GYROSCOPIC WAVES CONNECT SURFACE AND DEEP WATERS IN THE WESTERN MEDITERRANEAN SEA

Hans van Haren *, [1]

In the Mediterranean Sea, the tidal currents are very weak, and currents are dominated by waves having frequencies at or slightly above the local inertial frequency f (= 2Ωsinφ, φ denoting the latitude and Ω the Earth rotation rate). Inertial currents are mostly generated by the wind, near the sea surface, from which they propagate into the ocean's interior as internal gravity waves, supported by density stratification caused by differences in salinity and temperature. However, our analysis shows anomalous inertial motions also in deep homogeneous water layers, where internal gravity waves cannot exist because there are no density differences within these layers. Therefore, we propose that these vertical motions across several homogeneous water layers between the surface and the deep ocean are caused by gyroscopic waves, which thus provide the means for the wind to perform mixing in the deep sea.

Motions that vary rapidly in the vertical, such as internal gravity waves, are presently seen as important for maintaining the deep, large-scale ocean circulation. This is because the necessary downward transport of heat via turbulent mixing might be caused by the breaking of such waves. They have frequencies σ, situated in between the local inertial frequency f and the stability frequency N that measures the rate of density decrease upward from the bottom: $f < \sigma < N$. In the vertical plane they propagate into directions that vary between purely vertical ($\sigma = N$) and purely horizontal (f), so that with conventional current meters, that measure only the horizontal currents, N-waves are in the horizontal plane observed as rectilinear, to-and-fro motions, whilst f-waves describe circular motions (see sketch in Fig. 1).

Any variations of such circular inertial motions in the vertical (current shear) also describe circular paths. Therefore the vertical current shear magnitude is a function that varies 'slowly with time', over time scales much larger than the inertial period (2π/f). This shear is important for the deformation of small-scale ocean motions (high-

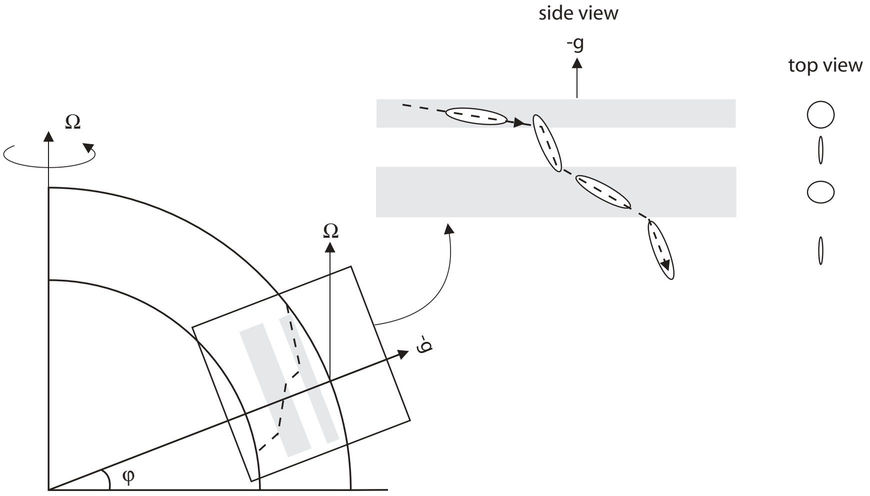

Fig. 1 Sketch of geometry of rotating earth and Mediterranean Sea, consisting of a sequence of stratified (grey bands) and homogeneous (white bands) layers. The latter support internal gravity and gyroscopic waves respectively. Near-inertial gravity waves have nearly horizontal currents associated with them, 'horizontal' being defined as perpendicular to the local, radially-inward direction of gravity. The gyroscopic waves orient themselves with respect to the direction of the Earth rotation axis, and hence are locally perceived as possibly having a strong vertical propagation component as well as currents whose projection on the horizontal plane takes the form of a rectilinear (to-and-fro) current.

*Corresponding author: hansvh@nioz.nl

[1] En collaboration avec Claude Millot, LOB-COM-CNRS, c/o Ifremer, La Seyne-sur-mer, France

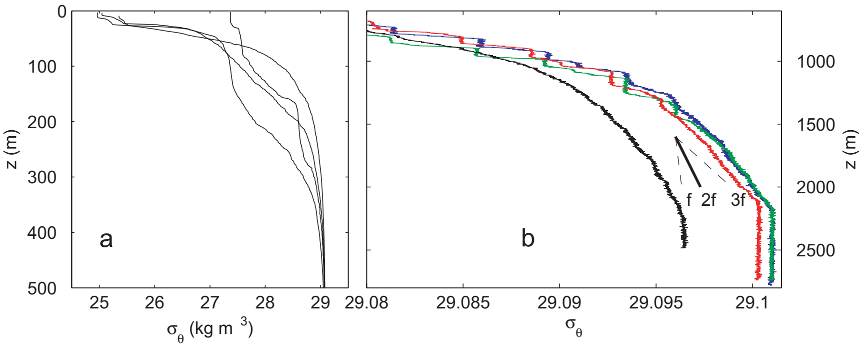

Fig. 2. Examples of potential density-depth profiles obtained using CTD in the Western Mediterranean Sea. *a*. 0-500 m with potential density referenced to the surface. *b*. The lower 2200 m of the profiles. The short sloping lines indicate density stratification yielding N = f, 3f (dashed lines) and N = 2f (heavy solid line).

frequency internal waves) to the point of breaking, thereby inducing deep-ocean turbulent mixing. In the ocean, the internal wave shear is predominantly found at inertial and tidal frequencies, albeit each has a different character. Within the physical oceanographic community, it is debated what motions of the two dominant frequencies are most important for small-scale internal wave generation. Internal waves of tidal frequencies are generated in localized areas via surface-tide interaction with topography, mostly near the shelf break (where the continental shelf plunges into the abyss). In contrast, inertial motions are generated anywhere in the ocean, but mostly near the surface via interaction with the atmosphere. One of the key questions is how energy from near-inertial motions is transferred into the deep ocean. To study the potential importance of inertial motions on deep-ocean mixing separately from tidal currents, instruments have been moored in the Western Mediterranean Sea, one of the few areas where tides are weak enough to be neglected.

However, it is not as simple as it looks: although the Western Mediterranean Sea is ideal for such study because of its depth (~3000 m), it is also one of the few ocean sites where deep-water formation occurs in winter. As free turbulent convection, responsible for the formation of this deep-water, is found at intermediate depths, a key problem is induced: the homogeneous (N = 0) layers formed by these processes cannot support internal gravity waves, so that near-inertial internal gravity waves can principally not exist given the observed density profiles (Fig. 2).

Nevertheless, (horizontal) motions near f are found dominant at all observational depths (100, 1000, 1800 and 2700 m), and between 1000-2700 m depth their amplitude barely varies (Fig. 3). There is a difference however in that the near-inertial motions at 100 and 1800 m (where N > f) are more or less circular in the horizontal plane, as expected for internal gravity waves, while, in contrast, the near-inertial motions at 1000 and 2700 m (where N = 0) are rectilinear,

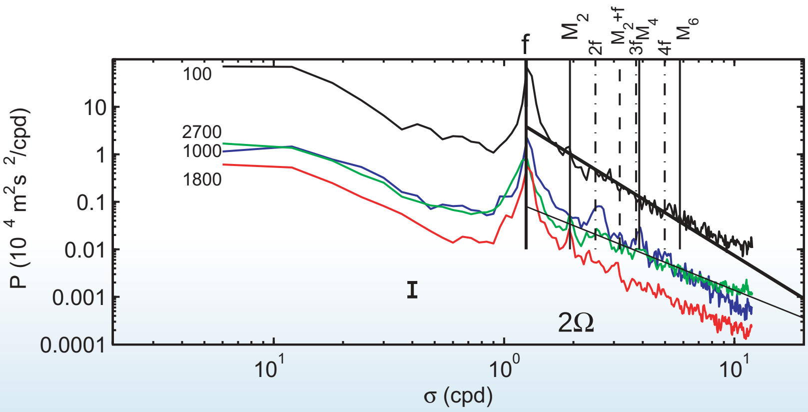

Fig. 3. Kinetic energy spectra (P) derived from 4 months of current meter observations at 100 m (black), 1000 m (blue), 1800 m (red) and 2700 m (green). Vertical lines denote lunar tidal frequencies M_n and inertial frequency f. Thcik and thin SLOPING solid lines denote slopes of σ^{-3} and σ^{-2} respectively.

which has not been observed before (Fig. 4). Our interpretation is that *these motions are the horizontal projection of motions that were propagating nearly vertically*. These represent a kind of waves known as gyroscopic waves, which are restored by the Coriolis force due to the rotation of the Earth. These waves are characterized by strong vertical currents and by a shear magnitude that varies rapidly. Apparently, they constitute at f a smooth transition between internal gravity waves in the stratified layers and gyroscopic waves in the homogeneous layers. It is suggested that these gyroscopic waves are the only means for internal waves to propagate to the deep ocean, crossing layers of N = 0, and thus they dominate deep-ocean mixing.

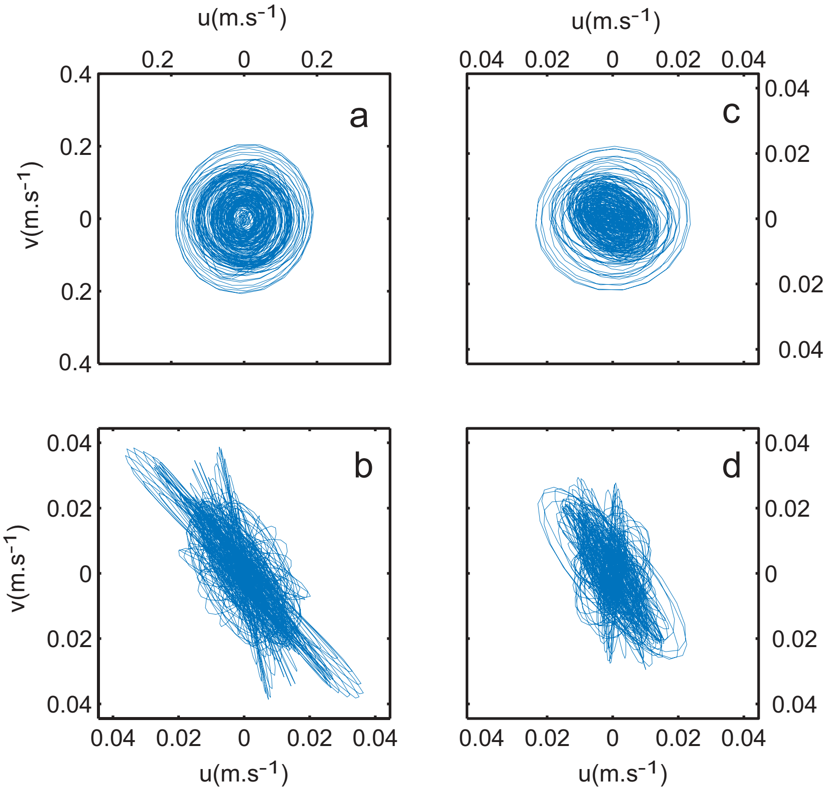

Fig. 4. Horizontal current records of near-inertial, band-pass filtered data [0.90f, 1.10f] at depths: *a*. 100 m (Note different scale from the others), *b*. 1000 m, *c*. 1800 m, *d*. 2700 m.