Geophysical Research Abstracts
Vol. 13, EGU2011-2058-1, 2011
EGU General Assembly 2011

On the impact of middle-atmosphere thermal tides on the propagation and dissipation of gravity waves

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The interaction between gravity waves and thermal tides is an important aspect of wave dynamics in the middle atmosphere. Solar thermal tides cause large variations in the background conditions, especially wind, through which gravity waves propagate. This induces a modulation of gravity-wave pseudo-momentum fluxes and thus a force back on the tidal structures. In past studies, the gravity-wave forcing on thermal tides was derived from gravity wave parameterizations with many underlying assumptions. Gravity wave parameterizations work in vertical columns in which time-dependence and horizontal inhomogeneities of the background conditions have been neglected. The main aim of the present study is to put these assumptions in question, especially concerning the propagation of gravity waves in thermal tides. We use a global ray-tracing algorithm combined with tidal data from a general circulation model. For a consistent comparison and for an evaluation of the conventional parameterization approach, we apply three different ray-tracing experiments in which successively assumptions on horizontal and temporal dependence of the background conditions have been omitted. This allows to mimic the effect of a conventional gravity wave parameterization within the ray-tracing setup. We show that, on one hand, time-dependence of the background conditions leads to a modulation of gravity-wave observed frequencies. The frequency modulation causes a modulation of the gravity-wave phase velocity so that it follows the shape of the background wind. Transient critical layers disappear. The force due to gravity waves is smeared out over larger vertical distances. The amplitude of the diurnal forcing is reduced by the effect of frequency modulation. On the other hand, horizontal inhomogeneities in the background conditions induce a refraction of the gravity waves into the jet-stream cores, thus minimizing their vertical travel time. Horizontal propagation can lead to large meridional displacements and an inter-hemispheric exchange of gravity wave energy. Local gravity-wave forces due to horizontal refraction can be attributed to three different mechanisms: horizontal divergence of the pseudo-momentum flux-tensor, turning of the horizontal wave vector and horizontal stretching or shrinking of the gravity-wave field, respectively. The first two contributions are mainly of the order of 10% to 30% whereas the last is able to reduce the dominant forcing up to 60% in the lower mesosphere. We introduce generalized equivalent Rayleigh friction coefficients which map the gravity wave force on tidal winds and accelerations. Using these, it is shown that a clear, mostly uniform tidal damping, which originates from the Lindzen-type saturation hypothesis, disappears when horizontal and time dependence of tidal background conditions are taken into account.