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Orographic Drag Formation in Nonhydrostatic Pressure-Coordinate Dynamics I. Spectral Drag Resonances

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Based on nonhydrostatic, acoustically relaxed, viscous equations of atmospheric dynamics in pressure coordinates $\{x, y, p, t\}$, a consistent theory of orographically induced dynamic surface drag to the atmosphere is developed. The drag vector is computed as

$$\mathbf{Q} = \sum_k |\delta_k|^2 \mathbf{S}_k \ ,$$

where $|\delta_k|^2$ is the power spectrum of relative orography and $\mathbf{S}_k$ presents the spectral amplitude of wave drag. $\mathbf{S}_k$ is not dependent on orography, but is solely determined by the vertical distributions of mean temperature $T(p)$ and wind velocity $\mathbf{U}(p)$. Theory provides formulae for calculation of $\mathbf{S}_k$ via omega velocity $\omega(x, y, p_s)$ and its vertical derivative $(\partial\omega/\partial p)_{p_s}$ on the surface $p_s(x, y)$. The omega-velocity ω is solved from a nonhydrostatic wave equation [1], which forms a part of the present drag formation theory.

Comprehensive modelling of spectral wave amplitude $\mathbf{S}_k$ is carried out for wide range of vertical distributions $T(p)$ and $U(p)$, including both the model and experimental profiles. Differently from the homogeneous stratification with constant U and Väisälä-Brunt buoyancy frequency $N(p)$, in the stratified atmosphere narrow sharp resonant peaks appear in the $\mathbf{S}_k$. For this reason, $\mathbf{Q}$ becomes rather sensitive to spectral particularities of $|\delta_k|^2$. The prime moderator, determining the spectral locations and the amplitudes of resonances, is the jump of $N(p)$ at the tropopause, which is strongly amplified by wind variation with height, and especially by linear increase of $U(p)$ in the planetary boundary layer.

Obtained results impose upon significant revision of present ideas concerning the surface drag and wave drag formation as well as their parameterizations in the numerical weather prediction and climate models.

[1] Rõõm R., Zirk M., 2007. An Efficient Solution Method for Buoyancy-Wave Equation at Variable Wind and Temperature. *Mon. Weather Rev.*, **135**, 3633 - 3641.