Formation of two dimensional and three dimensional circulation responding to unsteady wave forcing in the middle atmosphere

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Lagrangian-mean meridional circulation is mainly driven by wave forcing. In many previous studies, a steady-state assumption is used for the analysis of the meridional circulation. In general, however, the wave forcing is not steady. When a stratospheric sudden warming occurs, for example, time scales of wave forcing is so short. So as to understand such transient behavior and formation of the circulation, we must investigate the time evolution of not only "slow" variable such as linearized PV but also "fast" variables such as horizontal divergence and ageostrophic vorticity. The purpose of this study is to theoretically examine the response of meridional circulation to unsteady wave forcing by using Green's function method.

In the first part of this study, we investigate the response to a zonally-uniform forcing. The steady solution of the meridional circulation is composed of two cells aligned in the vertical. For a forcing with a shaped of the step function in time, large-scale gravity waves are radiated, and a meridional circulation and an inertial oscillation finally remains. The time scale needed for the formation of the meridional circulation depends on the aspect ratio of the wave forcing structure, and it is determined by the group velocity of gravity waves and the spatial scale of the forcing. We also investigate the case for the forcing which changes gradually in time. When the forcing time change is slower than the inertial period, the meridional circulation always accords with that estimated using the "steady-state assumption". The distribution ratio of the wave forcing to the zonal-wind acceleration and the Coriolis torque is determined by the shape of the wave forcing and explained by the dimensional analysis.

Second, we investigate the response to zonally-nonuniform forcing. So as to focus only on the Rossby wave response, governing equations are derived following the method of balance equations. For the steady forcing case with the beta effect, the geostrophic flow becomes zonally asymmetric and has large magnitudes to the west of the forcing. For the step-function forcing, Rossby waves are radiated as a transient response. Time period needed to reach the steady state strongly depends on the strength of the linear relaxation.

Key words: middle atmosphere, circulation, wave forcing