Stratification Anomalies in the Ocean Interior

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Abstract

Internal waves and vortical mode are ubiquitous in the ocean, providing a conduit for energy transfer from tides and wind-driven circulation to fine- and micro-scale turbulence associated with internal-wave breaking and dissipation. Numerical simulations of a Garrett-Munk internal-wave field are used to study the interactions between internal waves and vortical mode, and the generation of turbulent mixing events and semi-permanent finestructure (vortical mode). Regions of reduced stratification are found to occupy between ~5% and 25% of the model domain, depending on the strength of the anomalies. Decomposition of 3-dimensional model fields into linear internal-wave and vortical-mode components shows that both influence stratification, with ~88% of the anomalies due to linear internal waves and ~40% due to vortical mode, the overlap in percentiles representing regions that are a combination of the two. The time evolution of anomalies is examined, from the initial generation to eventual dissipation. Results further describe the preconditions of these regions, including their relation to a subcritical Richardson number and overturning / mixing events as quantified via Thorpe scales and turbulent dissipation rate.

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Abstract

Internal waves and vortical mode provide a conduit for energy transfer from tides and wind-driven motions to fine- and micro-scale turbulence, internal-wave breaking and dissipation. Numerical simulations of a GM internal-wave field are used to study interactions between internal waves and vortical mode, and the generation of turbulent mixing events. Decomposition of 3D model fields into internal-wave and vortical-mode shows that both contribute to reduced stratification anomalies. Time evolution of anomalies show their relation to a subcritical Richardson # and overturning / mixing events as quantified via Thorpe scales and turbulent dissipation rate.

Methods

A 3-D pseudo-spectral model (Winters & de la Fuente, 2012) is used to solve the Boussinesq equations.

- Horizontally periodic, vertically bounded domain: ($L_x \approx$ 43km, $L_y \approx$ 5.4km, $L_z \approx$ 500m)
- Grid resolution: ($\Delta x = \Delta y \approx$ 84m, $\Delta z \approx$ 2m)

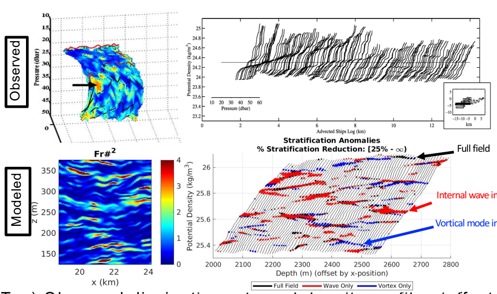
$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u} + \nabla p + f\hat{e}_3\times\vec{u} - b\hat{e}_3 = \vec{F}(x,t) + \nu_2\nabla^2\vec{u} + \nu_6\nabla^6\vec{u}$$

$$\frac{\partial b}{\partial t} + (\vec{u}\cdot\nabla)b + N^2 w = \kappa_2\nabla^2 b + \kappa_6\nabla^6 b$$

$$\nabla\cdot\vec{u} = 0 \qquad b = -g\frac{\rho'}{\rho_0}$$

The model was initialized with a linear GM wave field adjusted to allow for limited vertical and horizontal domain, and run for 24 hours to allow nonlinear adjustment. Following initial dissipation of high wave numbers, a near steady state was obtained.

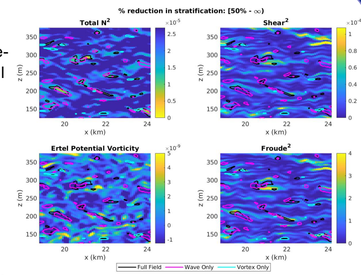
The linear *f*-plane equations have 3 solutions, two wave solutions, $\omega_{+/-}$, and a vortical mode, ω_0. The ω_0 solution represents vortical mode in the low Ro limit where vertical shear is associated with horizontal density gradients through the thermal wind relation. Using a linear decomposition (e.g., Bartello, 1995; Early et al., 2020), the internal wave and vortical mode components are separated to study their interactions. The decomposition projects the numerical data onto relevant linear solutions giving two inertia-gravity wave solutions and a geostrophic solution.

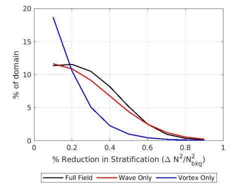


(Top) Observed dissipation rate and density profiles (offset by dist. along ship track), from Sundermeyer et al., 2005; and (bottom) modeled (Froude #)^2 and density profiles showing patchiness of high shear and low stratification.

Results

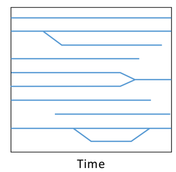
We analyze statistics of wave- and vortex-associated, or "full field" reduced stratification regions in both space and time. Reduced stratification regions were identified in the domain and occupy between ~5% and 20% of the model domain, depending on the strength of the anomalies (right).



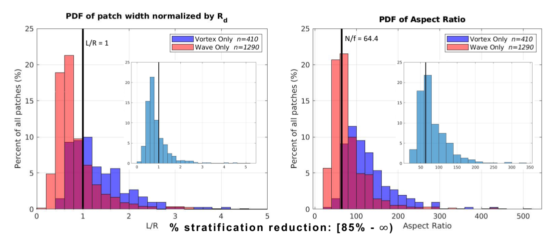


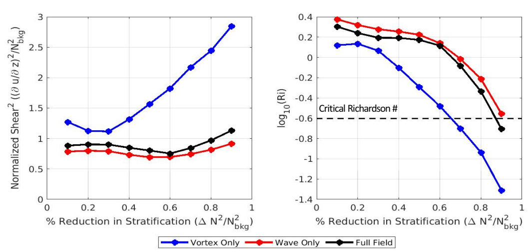
For weakly stratified regions, more of the domain is occupied by vortex-associated anomalies than wave-associated and full field. As stratification reduction increases, less of the domain is occupied by anomalies (left). Mixing occurs more completely in less than 1% of the domain.

Reduced stratification regions may form at any time in a model run, persist in time, split into multiple smaller regions, merge together, or disappear. The different scenarios are shown schematically to the right. The complete lifecycle is can be tracked in space and time for individual regions.

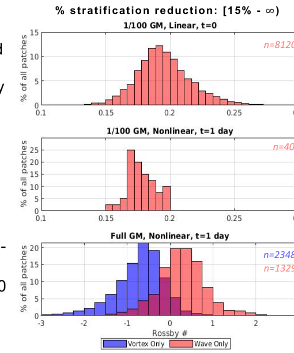


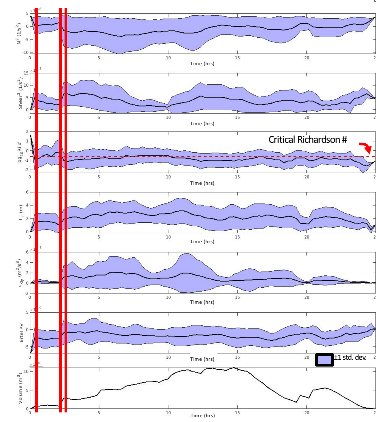
Vortex-only patches typically have horizontal scales of order the patch Rossby radius ($R_d = \sqrt{(\Delta N^2)}L_z/f$), while wave-induced patches have scales $<R_d$. Vortical mode regions with >85% reduction in stratification have horizontal width $>R_d$ and aspect ratio $L_h/L_z > N/f$. Internal wave regions with >85% reduction in stratification have horizontal widths $<R_d$, and aspect ratio slightly $>N/f$. Within regions of reduced stratification, shear increases as stratification decreases, leading to decreased Richardson # (Ri) (below).





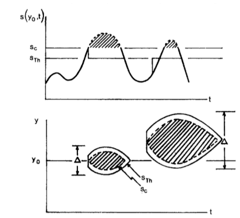
Runs using 1/100 GM energy level were analyzed at t=0, and after dissipative and nonlinear adjustment. Small-scale energy dissipated rapidly in both nonlinear and linear runs, leaving few regions of reduced stratification, and with neither generating significant vortical mode, confirming linear dynamics. At a full GM level, both internal-wave and vortical-mode anomalies yield order of magnitude larger Ro than 1/100 GM runs, consistent with nonlinear dynamics.





Tracking of individual reduced stratification regions (left) reveals regions of reduced stratification coinciding with increased shear and reduced Ri#, the latter a pre-condition for turbulent mixing. Variations in these parameters are also found to coincide with overturning events as indicated by Thorpe scale, L_T, increased dissipation rate, ϵ, and changes in Ertel PV.

The above results are qualitatively consistent with the ideas of Garrett and Munk (1972) for Ocean Mixing by Breaking Internal Waves. However, further investigation is needed to fully explain the observed parameter variations.



Conclusions

Reduced stratification regions were tracked in space and time showing the relationship between internal waves, vortical mode and turbulent mixing in the ocean. Further research is needed to assess the spatial and temporal characteristics of reduced stratification anomalies in a Lagrangian reference frame, and their impact on small-scale mixing. Examination of the preconditions and fate of these regions will give a more complete understanding of the entire lifecycle of these anomalies.

Acknowledgements

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