response is not related to the value of Ri_g at which mixing is suppressed but rather its rate, some of the modified and alternate second-order closure formulations, which change how abruptly turbulence decays under the influence of stratifying effects, may produce solutions in the two-dimensional upwelling setting more akin to KPP.

[82] The one-dimensional wind deepening study reveals that which scheme mixes more is dependent on both the wind stress magnitude and intensity of stratification at the base of the boundary layer. When boundary layer deepening is halted by the development of intense stratification at the pycnocline, entrainment is sustained with the M-Y scheme by downward diffusion of turbulent kinetic energy. No analogous process is represented in KPP. It is unclear in this case which behavior is more appropriate as the self transport of turbulence in such an environment is not yet well understood. While KPP contains no formulation for this process, shortcomings of the M-Y formulation for this term have also been suggested [*Stacey et al.*, 1999].

[83] The two-dimensional coastal upwelling experiments reveal that for moderate to low stratification the choice of parameterization had a significant impact on the resulting circulation close to shore, while at higher stratification, vertical mixing plays a weaker role producing nearly identical solutions with the two schemes. It is important to note that while this study emphasizes cases in which the forcing, initialization and physical constraints lead to significant differences in the performance of the two schemes, in many cases the differences produced may be negligible as their basic response to shear and stratification are qualitatively quite similar.

[84] It would be useful if the differences found between the performance with the two parameterizations suggested one to be superior to the other. Indeed, in some aspects the additional physics included in the M-Y scheme, such as diffusion of TKE or buildup of TKE in a vertically confined boundary layer, seem intuitively more correct. However, a conclusive statement cannot be made without comparisons with real data and/or high-resolution numerical studies that resolve the fine-scale structure of these processes. Hopefully the points of difference noted in this study can help direct such future efforts.

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References

Austin, J., and S. Lentz (2002), Inner shelf response to wind driven upwelling and downwelling, *J. Phys. Oceanogr.*, *32*, 2171–2193.

Blumberg, A. F., and G. L. Mellor (1987), A description of a three dimensional ocean circulation model, in *Three Dimensional Coastal Ocean Models*, *Coastal Estuarine Sci.*, vol. 4, edited by N. Heaps, pp. 1–16, AGU, Washington, D. C.

Blumberg, A. F., B. G. Galperin, and D. J. O'Connor (1992), Modeling vertical structure of open channel flow, *J. Hydraul. Eng.*, *118*, 1119–1134.

Burchard, H., and H. Baumert (1995), On the performance of a mixed-layer model based on the $k-\epsilon$ turbulence closure, *J. Geophys. Res.*, *100*, 8523–8540.

Burchard, H., and K. Bolding (2001), Comparative analysis of four second-moment turbulence closure models for the oceanic mixed layer, *J. Phys. Oceanogr.*, *31*, 1943–1968.

Canuto, V. M., A. Howard, Y. Cheng, and M. S. Dubovikov (2001), Ocean turbulence. part i: One point closure model—Momentum and heat vertical diffusivities, *J. Phys. Oceanogr.*, *31*, 1413–1426.

Galperin, B., L. Kantha, S. Hassid, and A. Rosati (1988), A quasi-equilibrium turbulent energy model for geophysical flows, *J. Atmos. Sci.*, *45*, 55–62.

Haidvogel, D. B., H. Arango, K. Hedstrom, A. Beckmann, and P. Malanotte-Rizzoli (2000), Model evaluation experiments in the North Atlantic basin: Simulations in nonlinear terrain-following coordinates, *Dyn. Atmos. Oceans*, *32*, 239–281.

Kantha, L. H., and C. A. Clayson (1994), An improved mixed layer model for geopysical applications, *J. Geophys. Res.*, *99*, 25,235–25,266.

Kim, J., and L. Mahrt (1992), Simple formulation of turbulent mixing in a stable free atmosphere and nocturnal boundar layer, *Tellus, Ser. A*, *44*, 381–394.

Kurzeja, R. J., S. Berman, and A. H. Weber (1991), A climatological study of the nocturnal planetary boundary layer, *Boundary Layer Meteorol.*, *54*, 105–128.

Large, W. G., and P. R. Gent (1999), Validation of vertical mixing in an equatorial ocean model using large eddy simulations with observations, *J. Phys. Oceanogr.*, *29*, 449–464.

Large, W. G., J. C. McWilliams, and S. C. Doney (1994), Oceanic verical mixing: A review and a model with a nonlocal boundary layer parameterization, *Rev. Geophys.*, *32*, 363–403.

Ledwell, J. R., A. J. Watson, and C. S. Law (1993), Evidence of slow mixing across the pycnocline from an open-ocean tracer-release experiment, *Nature*, *364*, 701–703.

Mellor, G. L. (2001), One-dimensional, ocean surface layer modeling: A problem and a solution, *J. Phys.*, *31*, 790–809.

Mellor, G. L., and T. Yamada (1974), A hierarchy of turbulent closure models for planetary boundary layers, *J. Atmos. Sci.*, *31*, 1791–1806.

Mellor, G. L., and T. Yamada (1982), Development of a turbulence closure model for geophysical fluid problems, *Rev. Geophys.*, *20*, 851–875.

Pacanowski, R. G., and S. G. H. Philander (1981), Parameterization of vertical mixing in numerical models of the tropical oceans, *J. Phys. Oceanogr.*, *11*, 1443–1451.

Peters, H. M., C. Gregg, and J. M. Toole (1988), On the parameterization of equatorial turbulence, *J. Geophys. Res.*, *93*, 1199–1218.

Price, J. F., R. F. Weller, and R. Pinkel (1986), Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling and wind mixing, *J. Geophys. Res.*, *91*, 8411–8427.

Shchepetkin, A. F., and J. McWilliams (1998), Quasi-monotone advections schemes based on explicit locally adaptive dissipation, *Mon. Weather Rev.*, *126*, 1541–1580.

Stacey, M. T., S. G. Monismith, and J. R. Burau (1999), Observations of turbulence in a partially stratified estuary, *J. Phys. Oceanogr.*, *29*, 1950–1970.

Troen, I. B., and L. Mahrt (1986), A simple model for the atmospheric boundary layer: Sensitivity to evaporation, *Boundary Layer Meteorol.*, *37*, 129–148.

Wijesekera, H., J. Allen, and P. Newberger (2003), Modeling study of turbulent mixing over the continental shelf: Comparison of turbulent closure schemes, *J. Geophys. Res.*, *108*(C3), 3103, doi:10.1029/2001JC001234.

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