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Transient growth of gravity waves in a horizontal shear flow leading to wave breaking

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Understanding the rate at which internal gravity wave energy is dissipated in the atmosphere and the ocean presents a theoretically challenging problem. Previous studies have found that interaction of gravity waves with a horizontally inhomogeneous mean flow leads to wave breaking and efficient mixing. Breaking of wave trains occurs as wave energy is concentrated near locations where the intrinsic frequency approaches the Brunt–Vaisala frequency due to group velocity reduction. However, direct numerical simulations showed that even a single gravity wave packet collapses in the trapping plane neighborhood due to an increase in density and vertical velocity that cannot be attributed to energy accumulation or to modal instabilities, thus linking wave breaking to transient nonnormal growth. Transient growth mechanisms of gravity waves are examined in this work by studying the evolution of small perturbations in a stably stratified, horizontally sheared flow. Localized wave packet trajectories are obtained, the energy growth mechanisms occurring are identified, and the potential role of perturbation growth in wave breaking is assessed. Regarding meridional propagation, the wave packet motion is limited by turning levels where the waves are reflected and trapping levels where the waves stagnate. Regarding perturbation energy amplification, two growth mechanisms can be distinguished: growth due to advection of zonal velocity and growth due to downgradient Reynolds stresses. The three-dimensional perturbations producing optimal energy growth reveal that these two mechanisms produce large and robust amplification of zonal velocity and/or density and vertical velocity, potentially leading to shear or convective instability. For large static stability, amplification of density perturbations in conjunction with vertical orientation of the constant phase lines close to the trapping level potentially leads to a convective collapse of the wave packet near the trapping level, in agreement with existing direct numerical simulation studies. For lower static stability and for waves with phase lines oriented horizontally, growth due to advection of zonal velocity dominates, leading to rapid growth of streamwise streaks within the localized wave packet and potentially to shear instability.