the relatively flat f-band (Figure 1b). Whilst the E_k(f)-"peak" frequency σ_p(f) is slightly blue-shifted with respect to f, $\sigma_p(f) = 1.02 \pm 0.01f$, the shear spectrum for the f-band **S**(f) shows a tendency for red-shift, with a mean $\sigma_p(f) = 0.97 \pm 0.01f$. Recall that $M_1 = 0.9638f$, here, whilst no peak is observed at K_1. The standard deviation is for 1.5 years' mean shear at many different depth levels. For individual z-levels in Figure 1b $\sigma_p = 0.966 \pm 0.003f$. In time, **S**(f) over the first 200 days (<day 570, before the obvious passage of a meddy, Figure 2), demonstrates a slightly further red-shift as $\sigma_p(f) = 0.96 \pm 0.015f$ (not shown), whilst in the period >day 600 mean **S** and E_k have $\sigma_p(f) = 0.99 \pm 0.015f$. In the former period, shear spectra are slightly more peaked at f and have larger variance by ~1/3 decade at D_3 than in the latter period, whilst no noticeable change in D_2-constituents is found between the periods. Only at σ < f and some $\sigma = D_3$ the vertical current difference variance equals twice the E_k − variance, implying maximum shear (currents showing permanently 180° phase difference).

[10] The association of D_3 with f is also observed in the time domain (Figure 2). The f-shear shows a flat pancake pattern reflecting the regularly maximum shear is confined to relatively thin layers. Shear magnitude remains large (>2π/f) for 3–6 days in such layers. D_3-current component amplitudes are, like f-current components, more homogeneous in the vertical, except for the odd sudden transition. There, large D_3-shear is found, which shows larger vertical coherence than **S**(f) over roughly $2\Delta z(f)$, still smaller than $\Delta z(D_2)$. The **S**(D_3) polarization coefficient $C_R(D_3) = 0.63 \pm 0.15$, much less than $C_R(f) = 0.96 \pm 0.04$ (C_R = 1 denotes purely circular motions, C_R = 0 rectilinear). These values correspond well with a linear internal wave model: C_R = 1,0.62 for f,D_3, respectively [*Gonella*, 1972]. Furthermore, large **S**(D_3) do not coincide (in z,t) with those of large **S**(f), especially when the vertical f-phase difference is not equal to 180°. As a result, the relatively smooth **S**(f) detailed pictures become more frayed at the edges, which implies that total shear magnitude varies over shorter time scales than sub-inertial scales for near-circular **S**(f).

4. Discussion

[11] Thin, O(10–100 m) layering of "large-scale" shear is commonly observed in the upper ocean [e.g., *Alford and Pinkel*, 2000]. However, depending on the observational tools, much thinner layering O(1 m) in near-surface stratification and shear is observed as well [*Marmorino et al.*, 1987; *van Haren*, 2000]. In all these observations, |**S**| seems relatively larger at f than at M_2, despite the usually larger E_k at the latter, and the shear is largest at the depth of largest stratification. This can be due to proximity of the atmosphere as its passing disturbances are considered a major source for inertial motions.

[12] For the deep ocean interior not many prolonged detailed observations exist on such layering, following classic vertical profiler observations [*Leaman and Sanford*,

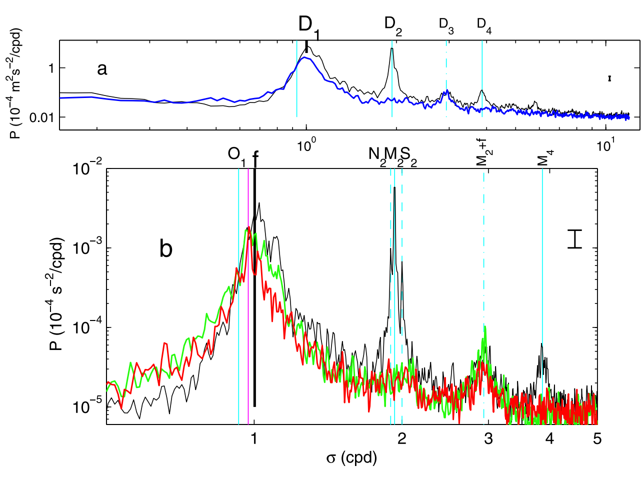

Figure 1. (a) Smoothed spectra of 1.5 years of kinetic energy E_k (black) and current difference over 30-m (blue) observed around 990 m. (b) Weakly smoothed spectral detail of E_k from Figure 1a. (black; scaled by 30-m) and 30-m shear around 1100 m (red) and 820 m (green). The vertical purple line indicates 0.97f, whilst K_1 is at f.

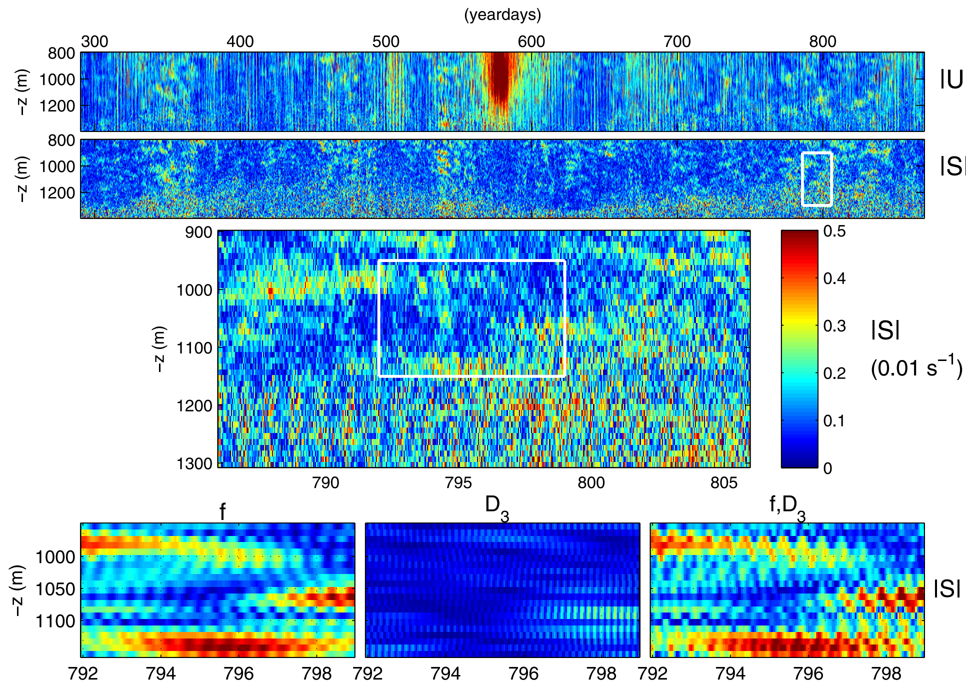

Figure 2. (top) Entire depth-time series of raw current (note the jet passage of a meddy between days 570–590) and 10-m shear amplitude data. Yeardays in 2005 are +366, in 2006 +731. (middle) Detail of raw shear. (bottom) Detail on three band-pass filtered series (with colors over the range [0, 0.0025] s^{-1}). The filter bounds are [0.85, 1.15]f and [0.9, 1.07]3f, with the two bands added prior to shear computation for the third panel.

1975]. The present long record of, somewhat limited in vertical resolution, moored ADCP-data shows a similar trend as in the near-surface observations: in the ocean interior $\mathbf{S}(f) \gg \mathbf{S}(D_2)$. This confirms the general notion that, outside source regions, internal tides predominantly have large vertical scales [e.g., *St. Laurent and Garrett*, 2002], but these scales are exceptionally large at the present site. However, this does not rule out the role of internal tides on ocean mixing, because they may generate near-inertial motions and shear in the interior. Two possible mechanisms to explain the fairly large $E_k(f, D_3)$ near the critical diurnal latitude are distinguished: a non-linear transfer of energy from $D_2 \rightarrow D_1$, D_3, and SR.

[13] The observational latitude is "exactly" critical for SR-generated S_1, and just 1.2° north of the f = M_1-latitude. Despite this latitudinal discrepancy, the result of SR(M_1) is still expected to be somewhat noticeable due to finite horizontal scales [*MacKinnon and Winters*, 2005]. Indeed, relatively large $E_k(f)$ and $\mathbf{S}(f)$ are observed, but much less peaking at M_1, S_1 [and not at all at N_1] than is expected from a direct transfer from sharp harmonic $E_k(M_2, N_2, S_2)$. Consequently, a spring-neap cycle is not observed in shear. Either, E_k contains relatively large barotropic D_2-energy and very little barotropic D_1-energy, or the SR-generated D_1 rapidly transfer energy to neighbouring 'noise' internal wave bands, or SR is not the only mechanism transferring energy to small inertial scales. Small-scale motions are more subject to non-linear interactions, which may broaden spectral peaks and thus blur SR-evidence away from a local source, e.g. near a continental slope [*Gerkema et al.*, 2006]. As with previous data [*van Haren*, 2005], bicoherence analysis of the present data yields virtually no significant results supporting SR (not shown), which is not surprising as sharp harmonic M_1,S_1 are not observed. Two more problems occur in explaining the observed f-band directly using SR. Firstly, the *shear* spectrum 'peaks' at M_1, but $E_k(f)$ not. The latter's $\sigma_p(f)$ = 1.02 cpd is not half a known [tidal] constituent. Secondly, if the shear's $\sigma_p(f)$ = 0.97 cpd represents SR[M_1], the associated free waves must have propagated poleward, which is impossible in traditional internal gravity wave theory (using large N).

[14] Alternatively, the relatively broadband, and slightly blue-shifted, $E_k(f)$ point at "locally", to within 100 km in latitudinal direction, generated inertial motions following a geostrophic adjustment process. This may be through an atmospheric storm, but also through thin strongly stratified layers tilted by horizontally short-scale internal [tidal] waves, although the precise mechanism for enhancement at this locality is not obvious despite strong insolation. The observed red-shift in $\mathbf{S}(f)$ may then reflect trapping of poleward propagated waves at the extension of the lowest inertio-gravity wave (IGW)-limit σ_l to sub-inertial frequencies σ_l < f accounting for local weak stratification (weakest observed N = 6f using Δz = 10 m, yielding $\sigma_l \approx 0.97f$). At $\sigma = \sigma_l$ (and $\sigma = \sigma_h > N$) the shortest IGW-scales are found. Except for spatially and temporally localized low-frequency vorticity areas, this is the only means for internal inertial waves to propagate poleward from their f-latitude. The fact that here $\sigma_l \approx M_1$ seems merely a coincidence and similar sub-inertial f-peaks have also been observed at high latitudes [*van Haren*, 2006].

[15] As the non-sharp harmonic f-peak is reflected in D_3 in the present data, D_3 is a non-linear interaction reaction [not SR] result between f and D_2, rather than a tidal constituent. It unlikely represents Doppler shifting, because the tidal currents are not the moving source of f/D_1, as in the

model of [*Xing and Davies*, 2002] and just like D_4 from $D_2 + D_2$, confirming the negligible spectral difference between Eulerian and isotherm-following shear observations [*van Haren*, 2000]. The observed polarization rejects "Doppler shifting" as a dominant explanation for D_3 here. This is also suggested from D_3(z,t), being in between the pancake appearance of f-motions and the vertically aligned D_2. Future investigations should address why **S**(D_3) is not found at the same z-levels as **S**(f) and the reason for the 180°-phase difference or maximum shear across layers of large N, as thin as they may be. Possibly, sub-inertial motions, trapped poleward from their generation latitude in weak-N layers, adjust their shear across large-N layers in which turbulent exchange is [initially] weak.

5. Conclusions

[16] In the deep open ocean interior of the Canary Basin 1.5 years of ADCP-data demonstrate that dominant D_2-energy is not associated with large vertical current shear at the same frequency: the shear spectrum only shows peaks at f($\approx D_1$) and 3f($\approx D_3$) thereby, more than the E_k-spectrum, resembling the GM-spectrum outside the interaction frequencies. In the vertical, f-scales are at least 10 times smaller than D_2-scales, causing f-shear variance 100 times larger than D_2-shear. Similar observations were made in shorter ADCP-records above Great Meteor Seamount (GMS), also at φ = 30°N, except that D_2-tidal amplitudes were twice those presented here. Whilst E_k(f) is 2–10 times larger than observed elsewhere, $\Delta z(D_2)^2$ [shear variance] is 10 times larger [smaller] than elsewhere.

[17] In z,t, f-shear is organized in flat pancake structures of O(10 m) thickness and 3–6 days duration that are frayed by D_3-modulations. The observed z,t,σ separation of **S**(f) and **S**(D_3) questions (non-)separability in the vertical wavenumber (m-) domain.

[18] Although E_k(f) and **S**(f) are much broader than deterministic tidal harmonics, E_k(f) 'peaks' at 1.02f and **S**(f) 'peaks' at 0.97f. The latter frequency equals the lower short-wave limit of the IGW-band considering *minimum* stratification N = 6f (Δz = 10 m), and equals M_1. This suggests that E_k(f) is generated locally within 100 km in latitudinal direction by a mechanism that is several times more powerful (or less dissipative) than at other latitudes. It may be SR, in addition to local geostrophic adjustment, provided the resonant frequencies spread energy into the neighbouring bands swiftly, whilst free waves propagate poleward to become trapped at the lower IGW-limit.

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