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 in the middle atmosphere is important for the earth climate because it globally transports minor species such as ozone and changes the temperature structure through adiabatic heating/cooling associated with its vertical branches. This meridional circulation is mainly driven by remote redistribution of the momentum by atmospheric waves. In many previous studies such as Haynes et al. (1991), a steady-state assumption is frequently used for the analysis of the meridional circulation. In general, however, the wave forcing is not steady. Thus, dynamical understanding under the steady-state assumption is limited. When a stratospheric sudden warming occurs, for example, time scales of wave forcing is so short that behavior of the resultant circulation may differ from that expected under the steady-state assumption. So as to understand such transient behavior and formation of the circulation, we must investigate the time evolution of not only “slow” variable (linearized potential vorticity) 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. In the first part of this study, we examine a two-dimensional problem using a Boussinesq equation system in which a zonally-uniform unsteady forcing is given. In the second part, the three-dimensional response to a zonally-nonuniform and unsteady forcing is examined using a balance equation which is derived in this study.
As large-scale atmospheric response to the forcing can be described as a linear response, the method of Green’s function, which is a response to the delta function, is one of useful approaches for analysis of the linear response to forcing. By using the Green's function method, we mainly examine the response to a wave forcing in the zonal momentum equation.
First, we investigate the response to the zonally-uniform forcing. The steady solution of the meridional circulation responding to a constant forcing is composed of two cells in the vertical. For a forcing with a shaped of the step function in time, gravity waves are radiated as a transient response, and a meridional circulation with an inertial oscillation finally remains. The quasi-steady meridional circulation accords well with the steady state solution for a constant forcing. The time scale needed for the formation of the meridional circulation depends on the aspect ratio of the wave forcing structure, as is consistent with a theoretical expectation. In addition, it is shown that the group velocity of gravity waves and the spatial scale of the forcing determine the time scale of the circulation formation. 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 also investigated. The distribution ratio is determined by the shape of the wave forcing and explained by the dimensional analysis.
Second, we investigate the response to zonally-nonuniform forcing. In this case, it is expected that Rossby waves are radiated as transient response because of beta effect. So as to focus only on the Rossby wave response, governing equations are derived following the method of balance equations used by Leith (1980). For the steady forcing case with 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. Rossby waves having smaller zonal wave

numbers radiated faster from the forcing region. Time period needed to reach the steady state depends strongly on the strength of the linear relaxation.

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