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Flow-dependent Ekman theory and its application to shallow water models

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Classic Ekman theory has long been a powerful framework for understanding the influence of wind forcing on the ocean and it predicts a horizontal transport in the near-surface ocean, which is inversely proportional to the Coriolis parameter, f. Spatial variability of the transport also generates vertical velocities (Ekman pumping), further providing a boundary condition for the interior flow. A modification to the classic theory (Stern 1965 and Niiler 1969) has considered the curvature of ocean currents and thus transport is instead mathematically associated with the absolute vertical vorticity, $f + \zeta$. This modification was derived assuming simple shear flows and has recently been extended to more complicated flow fields (Wenegrat and Thomas 2017). Here, we further extend earlier theories and consider different parameterizations of the Ekman layer in a two-layer shallow water model. Such models typically represent winds as a body force over the upper layer. We instead assume a sub-layer within the upper layer and this thin Ekman layer obeys pressureless dynamics that reduces the parameterizations mentioned above in the appropriate limits, but also allows for time dependence (including for example, inertial oscillations). Wind stress is applied to the Ekman component only, whereas pressure terms drive the interior flow. The latter is driven by Ekman pumping, which appears in the upper layer mass equation. Turbulent simulations are then carried out and differences between this new model and results using the more traditional representation of wind stress as a body force are discussed.