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Numerical Modeling of Nonlinear Interactions of Spectral Components of Acoustic-Gravity Waves in the Middle and Upper Atmosphere

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Acoustic-gravity waves (AGWs) measured at high altitudes may be generated in the troposphere and propagate upwards. A high-resolution three-dimensional numerical model was applied for simulating nonlinear AGWs propagating from the ground to the upper atmosphere. The model algorithms use finite-difference analogues of main conservation laws. This methodology lets us obtaining physically correct generalized wave solutions of the nonlinear equations. Horizontally moving sinusoidal structures of vertical velocity on the ground are used for AGW excitation in the model. Numerical simulations cover atmospheric regions having horizontal dimensions of 800 km and 600 km vertically. Vertical distributions of the mean temperature, density, molecular viscosity and thermal conductivity are specified using standard empirical models of the atmosphere.

Simulations were made for different horizontal wavelengths, amplitudes and speeds of wave sources at the ground. AGW amplitudes increase with height and waves might break down in the middle and upper atmosphere. Nonlinear interactions may lead to instabilities of the propagating waves and to creations of smaller-scale perturbations. These perturbations may increase temperature and wind gradients and could enhance the wave energy dissipation.

In this study, the wave sources contain a superposition of two AGW modes with different periods, wavelengths and phase speeds. Larger-scale AGW modes may change the background conditions for the smaller-scale wave modes. Thus, the larger-scale AGWs can modulate amplitudes of small-scale waves. In particular, interactions of two wave modes could sharp vertical temperature gradients and make easier the wave breaking and turbulence generating. On the other hand, small-scale wave modes might change dissipation and modify larger-scale modes.

INTRODUCTION

- **Acoustic-gravity waves (AGWs) measured at high altitudes may be generated in the troposphere and propagate upwards.**
- **A high-resolution three-dimensional numerical model was used for simulating nonlinear AGWs propagating from the ground to the upper atmosphere.**
- **The model algorithms are based on finite-difference analogues of main conservation laws. This methodology lets us obtaining physically correct generalized wave solutions of the nonlinear equations.**
- **Numerical simulations were made in atmospheric regions having dimensions of 800 km horizontally and 600 km vertically.**
- **Vertical distributions of the mean temperature, density, molecular viscosity and thermal conductivity are specified using standard models of the atmosphere.**
- **Horizontally moving sinusoidal structures of vertical velocity on the ground are used for AGW excitation in the model.**
- **Simulations were made for two AGW modes with horizontal wavelength of λ_{x1} = 100 km, phase speed c_{x1} = -50 m/s (Wave 1) and λ_{x1} = 400 km, c_{x2} = 150 m/s (Wave 2).**
- **The surface wave sources contain the wave 1 or wave 2 individually (one-wave excitation) or the sum of waves 1 and 2 (two-wave excitation).**

Vertical Velocities for Individual Waves

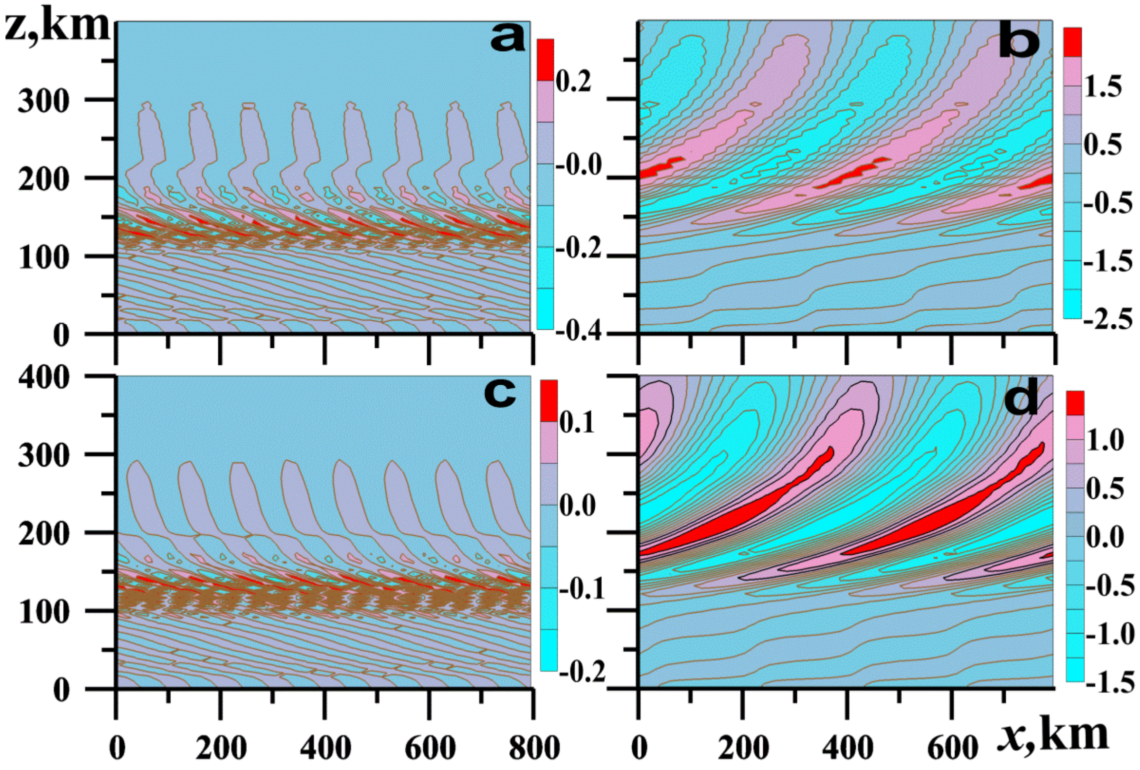

Figure 1. Distributions of vertical velocity (in m/s) in the vertical plane directed along the horizontal phase speed for the one-wave excitations by the wave 1 with amplitude at the ground W_{01} = 0.1 mm/s (a, c) and the wave 2 with W_{02} = 0.15 mm/s (b, d) at times t = 7 hr (a,b) and t = 30 hr (c,d).

Below 100 km altitude, one can see inclined wave fronts typical for IGWs. Vertical wavelengths are larger for the wave 2 having larger horizontal phase speed than that for the wave 1.

Vertical Velocities of Wave Superposition

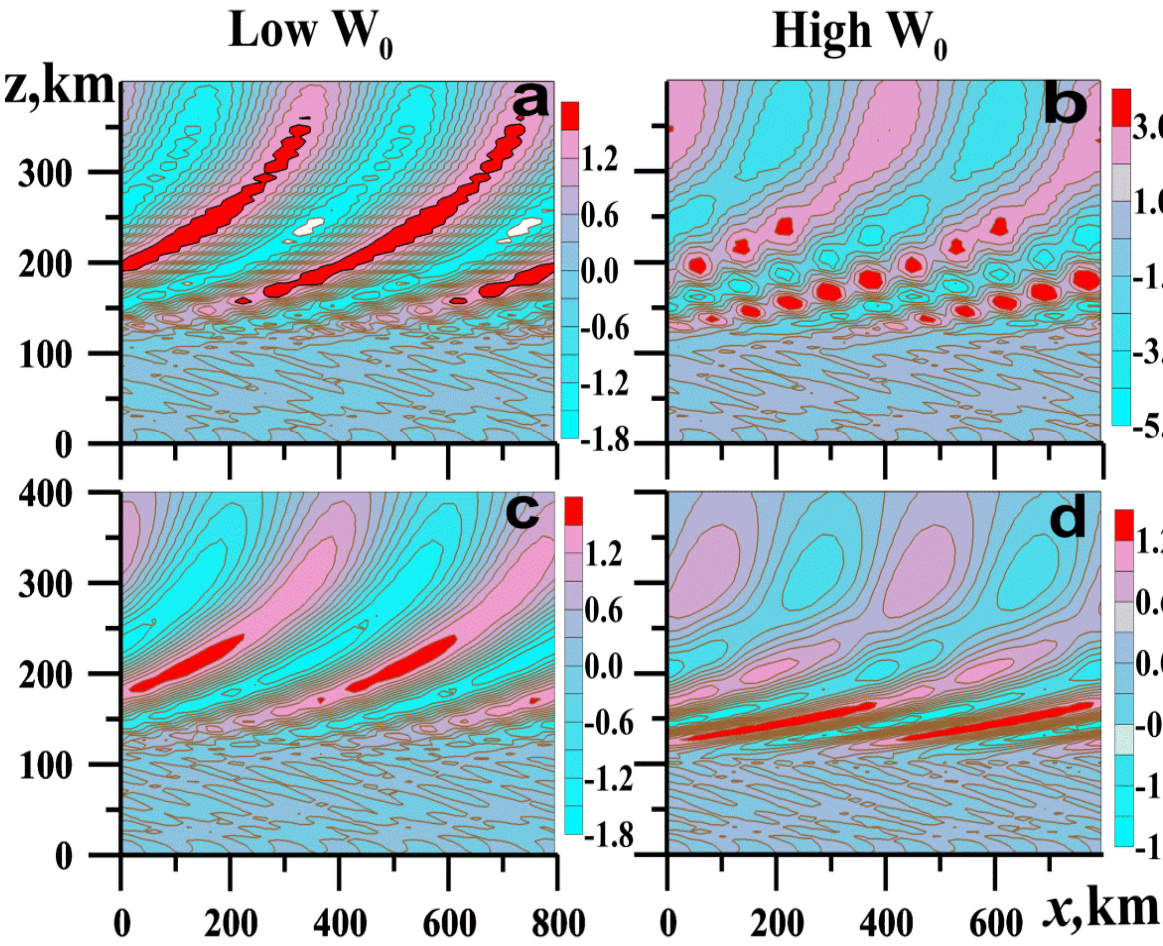

Figure 2. Distributions of vertical velocity (in m/s) in the vertical plane directed along the horizontal wave speed for the two-wave excitation by the superposition of the waves 1 and 2 with the surface wave amplitudes W_{01} = 0.1 mm/s, W_{02} = 0.15 mm/s (left) and W_{01} = 0.3 mm/s, W_{02} = 0.45 mm/s (right) at times t = 7 hr (a,b) and t = 30 hr (c,d) after the wave source activation.

Interactions of the larger-scale wave 2 and the smaller-scale wave 1 produce small-scale perturbations in the middle and upper atmosphere. They increase gradients of hydrodynamic fields, make easier wave breaking and increasing dissipation.

Vertical Profiles of Vertical Velocity

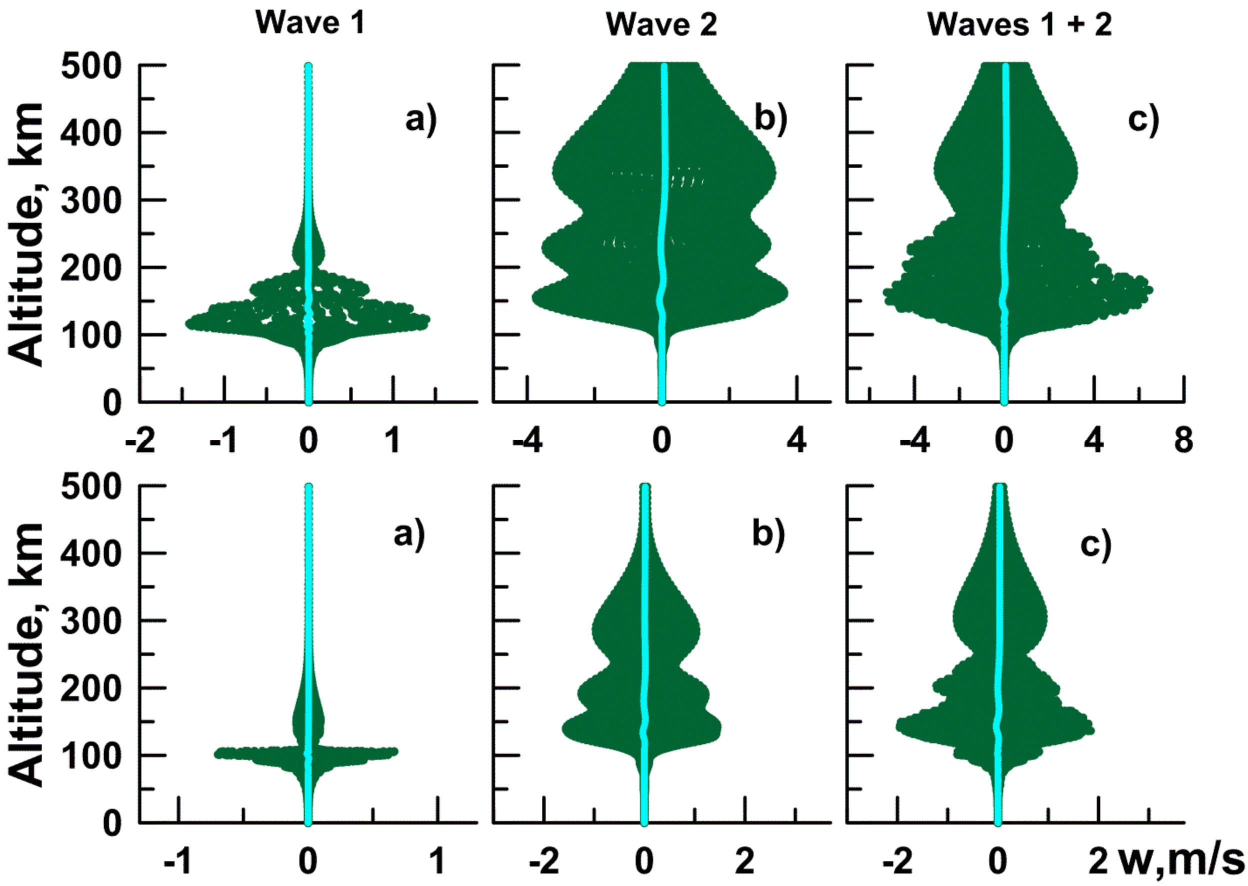

Figure 3. Overlapping vertical profiles of wave vertical velocity for the one-wave excitation by the wave 1 with W_{01} = 0.3 mm/s (a), by the wave 2 with W_{02} = 0.45 mm/s (b) and for the two-wave excitation by waves 1 and 2 (c) at times t = 7 hr (top) and t = 30 hr (bottom).

Increased dissipation in the case of the two-wave surface excitation by the waves 1 and 2 leads to their amplitudes in the panels (c) to be smaller than the sum of amplitudes of the individual one-wave excited those waves in the panels (a) and (b).

Vertical Profiles of Horizontal Velocity

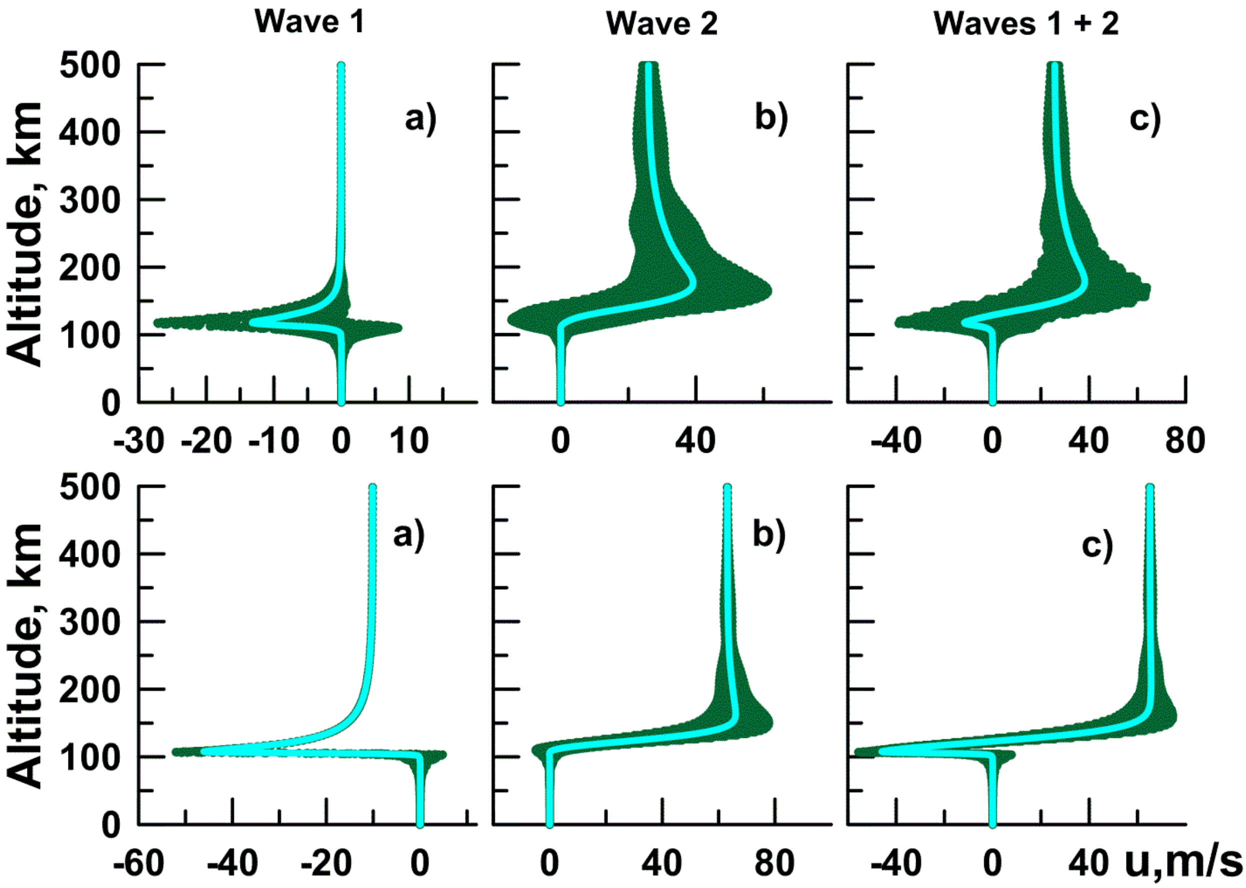

Figure 4. Same as Figure 3, but for horizontal velocity.

Thick lines in Figure 4 show the wave-induced changes in the mean horizontal velocity. The mean flows at altitudes above 100 km are westward for the wave 1 in the panels (a) and eastward for the wave 2 (b) in the case of the one-wave surface excitation. The two-wave excitation by the sum of waves 1 and 2 in the panels (c) creates westward mean fluxes at altitudes 100 – 130 km and eastward flows above.

Vertical Profiles of Temperature

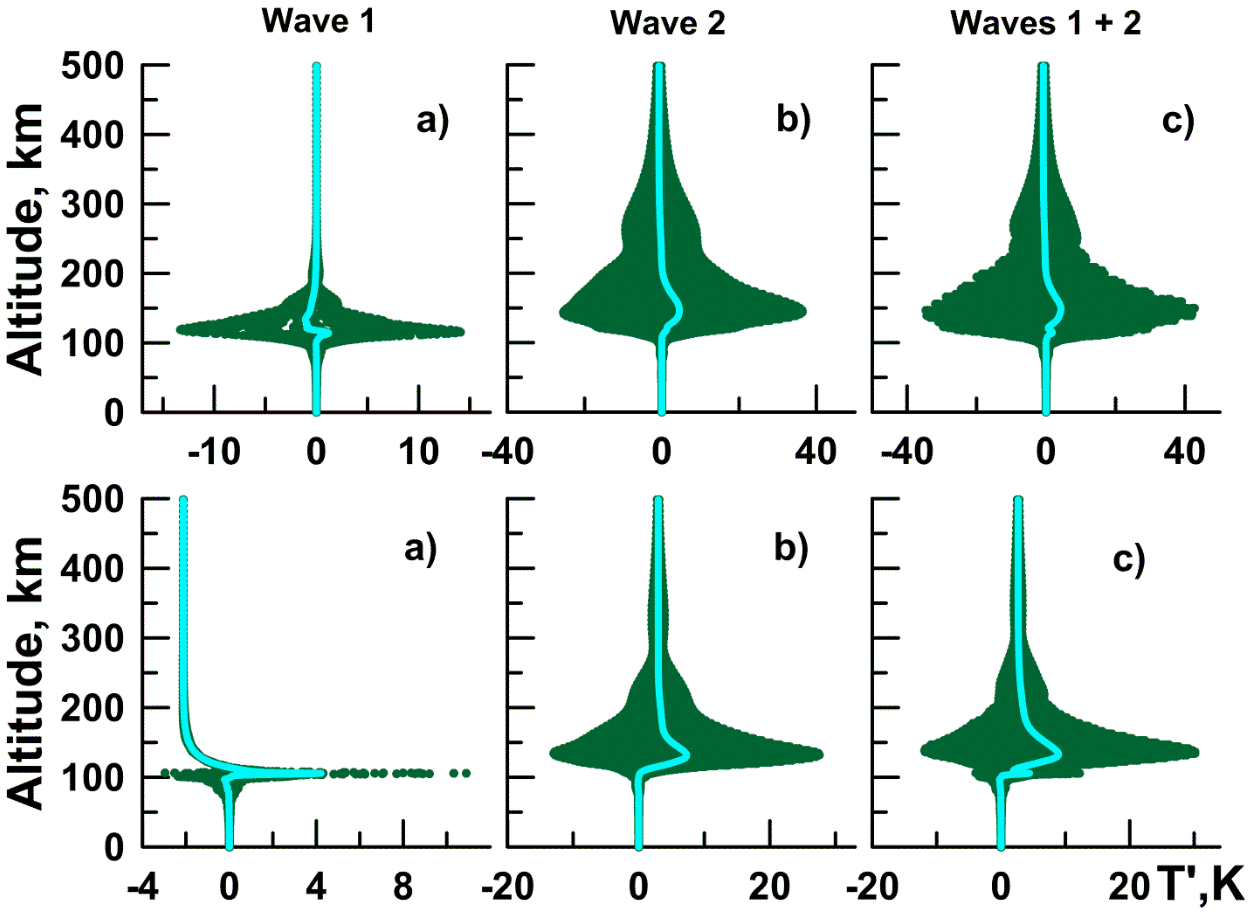

Figure 5. Same as Figure 3, but for temperature.

Dissipating AGWs may produce heating and cooling of the atmosphere. The one-wave excitation by the wave 1 in the panels (a) produces increases in the mean temperature at altitudes of high dissipation at 100 – 130 km and cooling above. The one-wave excitation by the wave 2 and the two-wave excitation by waves 1 and 2 make heating at all altitudes above 100 km in the panels (b) and (c).

Time Changes in Vertical Velocity Variances

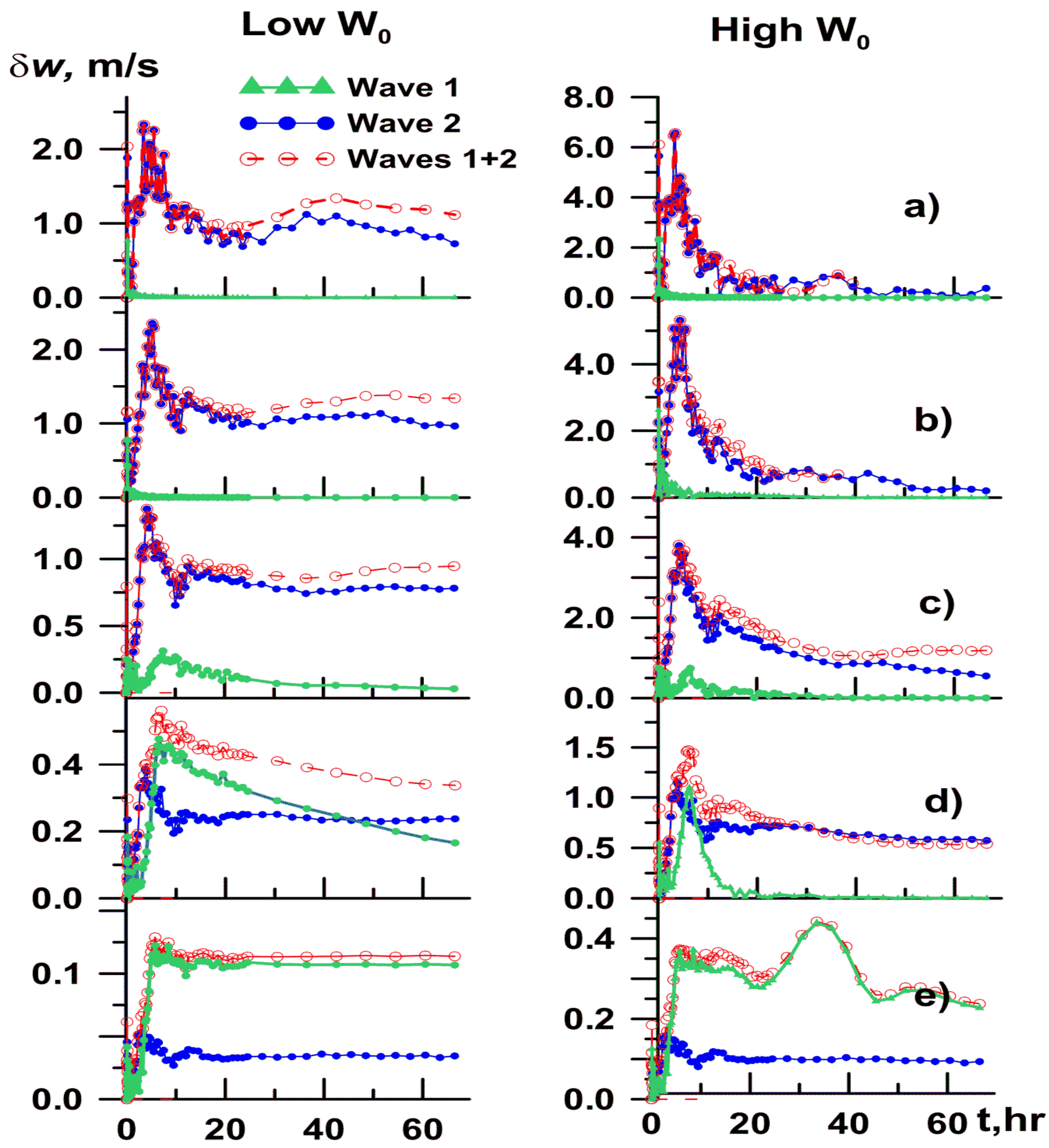

Figure 6. Changes in the standard deviations of vertical velocity at altitudes 250 km (a), 200 km (b), 150 km (c), 130 km (d), 100 km (e) for the one-wave excitations by the wave 1 (green) and the wave 2 (blue), also for the two-wave excitations by the superposition of waves 1 and 2 (red) versus time after triggering the surface wave sources with low (left) and high (right) amplitudes.

After arrival of the main IGW modes from the surface source, quasi-stationary wave regimes established at all altitudes. Steep decreases in wave amplitudes in Figure 6 are caused by the wave energy transfer to the mean flow.

Time Changes in Temperature Variances

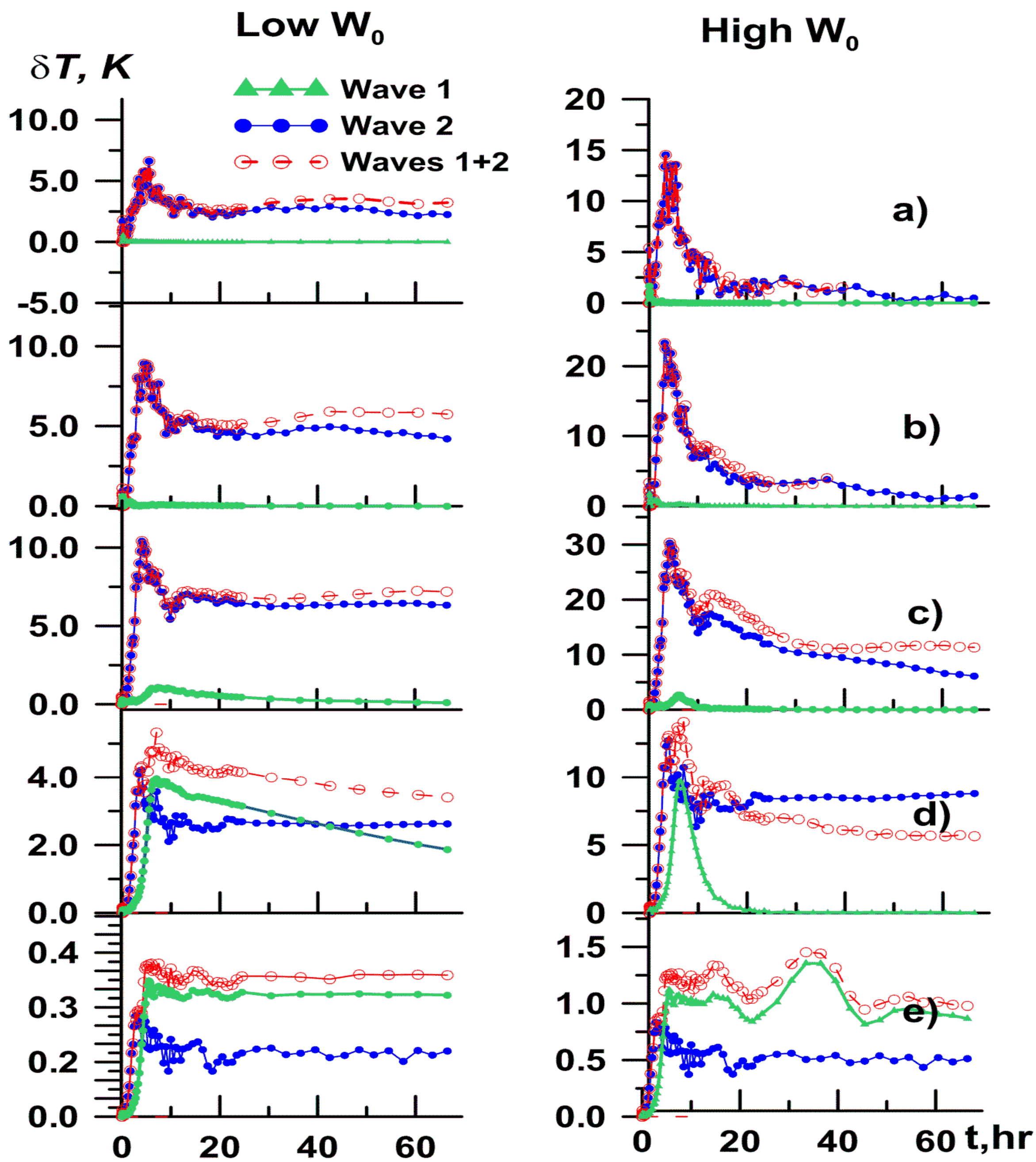

Figure 7. Same as Figure 6, but for the temperature standard deviation.

Below the altitude of 150 km, AGW amplitudes for the two-wave excitation by the superposition of waves 1 and 2 (red lines) are generally smaller, than the sum of green and blue lines corresponding to individual amplitudes of the waves 1 and 2 for the one-wave excitations at the lower boundary of the model.

Horizontal Velocity Variances

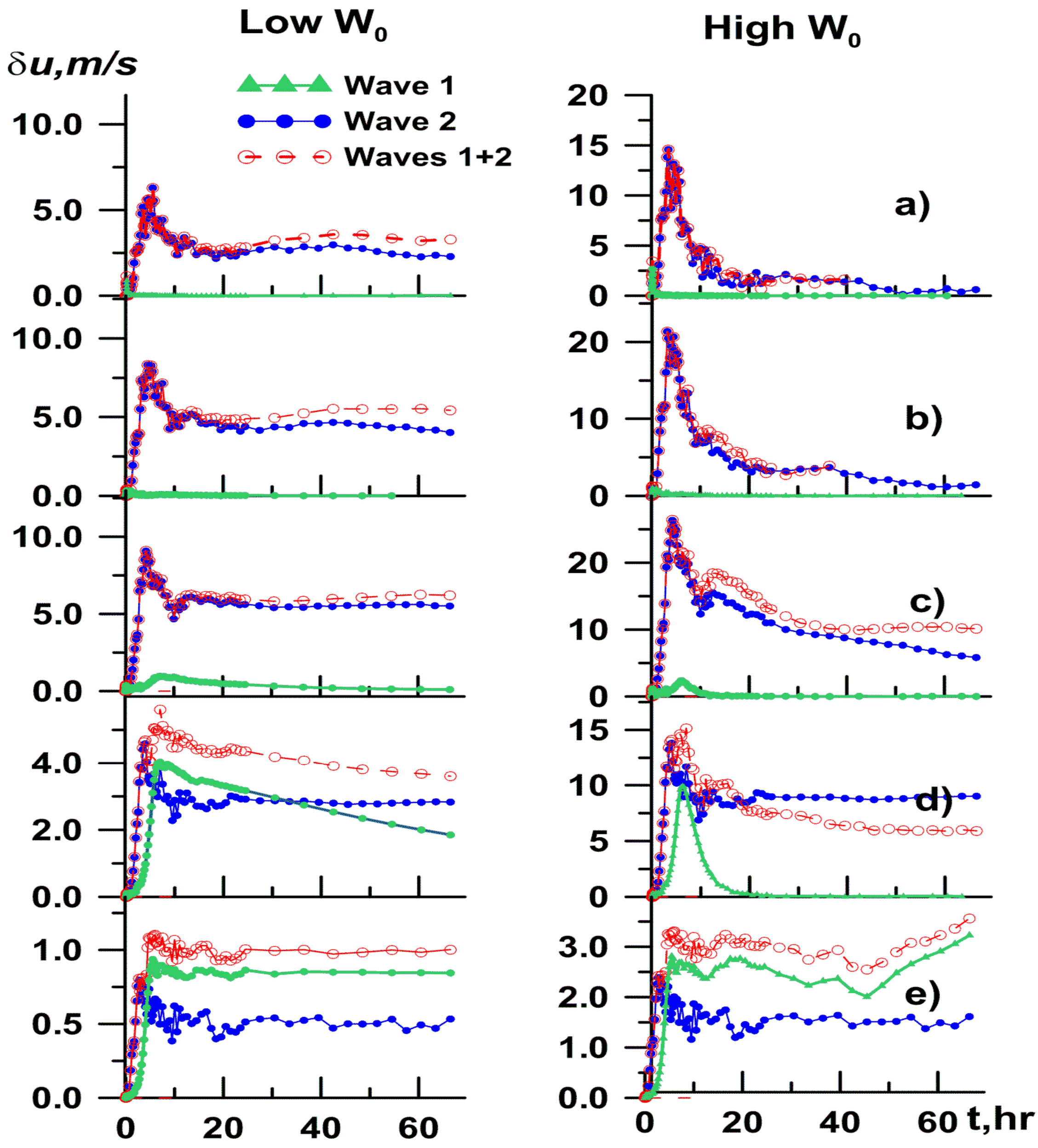

Figure 8. Same as Figure 6, but for the horizontal velocity standard deviation.

Above 150 km, AGW amplitudes in the case of two-wave excitation by the superposition of waves 1 and 2 (red lines) are frequently lager than the sum of green and blue lines showing their individual amplitudes for the one-wave excitation at the ground.

Time Changes in the Mean Flow Velocity

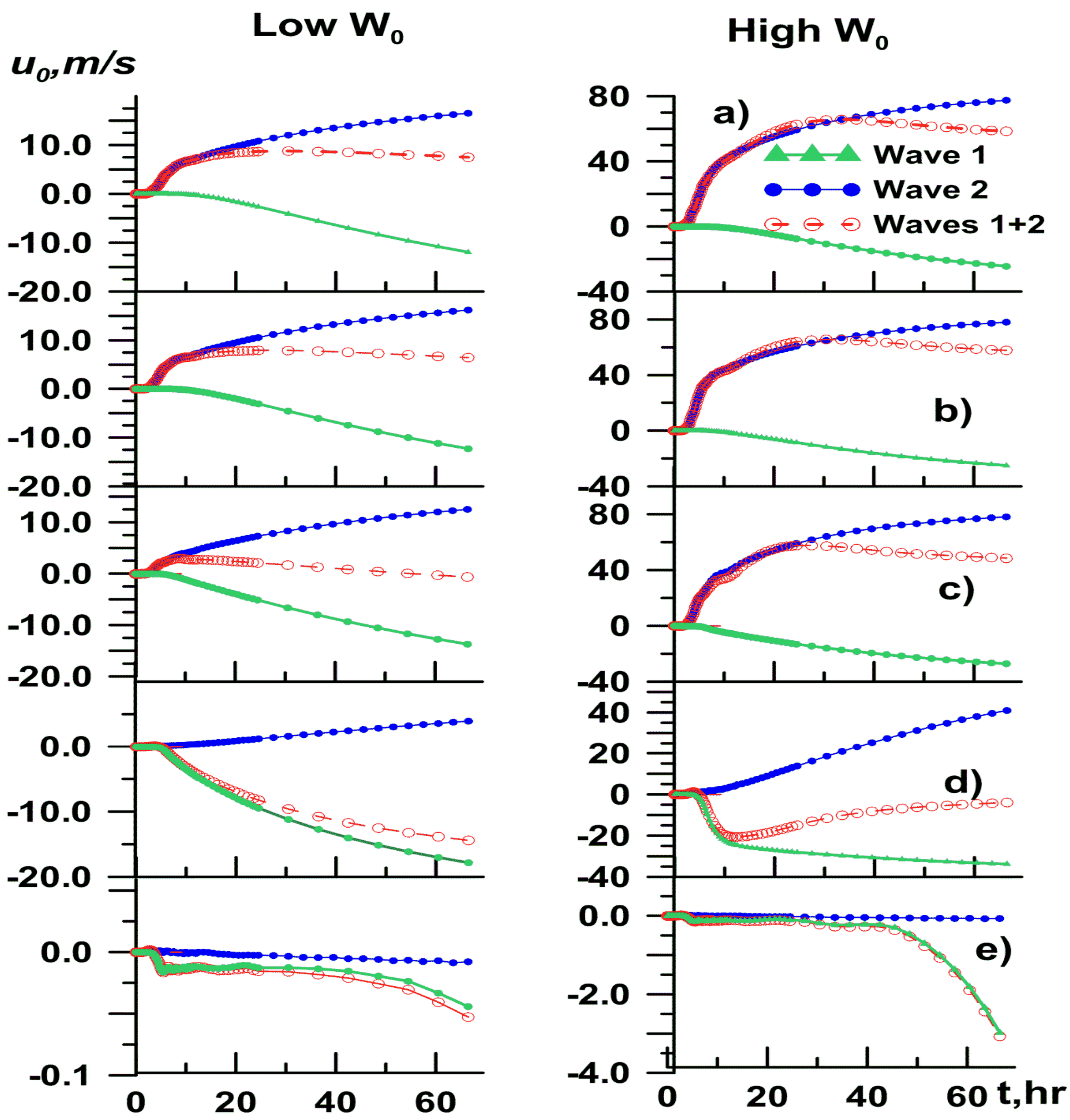

Figure 9. Changes in the wave-induced mean horizontal velocity at altitudes 250 km (a), 200 km (b), 150 km (c), 130 km (d), 100 km (e) for the one-wave excitations by the wave 1 (green), wave 2 (blue), also for the two-wave excitation by the superposition of waves 1 and 2 (red) versus time after triggering the surface wave sources with low (left) and high (right) amplitudes.

The westward wave 1 (green lines) produces westward horizontal mean flows (green lines), and the eastward wave 2 (blue lines) makes eastward horizontal mean flows (blue lines).

Time Changes in the Mean Temperature

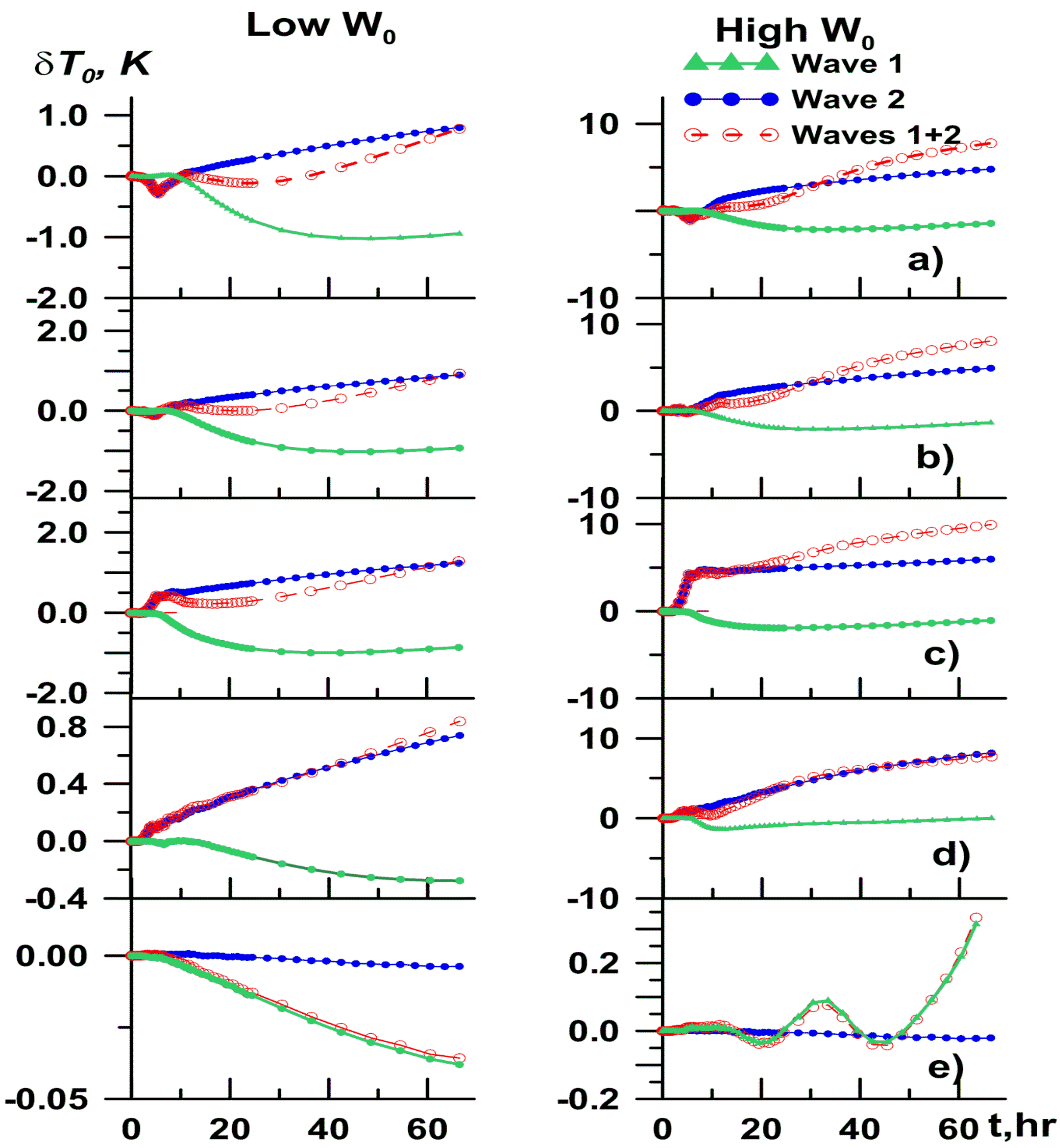

Figure 10. Same as Figure 9, but for the wave-induced changes in the mean temperature.

For the one-wave excitation, the wave 1 (green lines) having smaller vertical wavelengths produces general cooling in the upper atmosphere. The one-wave excitation by the wave 2 (blue lines) and the two-wave excitation by the superposition of the waves 1 and 2 (red lines) give general heating of the upper atmosphere.

Time Changes in Wave Momentum Fluxes

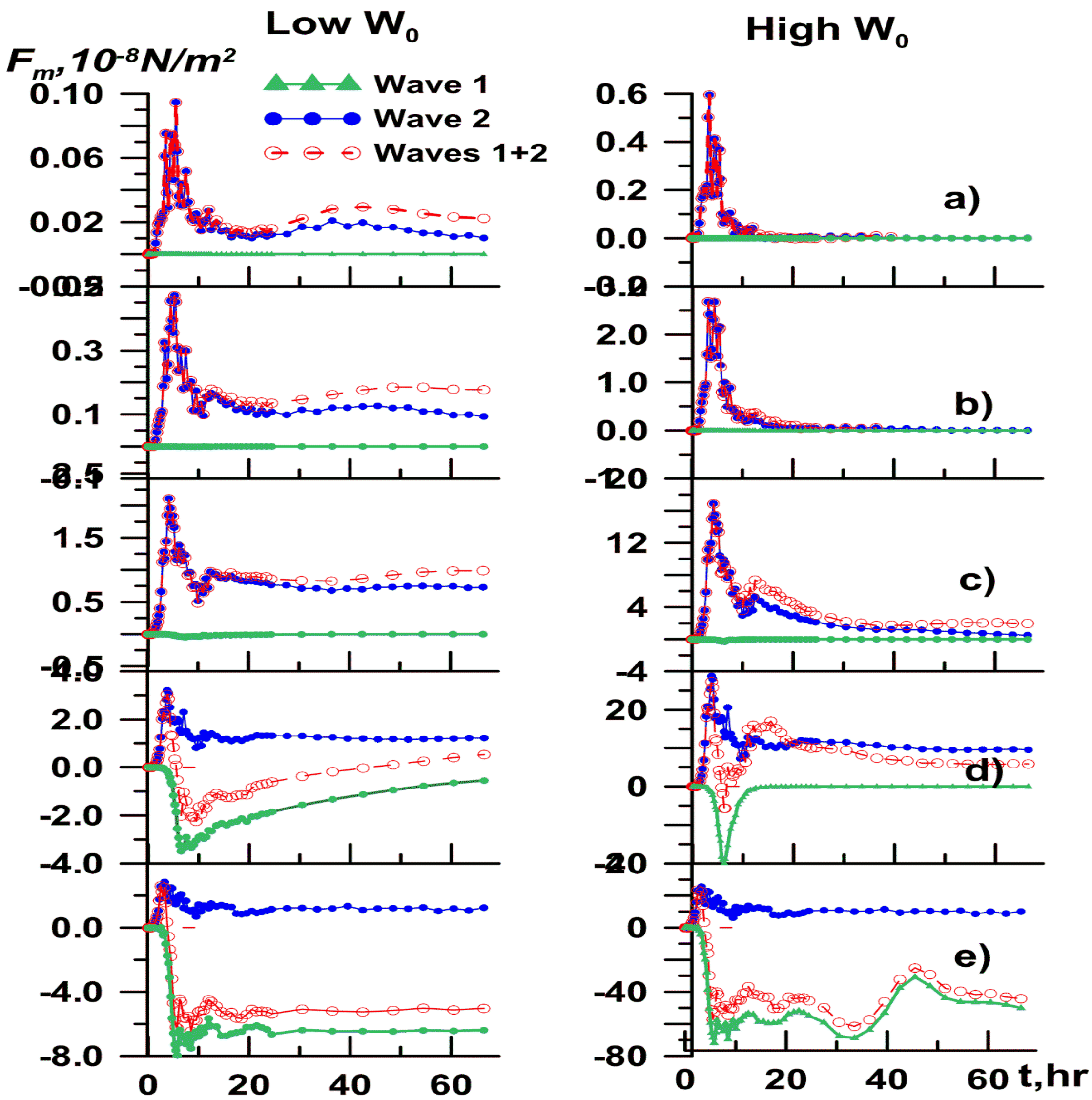

Figure 11. Changes in the wave momentum flux at altitudes 250 km (a), 200 km (b), 150 km (c), 130 km (d), 100 km (e) for one-wave excitations by the wave 1 (green) and the wave 2 (blue), also for the two-wave excitations by the superposition of waves 1 and 2 (red) versus time after triggering the surface wave sources with low (left) and high (right) amplitudes.

Momentum fluxes for the individual wave 1 are generally negative (westward), while the wave 2 momentum fluxes are positive (eastward). Magnitudes of wave momentum fluxes are larger for the wave 1 below 150 km altitude and are larger for the wave 2 above.

Time Changes in Wave Energy Fluxes

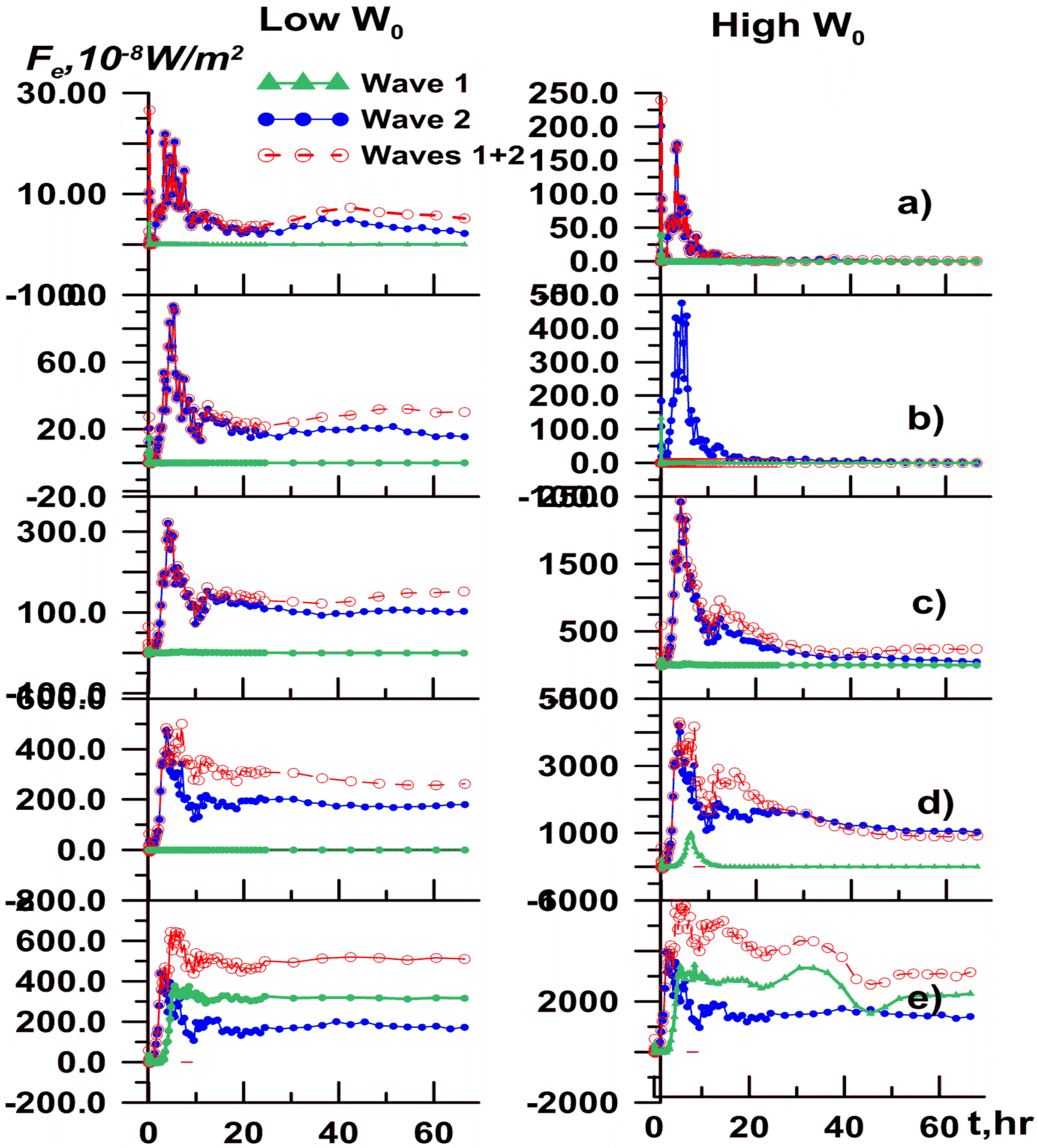

Figure 12. Same as Figure 11, but for the wave energy flux.

Wave energy fluxes for all wave modes in Figure 12 are positive (upwards). Energy fluxes for the wave 1 are smaller above altitudes 120 km due to larger dissipation of this wave.

Wave Accelerations and Heat Influxes.

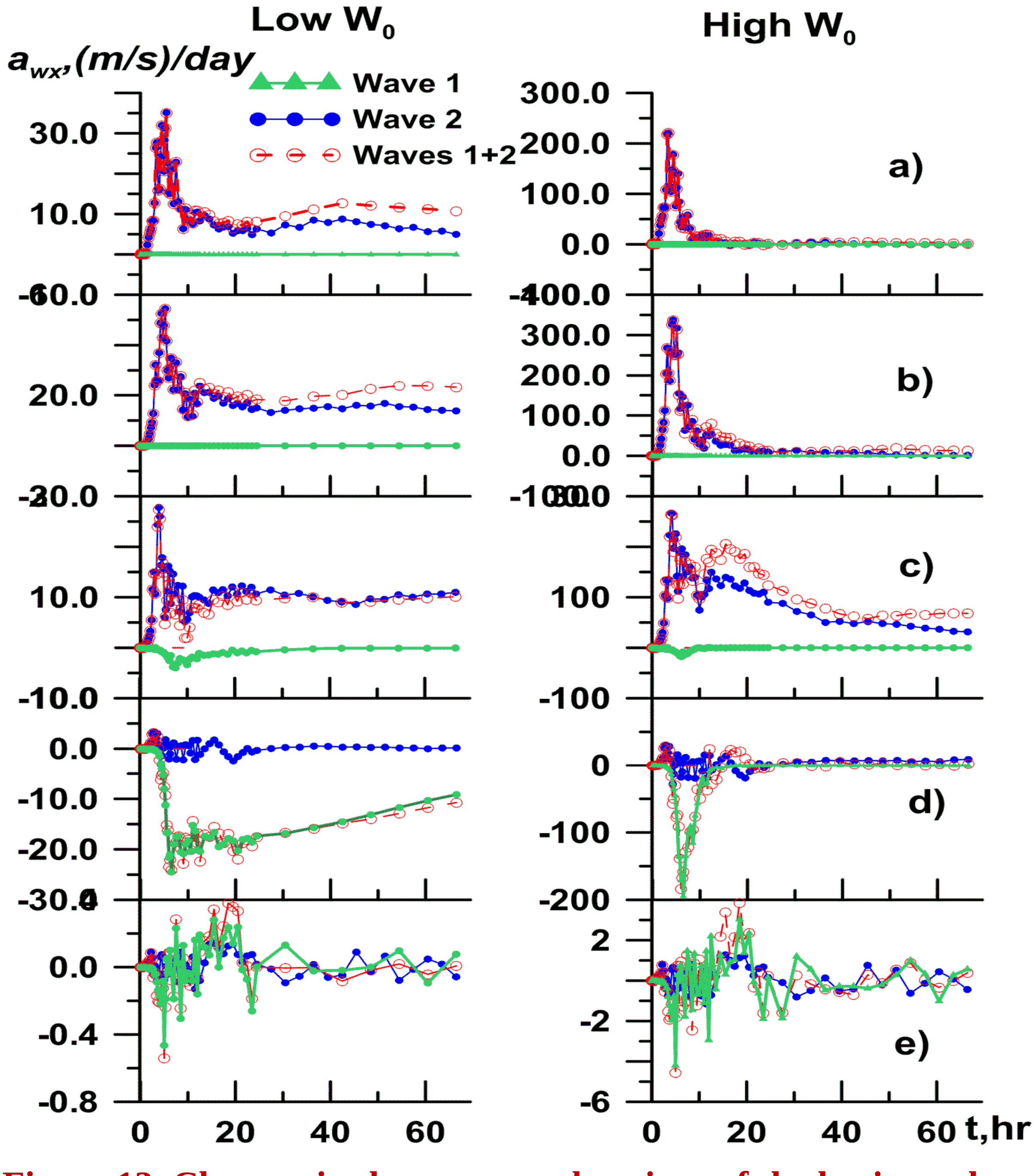

Figure 13. Changes in the wave accelerations of the horizontal mean flow at height 250 km (a), 200 km (b), 150 km (c), 130 km (d), 100 km (e) for the one-wave excitations by the wave 1 (green) and the wave 2 (blue), also for the two-wave excitation by the superposition of waves 1 and 2 (red) versus time after triggering of surface wave sources with small (left) and high (right) amplitudes.

Wave accelerations are generally negative (westward) for the wave 1 and are positive (eastward) for the wave 2.

CONCLUSION

- **Larger-scale AGWs can modulate amplitudes of smaller-scale waves.**

- **Interactions of two wave modes could sharp vertical temperature gradients and make easier the wave breaking and generating of turbulence.**

- **Nonlinear interactions between larger- and smaller-scale wave modes might change processes of wave dissipation and modify dynamical and thermal AGW impacts in the upper atmosphere.**

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- **References.**

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