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Monthly periodicity in acoustic reflections and vertical motions in the deep ocean

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[1] A recent, 1.5 years long record of acoustic Doppler current profiler (ADCP)-data from the Canary Basin (North-Atlantic ocean) likely reflects vertical zooplankton migration between 800 and 1400 m. This record clearly distinguishes 3 major periodicities of down- and upgoing motions to within a precision of ~1/400: a daily, a seasonal and a monthly cycle. Largest daily excursions occur during full moon. The directly observed hourly mean vertical velocity amplitudes of $|w| = 0.025 \pm 0.01$ m s^{-1} are too slow for particles from the observational depths to reach the zone of moon- (and only very weak sun-) light penetration in half a day. It is shown that no physical (internal wave), geochemical or sinking food mechanism can trigger the daily and monthly cycles, which are coupled. It is speculated that an entrained biorhythm running precise internal biochemical clocks controls the vertical migration.

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1. Introduction

[2] Acoustic backscattering is a well-developed and useful tool to estimate e.g. suspended material and fish in the ocean [*Urick*, 1975]. Acoustic scattering off suspended material has been successfully exploited for estimation of 3-D ocean currents, resulting in acoustic Doppler current profilers (ADCPs) now commonly used by physical oceanographers. Soon after the development of such instruments in the early 1980's, an ADCP showed (daily) periodic variations in the vertical current component w *and* in 'acoustic backscatter echo intensity' I in the upper ocean [*Schott and Johns*, 1987]. Such daily variations were considered a contamination of the ADCP's (physics) signals, as they could not be related to any ocean dynamics. Considering the typical acoustic wavelength, as stated in the manufacturer's manual, and using towed nets near an ADCP, it was established that variations in I [*and* w] were not associated with horizontal currents, but with vertically migrating zooplankton [*Flagg and Smith*, 1989]. As will be demonstrated here using a 1.5 years long hourly sampled record, ADCP-data can be useful to study such vertical motions well below the photic zone. Lacking net-tows, which are impossible at such time scales, detailed analysis and reference to previous daily [*Plueddemann and Pinkel*, 1989] (hereinafter referred to as PP) and near-surface seasonal cycle observations [*Fischer and Visbeck*, 1993] will be used to show that the most likely explanation for the observed variations in w and I is zooplankton migration, clearly distinguishable from (water mass, internal wave) physics and geochemistry processes. It is speculated that this questions the precision of plankton's internal clocks, because clock resetting by external triggers seems not possible. External clock resetting is hitherto considered the most plausible explanation for migration close to the sea surface.

[3] Well before the era of ocean acoustics, vertical migration of zooplankton has been known [*Latreille*, 1829; *Murray and Hjort*, 1912; *Cushing*, 1951]; fishermen catch most during nighttime as sealife feasts on plankton abundancy near the surface, whilst copepods like *Calanus finmarchicus* are reputed for their 'diapause' at great depths (600–1000 m) for at least several months in winter [*Hirche*, 1996]. In contrast, fortnightly and monthly rhythms are not commonly observed in the deep-sea [*Palmer*, 1995], although direct effects of moonlight have been reported for near-surface migration [e.g., *Tarling et al.*, 1999; *Hernández-León et al.*, 2001]. Most scientific knowledge on such daily and seasonal migration comes from horizontal and vertical tows using fine-mesh closing nets. Although plankton abundance is generally found near the surface, live decapoda have been found at 4000–5000 m [*Murray and Hjort*, 1912; *Farran*, 1926]. At such great depths zooplankton still seem to migrate vertically, some over the entire water column, but others not reaching the surface light-zone. However, periodicities of large and deep vertical migration are unclear [*Vinogradov*, 1961].

[4] Many explanations for the trigger of plankton migration have been offered over time, ranging from biorhythm, light intensity variations, predation pressure and starvation to temperature variations [e.g., *Murray and Hjort*, 1912; *Russell*, 1927; *Thorisson*, 2006]. The latter three may be relevant for triggering seasonal migration, including sinking fecal pellets or phytoplankton for food [*Thorisson*, 2006]. However, these cannot be relevant for daily migration when deeper than 100 m below the surface, because sinking is too slow <0.002 m s^{-1}, the maximum rate found for (shallow seas) heavy diatoms [*van Haren et al.*, 1998]. Similarly, studies on predation pressure do not show a unique correlation between predators' and prey motions [*Enright and Honegger*, 1977]. Thus, considering the strict daily, but also seasonal, migrations, a (light-induced) biorhythm seems most plausible, except that migrations also occur at great depths well below 1000 m. Although photographic plates are still blackened after several hours of mid-day exposure at 1000 m, but not at 1700 m [*Murray and Hjort*, 1912], the 480 nm irradiance level is $<10^{-7}$ times the near-surface value at 600 m in the Canary Basin [*Kampa*, 1970]. This already demands extremely sensitive photo-receptors in zooplankton to trigger its migration. During full-moon,

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Table 1. Upward Looking 20° Vertical Slant Angle RDI-ADCP Mooring Details

	CB	GMS
Latitude	30° 00.070′N	30° 00.016′N
Longitude	023° 08.250′W	027° 48.627′W
Waterdepth	5137 m	4550 m
Data start	17/10/2004	20/10/2004
Data end	20/05/2006	15/12/2005
Transmission length	39 m	28 m
Instrument depth	1450 m	1370 m
First bin	1404 m	1330 m
# bins × bin size	60 × 10 m	50 × 10 m
Ensemble period	3600 s	900 s

the same low irradiance level is found at even shallower 100–150 m [*Kampa*, 1970].

[5] Yet, 13 days of moored 67 kHz acoustic measurements between 0 and 1200 m clearly show three different *daily* migratory pathways, between 100 and 300 m, between 200 and 550 m and between 650 and 1000 m (PP). Vertical speeds of 0.01–0.04 m s^{-1} are measured for durations of 1–2 hours (see also overview by *Ott* [2005]), which compare well with isolume-depth changes [*Roe and Harris*, 1980]. PP's acoustic data are attributed to (non-resonant) reflections off suspended material having scales $>O(1-10)\cdot 10^{-3}$ m, typical for zooplankton (PP). The time-series of similar acoustic data presented here are from greater depths (800–1400 m) and so long that they allow determination of precise periodicity up to seasonal scales using spectral analysis.

2. Data and Methods

[6] An upward looking, hourly sampling four-beam 75 kHz ADCP was mounted in the top-buoy of a 3700 m long mooring in the Canary Basin (CB) between October 2004–May 2006 (Table 1 for details). A second ADCP was moored near Great Meteor Seamount (GMS), sampling a range of 500 m once per 15 minutes for a shorter period of time. The CB-ADCP ranged ~600 m from the head. Pressure and tilt sensor information showed that the moorings did not move much, <1.5° tilt angle implying excursions across <1.2 m in the vertical z and <100 m in horizontal x, y directions, due to two large, elliptically shaped, low-drag, ~350 kg net buoyancy elements. As a result, mooring motion did not affect the observations.

[7] As the I-data are dominated by the attenuation of sound through the water column, the estimate of suspended particle signal dI is obtained by subtracting the time mean ⟨⟩ from the raw data (PP),

$$\mathrm{dI}(z,t) = \mathrm{I}(z,t) - \langle \mathrm{I} \rangle (z). \qquad [\mathrm{dB}] \tag{1}$$

For studying daily variations, a composite is also computed per selected monthly period

$$\mathrm{dI_c}(z,t) = \frac{1}{N}\sum_{n=1}^{N} \mathrm{dI_n}(z,t), \qquad (N = 30 \text{ days}), \tag{2}$$

where $\mathrm{dI_n}$ represents dI at a given day n (PP). Similarly, composite w_c is computed from w.

[8] From hydrographic observations during the deployment and recovery cruises it is found that the ADCP's occasionally range through the lower part of Mediterranean outflow water, which commonly propagates in large eddies ('Meddies'). ADCP's temperature variations are moderate, except when such Meddy passes, e.g. between days 565 and 600 (Figure 1a).

3. Observations

[9] The 19-months CB-dI-time-series clearly shows a seasonal cycle with values as large as 20 dB above the winter minimum observed during late summer/autumn (Figure 1b). This and other dI-cycles have no correspondence with Meddy-passages and, therefore, cannot be associated with possible variations in suspended matter due to water mass changes. Superposed on the seasonal cycle are monthly and daily period variations, persistent throughout the year but most visible in late winter/spring. At ~1100 m, minimum daily variations occur during new moon when, in general, dI has large value. Typical full-moon variations exceed 10 dB. However, a spring-neap cycle, the fortnightly beat of dominant lunar and solar semidiurnal tidal currents, is not observed. These daily and monthly cycles are also observed in w-data (Figure 1c).

[10] Such observations are found over the entire ADCP-range, albeit varying in intensity (Figure 2). The persistency of daily variations throughout the year is visible as the striped pattern over the entire depth range in Figure 2. The largest daily variations in dI and the corresponding largest w-amplitude are found in deep layers closest to the ADCP. In contrast, the monthly variations are most pronounced in mid-range, 900–1200 m. During full-moon, excursions cover the full range of ADCP-observations, between dI-sub-maxima near 800 and 1400 m. A detail from late-spring

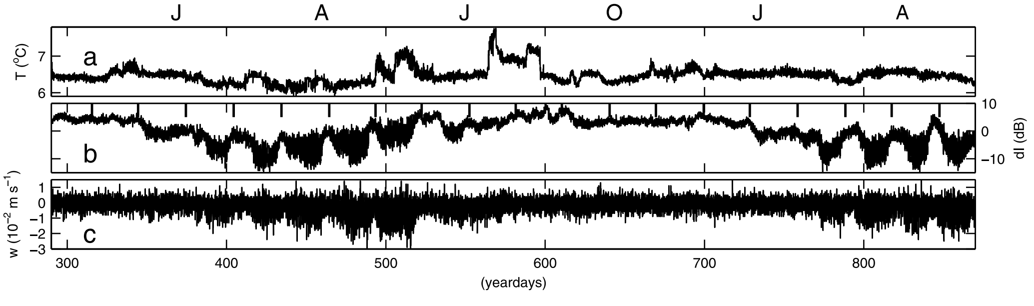

Figure 1. Entire 19 months of CB-ADCP time series. (a) Temperature at 1450 m. (b) Echo intensity dI relative to its time mean at 1100 m. The heavy vertical ticks indicate times of new moon. (c) Vertical current at 1100 m. Time in 2005 is yearday +366, in 2006 yearday +731. All time axes are meridian-corrected to local time (LT).

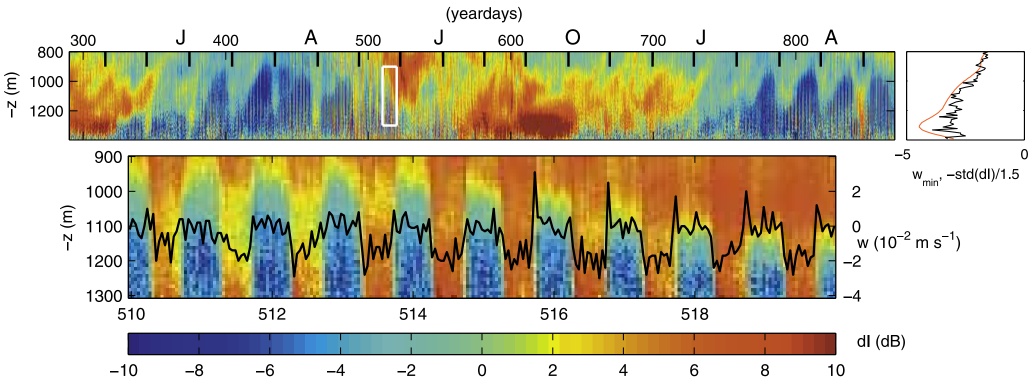

Figure 2. (top left) CB depth-time series of dI and (bottom) detail from rectangle, at the transition between spring and summer, with w from 1250 m superimposed (solid line; scale to the right). (top right) 1.5 years mean of dI-variability (red) and average negative w (black), as a function of depth (scale far left).

(Figure 2) shows $|w| = 0.025 \pm 0.01$ m s^{-1} (2000 m day^{-1}) and overall largest $|w| > 0.04$ m s^{-1}. These values are exactly in the range of values attributed to zooplankton migration closer to the surface [e.g., *Ott*, 2005].

[11] Daily dI-variations do not exhibit a sinusoidal signal, as would be expected from a solar-driven variation, but a more rectangularly shaped periodicity, with maxima during 9–11 hours and minima during slightly longer periods in the detail of Figure 2. End of May, sun sets at 18:55 and rises at 05:10 at 30°N. Periods of minimum down- and maximum upward w are shorter, varying between 1 and 4 hours (Figures 2 and 3).

[12] The short periods of peaking w are clearly visible in daily composite plots from 1-month of 15-minutes sampled GMS-data that better resolve w (Figure 3). The GMS-data do represent the open ocean CB-data, although (semidiurnal tidal) advective currents associated with the topography blur daily patterns above GMS. As in CB-data, summertime dI- and w-variations are weaker, implying relatively weaker migration of the larger dI-stock across only 150 m and at greater depths than in winter/spring. Note that w is independent of changes in backscattering material abundance or physiological appearance of zooplankton, that is in dI-variations. In winter/spring, daily variation (in dI *and* w) is more or less across the entire ADCP-range, but it does not extend above it. In both periods, the timing of vertical motion reflects the length of daytime. Sinking commences 30–60 minutes after sunrise, with largest negative w occurring 1–2 hours later, whilst largest upward w is found 1.5–2 hours before sunset, upward motion halting 1 hour later. This pattern closely resembles near-surface (0–240 m) daily variations of vertical motions that are directly triggered by sunlight [*Thomson and Allen*, 2000].

[13] Power spectra confirm the above dI-observations, with a sharp harmonic peak at the diurnal solar frequency $S_1 \pm 0.0025$ cpd and, commensurate with the rectangular time series' shape, many higher harmonics (Figure 4a). The CB-dI-signal is *not* significantly affected by advection due to horizontal currents, e.g., induced by internal waves, as is inferred from comparison with kinetic energy (E_k) spectra. The E_k show a completely different series of peaks, with a broad band near the Earth's rotational inertial frequency f, the lower limit of the internal gravity wave band under large stratification, a dominant peak at semidiurnal lunar M_2 instead of solar S_2, and peaks at different, more broadband inertial-tidal higher harmonics. In contrast, w-spectrum closely resembles dI's.

[14] In details, the dI-spectrum varies in (z, t). In time, its 1.5 years mean is dominated by late-winter/spring data, as summertime spectra show a small peak at S_1, whilst lacking higher harmonics and showing a weak advection peak at M_2 (not shown). In depth, between 900 and 1200 m, dI shows two side-peaks around S_1 (Figure 4b). These reflect the monthly variation, which is ~29 days ($M_1 - S_1$ beat period =

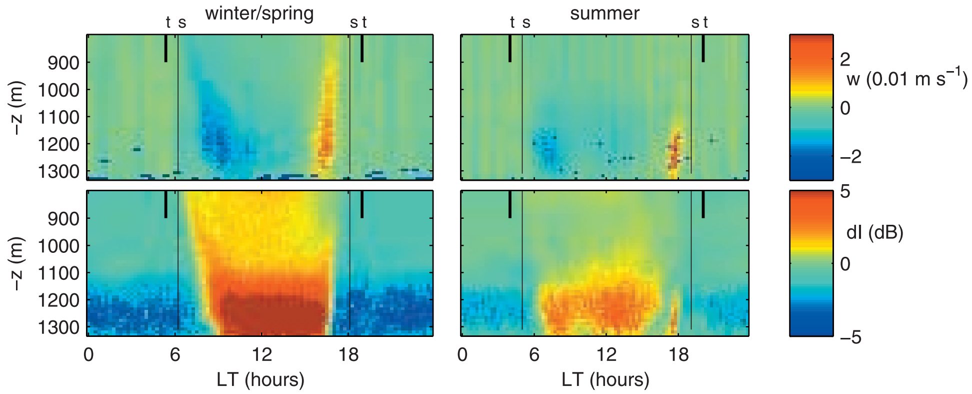

Figure 3. Monthly composite plots using equation (2) of 24-h w and dI from 15-minute GMS-data. (left) Late winter/spring situation (data around day 435, March 12). (right) Summer situation (data around day 535, June 20). t indicates nautical twilight and s sunrise, sunset.

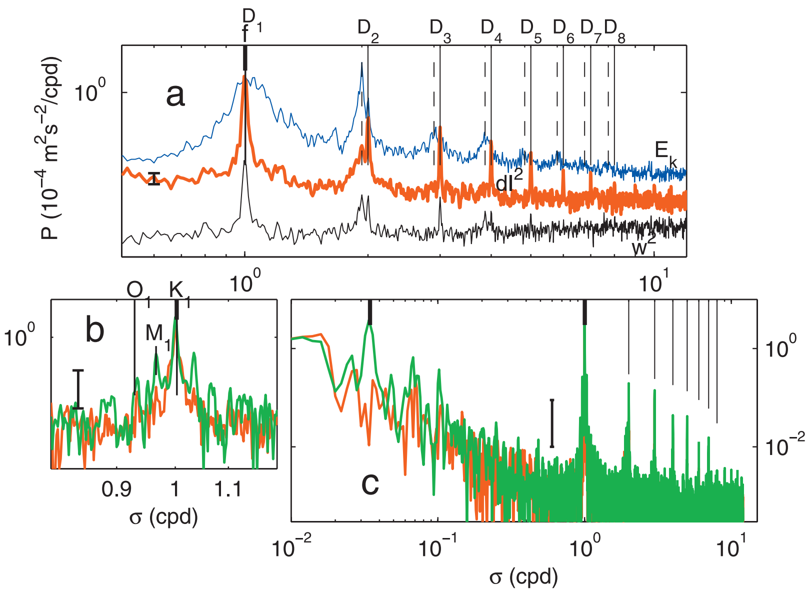

Figure 4. CB 1.5 years mean frequency (cycles per day, cpd) spectra. (a) Smoothed daily (D1) and higher harmonics detail of kinetic energy Ek (blue), dI (red; arbitrary units) and w (black) observed at 900 m. Solid lines indicate solar S-frequencies, dashed lines lunar M. (b) Near-raw daily detail of dI at 1100 m (green) and 900 m (red). (c) Entire spectra of Figure 4b.

29.5 days). The peak at 1/29.5 days (0.033 ± 0.0025 cpd) as large as S_1 evidences interaction between the monthly modulation of dI and its daily variation (Figure 4c). As the latter evidences zooplankton migration, because no physical or geochemical processes can explain the dI- and w-spectra and because the data resemble previous observations attributed to such migration [e.g., PP; *Thomson and Allen*, 2000], the monthly (and seasonal) modulation is most likely due to zooplankton biology as well. It is unclear why the monthly variation is found so strong at this particular depth-range, at the bottom of the Mediterranean water, well below moonlight penetration and yet in strict phase with the local moon's periodicity. Like for the internal wave band (frequencies >f), no correspondence is found between dI,w and the physical processes dominated E_k at the monthly period: at frequencies <f E_k only peaks at 1/110 days (not shown). The periodic (seasonal) change in acoustic reflectance may be due to sub-inertial advection or represents changes in physiology (species structure) or in (migrating) group-behaviour.

[15] Further evidence of significant deep daily zooplankton migration not reaching the photic zone is found in yearlong ADCP-data from the Western Mediterranean Sea between 1900 and 2350 m in nearly homogeneous water (not shown). There, the dI-signal is too weak to estimate vertical migration speeds from the (z, t) series and directly measured $w = 1–2 \cdot 10^{-3}$ m s^{-1} or one decade smaller than in the present data.

4. Discussion

[16] Even if the present CB/GMS-observed $|w| \approx 0.025$ m s^{-1} were maintained over the entire water column, particles would have no time left to stay at the depths of the ADCP range or in the photic zone: they would have to be constantly moving vertically, which is not observed. The observed vertical variations cannot be triggered by internal waves, as diurnal (inertial) motions have a broad rather than a narrow band appearance yielding a 3–5 days "intermittent" instead of a monthly modulation. Furthermore, under given density stratification vertical excursions can theoretically never be larger than 100 m, and were observed <25 m. Under the assumption that the present observations do describe vertical zooplankton migration, we speculate how this plankton is capable of following the sun's periodicity, daily and seasonal, and especially also the moon's periodicity, at such great resting depths of 1300 m or more, where (moon)light intensity is just too weak to be sensed by photographic plates [*Kampa*, 1970]. Are the zooplankton moonstruck?

[17] It seems that the sharp monthly-daily migrations are most likely related with a biorhythm that is perhaps originally induced by (sun and moon) light variations on species living higher up in the water column prior to moving to greater depths at later life stages, as e.g. occurs for *Calanus cristatus* [*Vinogradov*, 1961]. One could argue, using the observation of precise seasonal variation of the daily cycle, that the gene-controlled internal clocks are reset daily, as in many terrestrial organisms [*Winfree*, 2001], when reaching depths where sunlight just barely penetrates. However, dI-observed plankton are at their greatest depth during daytime and their clocks definitely cannot be reset to follow the moonlight cycle, which suggests large memory persistence in time. Some memory persistence of such biorhythms has been established in laboratory experiments for shallow (tidal) water species (S. Avent et al., Diel vertical migration in zooplankton: Experimental investigations using video-microscopy and plankton mini-towers, available at http://userwww.sfsu.edu/~bioocean/research/minitowers/minitower.html, 2006) and for day-night rhythms [*Enright and Hamner*, 1967], but presently of unknown length. This requires further study.

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