Sharp near-equatorial transitions in inertial motions and deep-ocean step-formation

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[1] The near-equatorial region is importantly different from other ocean areas: it acts as a barrier for large-scale meridional circulation, because the strongest currents are directed East-West, and it shows weak interior mixing despite large internal wave shear. All seems related to a change in importance of the vertical 'inertial' component of the earth's rotation. As rotational effects dominate large-scale ocean motions through a geostrophic balance, they become negligible at the equator. Here, deep-ocean observational evidence is presented of hitherto neglected rotational effects. It is demonstrated that when the equator is approached near-inertial internal wave motions very suddenly rather than smoothly change polarization from near-circular to near-rectilinear within half a degree across latitudes $|\varphi| = 1.5 \pm 0.5°$. At the same latitudes sudden transitions are observed of large-scale kinetic energy and small-scale density stratification variations. Understanding the above requires a non-traditional approach in which the horizontal component of earth's rotation is considered. **Citation:** van Haren, H., (2005), Sharp near-equatorial transitions in inertial motions and deep-ocean step-formation, *Geophys. Res. Lett.*, *32*, L01605, doi:10.1029/2004GL021630.

1. Introduction

[2] In order to maintain the large-scale meridional overturning circulation in the ocean at great depth, internal wave induced mixing is crucial [*Munk and Wunsch*, 1998; *Wunsch and Ferrari*, 2004]. About half of this deep-ocean mixing is generated through conversion of surface tides to internal waves via interaction with topography, the other half through wind. Passing atmospheric disturbances transfer energy to near-inertial motions at local frequency $f = 2\Omega\sin\varphi$, the vertical component of the earth's rotational vector $\boldsymbol{\Omega}$ [*Millot and Crépon*, 1981]. This energy can be transferred to gravity waves in the ocean interior at frequencies (σ) just larger than f ($1.00f < \sigma < 1.09f$) when they propagate towards lower latitudes [*Garrett*, 2001], or, when considered on a spherical shell, just smaller than f ($\sigma \approx 0.99f$) towards higher latitudes [*Maas*, 2001]. Near-inertial waves can also propagate into the interior when generated via surface fronts [*Xing and Davies*, 2004]. Internal gravity waves exist between $f < \sigma < N$, with $f \ll N = (-g/\rho\partial\rho/\partial z)^{0.5}$ the buoyancy frequency of stable density (ρ) stratification and g denoting the acceleration of gravity in the negative z-direction.

[3] Although it is long known that most internal wave energy is indeed observed at oscillatory near-inertial and tidal frequencies [e.g., *Fu*, 1981], recent evidence [*Alford*, 2003] suggests that approximately half of the near-surface internal wave shear resides at near-inertial frequencies ($\sim$1.02f). In reality, this shear is found at the stratification below the 10–20 m thick wind-mixed layer [*van Haren et al.*, 1999]. This is important for ocean mixing, because vertical current shear $\mathbf{S} = (\partial u/\partial z, \partial v/\partial z)$, with (u, v) the horizontal current components, leads to shear instability, a key mechanism to destabilize stratification [*Turner*, 1979]. Generally, except at the top of a frictional Ekman layer, an oscillatory motion implies oscillatory shear. However, near-inertial motions describe a pure circularly polarized path ($|u| = |v|$) in the horizontal, so that their shear magnitude $|\mathbf{S}|$ is theoretically constant with time, or, in practice, a slowly varying function of time, much slower than the inertial period [*van Haren*, 2000]. As will be shown here, near-inertial horizontal current polarization can change sharply in the deep ocean, not just at its pycnocline depth, which accordingly may have implications for $|\mathbf{S}|$.

[4] In practice in the deep ocean $N < 10f$, and further decreasing with increasing depth, and in theory especially near-inertial waves can become trapped near the bottom [*Gerkema and Shrira*, 2005]. This is because in a non-traditional approach [*Saint-Guily*, 1970; *LeBlond and Mysak*, 1978] the internal wave band is extended and includes the gravity waves (which exist in the band $f < \sigma < N$ in the limit $N \to \infty$) and gyroscopic waves (for $N \to 0$, so that north-south propagating waves exist in the band $0 < \sigma < 2\Omega$). In this approach, the horizontal component of the earth's rotation $\tilde{f} = 2\Omega\cos\varphi$ cannot be neglected in the horizontal and vertical (w) momentum equations, which read in linearized form:

$$u_t - fv + \tilde{f}w = -p_x \tag{1a}$$

$$v_t + fu = -p_y \tag{1b}$$

$$w_t - \tilde{f}u = -p + b, \tag{1c}$$

in which subscripts denote partial differentiation, p denotes pressure and b a buoyancy term. Pure gyroscopic motions are always circularly polarized in their plane of propagation. However, this plane may be very strongly tilted to the horizontal, so that when projected in the plane of (u, v), motions appear rectilinearly polarized as observed in the Western Mediterranean Sea [*van Haren and Millot*, 2004]. As a result, in weakly stratified waters, where gyroscopic waves dominate gravity waves, the near-inertial shear magnitude can become a relatively fast varying function of time, no longer associated with a slowly varying background N.

[5] Near the equator we do not (necessarily) focus on weak N, but on very small f, and in the zonal equation of

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motion (1a) $\tilde{f}$ w ≈ fv [*Veronis*, 1963b] and the $\tilde{f}$-term is important for ocean dynamics in a near-equatorial range between critical latitudes φ_c. Previously, these latitudes were estimated for large-scale flows as $|\varphi_c| \ll 1°$, assuming $w/u \leq 10^{-3}$ [*Veronis*, 1963b], and for large-scale equatorial planetary waves as $|\varphi_c| \leq 2°$ [*Munk and Moore*, 1968]. The latter is equal to the meridional extent of an (eastward) zonal barotropic current in an ocean of about 4000 m depth considering a spherical shell [*Veronis*, 1963a]. Recently, small-scale turbulence dissipation in the upper 1000 m of the ocean was observed by [*Gregg et al.*, 2003] to reduce strongly for $|\varphi_c| \leq \sim 2–3°$ with respect to mid-latitudes, despite abundant internal waves. The authors argued that their observations more or less confirmed a model suggesting a latitudinal dependence for internal wave mixing by a factor $L(f, N) = f \cosh^{-1}(N/f) \approx f$. This is debatable however, as L is a relatively smooth change towards the equator, without considering the latitudinal dependence of specific internal wave generation [*Hibiya and Nagasawa*, 2004]. Such smooth change is also predicted for the near-inertial spectral peak, which eventually vanishes at the equator for global solutions [*Munk*, 1980]. Thus, theoretically one does not expect any sudden variations in the properties of near-inertial motions when approaching the equator, assuming that N remains unchanged.

[6] As will be demonstrated here, in practice near-inertial and general internal wave polarization suddenly break down near the equator, thereby possibly affecting local shear and thus mixing, also at great depths >1000 m.

2. Data

[7] Near-equatorial current meter records are evaluated as available from the database of OSU's buoygroup that contains thousands of records. Record selection followed the criteria: near the equator; yearlong records (to resolve near-inertial motions that have periods of O(100 days); in deep water away from topography (to avoid mixing induced by other dynamical processes); well below the permanent pycnocline (to study slow variations in relatively weak N); from an array of simultaneous measurements at different locations. Although not all criteria could be strictly enforced due to the limited amount of suitable data, 12 records are studied of at least 330 days length from ~2000 m depth in >4000 m water depth (Table 1). The data are from mechanical current meters that are sampled once per 15 min or slower. The bulk of the data was only available as low-pass filtered at 40 h cut-off, which does not affect the present analysis. These data are from the Indian Ocean, from an array south of Sri Lanka south of 6°N along 80°E. From the same transect 41 profiles of conductivity, temperature and depth (CTD) are available in the WOCE database. These profiles provide detailed information on density variations in the vertical. They are virtually the only near-equatorial CTD profiles in the database ranging from the surface down to depths >4000 m and away from topography.

3. Methods

[8] The observed *horizontal* currents are used to perform two types of spectral analysis. Kinetic energy spectra,

$$P_{KE}(\sigma) = P_{-}(\sigma) + P_{+}(\sigma), \tag{2}$$

Table 1. Moored Near-Equatorial Current Meter Data From the Atlantic Ocean (A), Indian Ocean (I) and Pacific Ocean (P)[a]

Code	Position NS	Position EW	H, m	z, m	Length/Period, days/years
P	09°55.1′S	109°0.0′W	5235	2890	520/1992-4
A	00°56.0′S	13°30.0′W	4150	2000	710/1992-4
I	00°42.9′S	80°30.6′E	4609	1965	410/1993-4
I	00°00.8′N	80°30.0′E	4666	1976	410/1993-4
I	00°45.2′N	80°29.4′E	4598	1967	410/1993-4
A	01°11.2′N	44°02.4′W	4110	2985	400/1992-3
A	01°33.0′N	44°00.6′W	4108	2020	330/1990-1
I	02°10.4′N	80°30.0′E	4490	2002	410/1993-4
I	03°35.0′N	80°31.2′E	4382	1957	410/1993-4
I	04°59.3′N	80°33.0′E	4329	1970	380/1993-4
I	07°50.3′N	53°54.4′E	5120	2000	560/1995-6
I	09°40.1′N	53°56.4′E	4609	2067	560/1995-6

[a]H denotes water depth; z denotes instrument depth.

the sum of the rotary current component spectra $P_{-}(\sigma)$, the clockwise spectrum, and $P_{+}(\sigma)$, the anti-clockwise spectrum [*Gonella*, 1972]. A measure for the current ellipse surface and polarization is the 'rotary coefficient',

$$C_R(\sigma) = (P_{-}(\sigma) - P_{+}(\sigma))/P_{KE}(\sigma), \tag{3}$$

C_R is equal to zero for purely rectilinear motion and equal to one for purely circular motion, its sign indicating the direction in which the ellipse is traversed. Under symmetric forcing (equal for both rotary components) and neglecting frictional stresses its magnitude is modelled [*Gonella*, 1972],

$$|C_R(\sigma)| = \frac{2\sigma f}{\sigma^2 + f^2}. \tag{4}$$

At frequencies within the internal wave band (4) describes free gravity waves, for $f \ll N$.

[9] The CTD data are used to compute 'large-scale' background stratification, over vertical distances of typically 40 m (N_{40}), and 'short-scale' stratification over 2 m vertically (N_2). The standard deviation of N-variations over a certain vertical distance of several 100's of meters is a measure of 'steppiness' in a vertical density profile. Large steppiness may be interpreted as large internal wave activity and also as a lack of large-scale smoothing due to decreased large-scale internal wave shear stress [*Turner*, 1979] and, thus, as a reciprocal measure for mixing.

4. Observations

[10] At deep-ocean mid-depth near $|\varphi| = 10°$ a near-inertial peak is apparent in the kinetic energy spectra (Figure 1). This peak disappears in the spectral environment when the equator is approached. However, the energy level at local f does not decrease, but the energy at surrounding frequencies increases. As a result, total kinetic energy increases. The f-peak looses its asymmetry in frequency between the examples shown from latitudes $|\varphi| = 10°$ and $|\varphi| = 5°$ before disappearing between $|\varphi| = 5°$ and $\varphi \approx 0°$ (Figure 1a), but a more dramatic change is seen in ellipse polarization (Figures 1b–1d). Following (4), horizontal near-inertial motions commonly describe a near-circular path $|C_R(f)| \approx 1$. This is observed at $|\varphi| = 5°$ and 10°. At both latitudes also a gradual decrease in polarization is

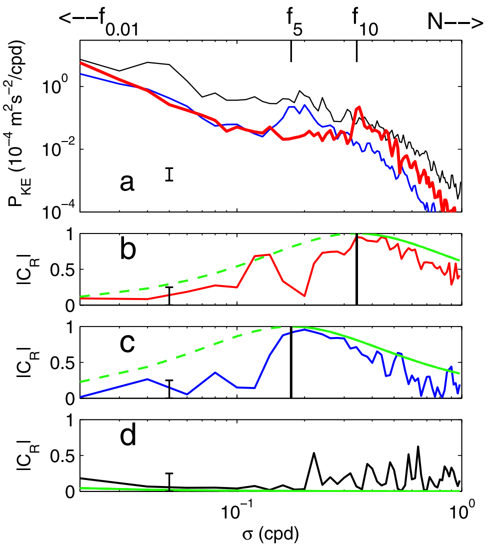

Figure 1. a. Frequency (in cycles per day; cpd) spectra of kinetic energy observed at about 2000 m depth from 3 different latitudes (Table 1) $\varphi \approx 0°$ (black), 5°N (blue), 10°N (red), with the inertial frequencies f_5 and f_{10} given for the latter two, while $f_{0.01}$ and buoyancy frequency N are outside the window. b. Rotary coefficient for $\varphi \approx 10°$N, with theory (4) in green (solid for $\sigma > f$) and the vertical bar at local f. c. As b., but for $\varphi \approx 5°$N. d. As b., but for $\varphi \approx 0°$.

observed for $\sigma > f$, typical for internal gravity waves. At sub-inertial frequencies occasionally a statistically significant peak is observed, e.g. at $\sigma \approx 0.5$ cpd in Figure 1b. Such peaks are not attributable to internal gravity waves. Although the nature of these motions is presently unclear when they are outside non-linear inertial-tidal interaction frequencies, their polarization suggests weakly asymmetrically forced motions, or, perhaps evidence of gyroscopic waves. At the equator, polarization cannot be significantly distinguished from $|C_R| = 0$, for all frequencies except at several relatively high frequencies (Figure 1d). This implies near-rectilinear motions at nearly all internal wave band frequencies, which is a most dramatic change for near-inertial motions.

[11] Another dramatic change between $|\varphi| = 10°$ and $\varphi \approx 0°$ is observed in examples of vertical density profiles, which show a high degree of steppiness at the equator and which are smooth some distance away from it (Figure 2). This difference is observed at all depths between ~100 m (the permanent pycnocline) and the bottom (4000–5000 m), independent of the large-scale stratification and independent of the vertical scale Δz for computing N, as long as $\Delta z \leq \sim 100$ m.

[12] Around 2000 m depth, a north-south transect using all 12 current meter records and 41 CTD profiles shows that the above observations yield a sharp transition in steppiness at $|\varphi| = 1.5 \pm 0.5°$ (Figure 3). The sharp transitions are more than twice as large as any of the other variations between neighboring stations along the transect. Equally sharp, and at the same transition latitude, one observes the above change in $|C_R(f)|$. This coincides with a sharp transition in total kinetic energy.

5. Discussion

[13] The observed association between near-inertial polarization and small-scale stratification implies a dramatic change in internal wave mixing properties in a very narrow latitudinal range around the equator. As was observed in the North Sea [*van Haren et al.*, 1999], large-scale near-circular near-inertial motions induce slowly varying large-scale shear magnitude, which associates with slowly varying background stratification so that the water column is marginally stable. Part of this balance is the occasional breaking of high-frequency internal gravity waves, thereby causing diapycnal mixing at the depth where the largest $|\mathbf{S}|$ and N are found. This balance remains until such near-inertial shear is lost (e.g. due to a change in atmospheric disturbances with time) and very thin stratified layers occur

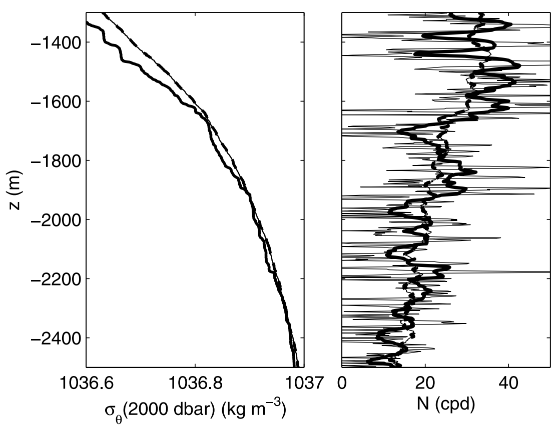

Figure 2. a. Examples of detail of density anomaly ($\sigma_\theta = \rho - 1000$ kg m^{-3}) profile referenced to ~2000 m depth observed at $\varphi \approx 10°$S (dashed) and $\varphi \approx 0°$ (heavy solid). b. Small-scale stratification N_2 (thin solid) and N_{40} (heavy solid) for $\varphi \approx 0°$. N_{40} (heavy dashed) for $\varphi \approx 10°$S shows the same large-scale mean values as near the equator, but much smaller variability.

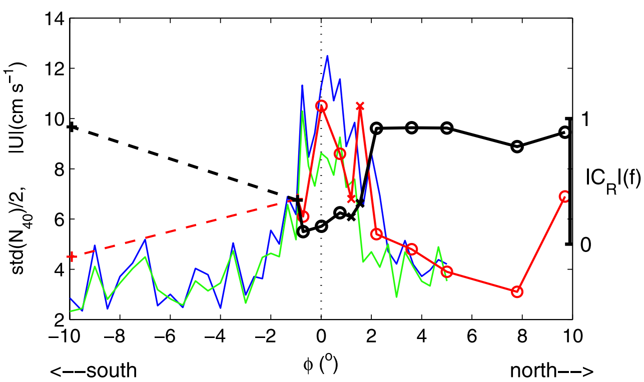

Figure 3. Transect of near-inertial rotary coefficient $|C_R(f)|$ (black; scale to the right; circles for Indian Ocean data; x for Atlantic Ocean and + for Pacific Ocean) and total kinetic energy (red) plotted together with the measure for steppiness $\{\Sigma(N_{40})\}^{0.5}$ in stratification N_{40} computed over intervals [1700–2100] m (blue) and [1900–2300] m (green) from 41 CTD stations along 80°E in the Indian Ocean.

supporting high-frequency $\sigma > N$ waves that are moved about by large $\sigma \approx N \gg f$ internal waves [*van Haren and Howarth*, 2004]. Such super-N waves could not exist when shear was still large ($|\mathbf{S}(f)| \sim N$).

[14] Such scale changes in near-inertial shear and stratification seem to govern most of the deep-ocean as well, although variations occur spatially rather than temporally. Thus, it is hypothesized that the sharp collapse of large-scale near-inertial polarization from circular to rectilinear at $|\varphi| \approx 1.5°$ causes a sharp change in shear magnitude, from slowly to fast varying with time. This can imply less internal wave breaking resulting in reduced mixing and more high-frequency kinetic energy for $|\varphi| \leq 1.5°$, compared to latitudes $|\varphi| > 1.5°$, as observed. Until recently, a spatial transition in near-inertial polarization was only observed in the Western Mediterranean Sea, across depths where $N \sim 2.5f$ changed to $N = 0$ [*van Haren and Millot*, 2004]. This was interpreted as evidence of a transition between internal gravity waves and gyroscopic waves, for which $\tilde{f}$ is important.

[15] Near the equator $\tilde{f}$ is important too for the dynamics [*Veronis*, 1963a, 1963b], and north-south propagating gyroscopic waves show horizontal motions aligned East-West, as more or less observed in the present, rather irregular near-equatorial data. However, it is not directly obvious that this change in dynamics implies the observed sharp transitions (Figure 3), which are much sharper than existing models predict. For $|\varphi_c| = 1.5°$ we find $w/u \approx 0.025$, w larger than for large-scale flows, but less than in free convection areas and probably typical for internal waves. The present observations demonstrate that future models of internal waves and mixing should incorporate the earth's rotation, in non-traditional form, so that the importance of inertial motions and shear are incorporated, inclusive their impact on other internal wave frequencies.

[16] **Acknowledgments.** The moored current meter data were obtained by PI's of several institutes, and are archived by Oregon State University (OSU)'s buoygroup, Corvallis, Oregon, USA. The CTD data were obtained from the CCHDO (former WHPO) archive, ensuring the WOCE data quality standard.

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