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Nonnormality increases variance of gravity waves trapped in a tilted box

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We study the prototype problem of internal gravity waves in a square domain tilted with respect to the gravity vector by an angle θ. Only when $\theta = 0$ regular normal modes exist, for all other angles wave attractors and singularities dominate the flow. We show that the linear operator of the governing PDE becomes non-normal for $\theta \neq 0$ giving rise to non-modal transient growth. This growth depends on the underlying norm: for the variance norm significant growth rates can be found whereas for the energy norm, no growth is possible since, in contrast to shear flows for which the mean flow feeds the perturbations, there is no energy source. We continue by showing that the nonnormality of the system matrix is increasing with θ and reaches a maximum for $\theta = \pi/4$. Moreover, with increasing tilt angle the growth rate is increasing as can be expected from the increasing nonnormality of the matrix. Our results imply that at least the most simple wave attractors can be seen as those initial flow fields that gain most of the variance during a given time period. We conclude that in a closed confinement with walls tilted with respect to gravity, internal wave variance can be maintained by transient growth of perturbations without a direct contribution of unstable normal modes.