A NEW MECHANISM FOR DEEP MIXING: INTERNAL WAVES EMITTED BY THE EDDYING CIRCULATION IN THE DEEP OCEAN

Jin-Song von Storch*
* *Max-Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany*

Summary Even though spontaneous imbalance has been extensively studied, mainly for idealized flows and with emphasis on atmospheric inertia-gravity waves, its existence and relevance in an eddying ocean under a realistic setting are unknown. By using an ocean general circulation model with a horizontal resolution of 1/10°, we show that spontaneous imbalance exists in the deep ocean. Consequently, inertia-gravity waves are continuously emitted by eddying flows. Under fairly general conditions, the subsequent refraction of these waves by the flows lead to wave capture, characterized by exponential growth of wavenumber and wave amplitude, leading finally to breaking of large-amplitude waves.

MODELING STRATEGY

We studied the role of spontaneous imbalance in an eddying ocean by performing a simulation with an OGCM developed within the German consortium project STORM. The model has a 0.1° horizontal resolution and 80 vertical layers. The simulation is suitable for studying spontaneous imbalance not only because of the high resolution. There are three other aspects that make the simulation distinct. First, it begins in 2005 from a simulation over nearly six decades driven by 6 hourly surface forcing derived from the NCAR/NCEP reanalysis following a 25-year spin up (see SI, also von Storch et al. 2011). Thus, the whole eddy field, including the part in the deep ocean, is essentially spun up and in a quasi-stationary state, ensuring a realistic representation of the vortical currents in the ocean. Second, tidal forcing is excluded from the STORM OGCM so that all tidally related inertia-gravity waves are absent in our simulation. Third, we replaced the 6-hourly wind forcing by its 5-day-running averages starting on 31st of May 2005 of the just described NCEP run. The inertial periods vary from 0.5 to 5 days in an area extending from poles equatorward to 5.7° latitudes, covering about 93% of the entire ocean surface. By using the 5-day running averaged wind forcing, the direct wind generation of inertial waves over this near-global area is strongly suppressed. After one month, the flows have essentially adjusted the smoothed wind forcing. We obtained a simulation of an oceanic state with realistic unsteady eddying currents, but without tidally induced and directly wind generated inertia-gravity waves. We use hourly 3-dimensional output for July 2005 of this simulation for the analysis presented below.

INTERNAL WAVES EMITTED BY EDDYING CURRENTS

Despite the fact that two important generation mechanisms of inertia-gravity waves are either completely eliminated or shut down to a large extent, our simulation produces strong variability at the frequency range of inertia-gravity waves, not only in the surface layers but also in the deep ocean. Fig.1 shows the square root of velocity variance at frequencies greater than inertial frequency f at about 1000 m depth. Inside the tropical oceans, where inertial periods become longer than a couple of weeks, it is difficult to separate inertia-gravity waves from other low-frequency (lower than one cycle per day) variability, such as those related to tropical instability waves, by using spectral analysis only. Outside the tropical oceans, where the variability of inertia-gravity waves is well separated from that of meso-scale eddies, strong variabilities at frequencies greater than f are found in the Southern Ocean and in regions of Gulf Stream and Kuroshio, and other boundary currents. With the separation we mean the distinction between the dominant time scales of meso-scale eddies that are of the order of weeks to months and those of inertia-gravity waves that are of the order of inertial periods or shorter, i.e. shorter than one day in the extra-tropical regions. The latter is not greatly distorted by wave capture (Bühler and McIntyre, 2005) and Doubler shift $\mathbf{U} \cdot \mathbf{k}$ so that the frequency range $\omega \geq f$ roughly covers frequency ω of the inertia-gravity waves generated by spontaneous imbalance. In other words, given the special setting of the simulation, the extratropical variability in Fig.1 represents an order-of-magnitude estimate of inertia-gravity waves emitted by the eddying currents. The magnitude of these waves reaches about one to two cm/s at 1000 m depth.

To further quantify these waves, we consider their spatial structures. Snap shots of high-pass filtered pressure anomalies show that there characteristics related to wave capture are also found for waves in the deep oceans in our simulation. The wavelengths are short and of the order of 20 to 50 km. The wavecrests are, by and large, perpendicular to the stream lines (red lines). The wave packets propagate along stream lines and behave like passive tracer advected by the flows, a features that becomes evident when comparing wavecrests with those 5 hours earlier. When putting the snap shots into a move, we see wavecrests traveling along flows with large velocities, as if they are passive tracer advected by the flows. Wave structures similar to those just described can be found whenever wherever flows with large velocities are found. We hence conclude that the waves in our simulation are consistent with waves emitted by unsteady vortical flows that undergo subsequent wave capture, during which wavenumber and wave amplitude grow exponentially and intrinsic group velocity decrease exponentially, similar to the waves described by O'Suillivan and Dunkerton (1995).

The general susceptibility to wave capture is further quantified by the square of the exponential stretching rate D. Bühler and MctIntyre (2005) showed that for strongly stratified and layerwise-two-dimensional and layerwise-non-divergent

[a)] Corresponding author. E-mail: jin-song.von.storch@zmaw.de

flows $\mathbf{U} = (U, V, 0)$, D is given by

$$D = U_x^2 + \left(\frac{V_x + U_y}{2}\right)^2 - \left(\frac{V_x - U_y}{2}\right)^2,$$

where suffixes denote partial derivatives. A non-zero curl acts always to diminish the stretching rate. If $D > 0$, there is a wavenumber that grows exponentially in time with stretching rate $\sqrt{D}$. On average, large positive values dominate negative ones in the Southern Ocean, whereas small values of D, often having both positive and negative signs, are found in the remaining regions. By and large, the Southern Ocean, where large variabilities at frequencies higher than f are found (Fig.1), represents a region where inertia-gravity waves are susceptible to wave capture on average. In the regions of Gulf Stream and Kuroshio, D is mostly positive, indicating susceptibility to wave capture. The amplitudes of D are however much smaller than those in the Southern Ocean.

CONCLUSIONS

We are able to show for the first time that the eddying currents in the deep ocean are capable of emitted internal gravity waves. These waves are then refracted by the flows and undergo wave capture, characterized by exponentially decaying intrinsic group velocity and wavelength.

References

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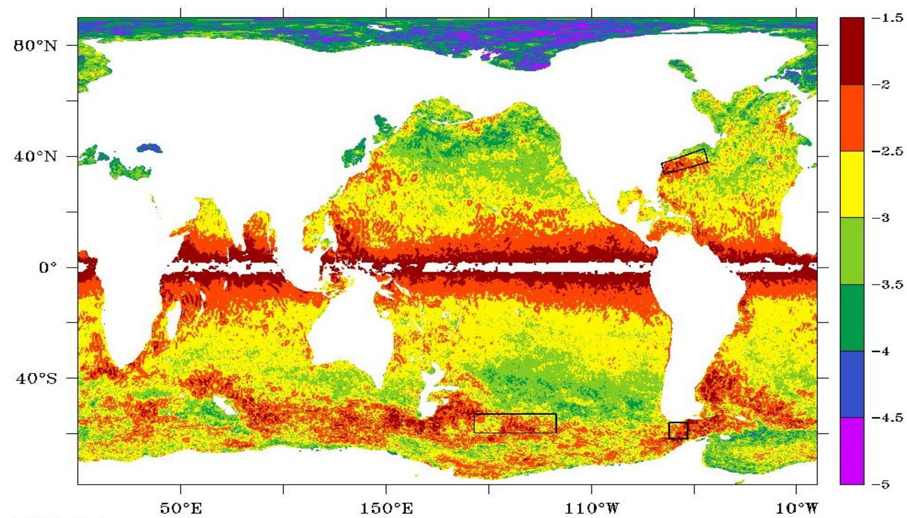

Figure 1. Square root of the sum of variances of zonal and meridional velocities at frequencies larger than the inertial frequency f at 1008 m. Units are m/s. Logarithms of the square root values are shown. Values between -2.5 and -2.0 correspond velocity values between 0.3 and 1 cm/s. Black boxes indicated areas considered in Fig.2.