Shear at the critical diurnal latitude

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[1] Around latitudes |φ| ≈ 30° where diurnal D1 equals the local inertial frequency f = 2Ωsinφ, 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 (D2), but a complete absence of D2-shear. Instead, shear is peaking at subinertial 0.97 ± 0.01f and terdiurnal 3f≈D2 + f ≈ D1 here), and vertical scales Δz(f) < 0.1Δz(D2). 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 frequencies $f$. The question is addressed analyzing open ocean moored current and shear observations at latitude $\phi = 30.0012 \pm 0.0009^\circ$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 $\phi = 28 \pm 30^\circ$, 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 $M_2$-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 trianulily weighted transmission length of nearly 40 m ensures relatively accurate ensemble averaged u, v (±5·10⁻³ m s⁻¹) at the expense of loss of vertical resolution. However, this length corresponds well with the vertical scale $\Delta z \approx 25$ 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, $N > 20 \pm 10 f$ using $\Delta z = 25$ m, $f = 0.7292 \times 10^{-4}$ 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
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 ($>2\pi/f$) 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 $\Delta z(D_3)$. 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: $C_R = 1.062$ for $f$, $D_3$, respectively [Gonella, 1972]. Furthermore, large $S(D_3)$ do not coincide (in $z,f$) 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, 1987].

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.
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 \( S(f) \gg S(D_2) \). 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 \( E_k(f, D_2) \) 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 \( S(f) \) 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 ‘noisy’ 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 [Gerkena 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 \( E_q(f) \) not. The latter’s \( \sigma_q(f) = 1.02 \) cpd is not half a known [tidal] constituent. Secondly, if the shear’s \( \sigma_q(f) = 0.97 \) 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, \( E_q(f) \) 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 \( S(f) \) may then reflect trapping of poleward propagated waves at the extension of the lowest inerto-gravity wave (IGW)-limit \( \sigma_1 \) to sub-inertial frequencies \( \sigma_1 < f \) accounting for local weak stratification (weakest observed \( N = 6 f \) using \( \Delta z = 10 \) m, yielding \( \sigma_1 \approx 0.97 f \)). At \( \sigma = \sigma_1 \) (and \( \sigma = \sigma_0 > N \)) 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 \( \sigma_1 \approx M_1 \) 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 $D_2$ from $D_2 + D_3$, 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 $D_2$ 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 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 $(\approx D_1)$ and $3(\approx D_3)$ 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 $\varphi = 30^\circ$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 $D_2$-modulations. The observed $z,t,\sigma$ separation of $S(f)$ and $S(D_3)$ questions (non-)separability in the vertical wave-number ($m$-) 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 $N = 6f$ ($\Delta z = 10$ 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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References


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