Modal and nonmodal perturbations of monochromatic inertia-gravity waves: Linear and nonlinear dynamics

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Motivated by the useful new insights from optimal-perturbation theory into the onset of turbulence in other fields singular vectors (SVs) in stable and unstable inertia-gravity waves (IGWs) have been determined within the framework of the Boussinesq equations on an f plane, with parameters typical for the mesosphere. The difference between the dynamics of normal modes (NMs) and SVs is characterized by a time-invariance in the comparative role of the various possible exchange processes between a NM and the basic wave, while a SV can have a highly time-dependent structure, allowing a more efficient energy exchange over a finite time. In cases where no unstable NMs are found, SV energy growth within one Brunt-Vaisala period can cover two orders of magnitude. An analytic theory can help understanding the mechanisms behind the optimal growth. An important process turns out to be the statically enhanced roll mechanism where a perturbation extracts its energy from the shear in a background velocity transverse to its horizontal direction of propagation, aided decisively be an initial strong convective energy exchange.

The development of the IGW after having been perturbed by its most important SVs or NMs is investigated by means of direct numerical simulations. The focus is on the primary 2.5D dynamics, neglecting the effect of secondary instabilities. Somewhat in contrast to the expectations from the linear theory it is found that the structures with the strongest impact on the IGW and also the largest turbulence amplitudes are the NM (for a statically unstable IGW) or short-term SV (statically and dynamically stable IGW) propagating horizontally transversely with respect to the IGW. This seems to be consistent with observations of airglow ripples in conjunction with statically unstable IGWs. In both cases these leading structures reduce the IGW amplitude well below the static and dynamic instability thresholds. The resulting turbulent dissipation rates are within the range of available estimates from rocket soundings, even for IGWs at amplitudes low enough precluding NM instabilities. SVs thus can help explaining turbulence occurring under conditions not amenable for the classic interpretation via static and dynamic instability. Partly due to the important role of the statically enhanced roll mechanism the turbulent velocity fields are often conspicuously anisotropic. The spatial turbulence distribution is determined to a large degree by the elliptically polarized horizontal velocity field of the IGW.