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The role of gravity wave drag in the formation and trend of the Brewer-Dobson circulation in the 21st century

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The stratospheric meridional distribution of atmospheric minor constituents such as ozone is largely affected by the Brewer-Dobson circulation (BDC) consisting of upwelling in the low latitudes and downwelling in the middle to high latitudes of each hemisphere. This circulation is considered to be driven by the body force in the middle latitudes in the stratosphere induced by the breaking and/or dissipation of waves propagating mainly from the troposphere. Previous works indicate that planetary waves are a main driver of the BDC. However, it is also recognized that the momentum deposition by synoptic-scale waves and gravity waves is important for the zonal momentum balance in the lower stratosphere. The purpose of this study is to quantify relative role of each kind of waves to the BDC driving mechanism. Moreover possible changes of the BDC in the future are examined using data from model simulations with the scenarios regarding greenhouse gases and ozone destruction species.

An analysis is made of simulation data over about 120 years using the Center for Climate System Research/National Institute for Environmental Studies Chemistry Climate Model (CCSR/NIES CCM). The contribution of different types of waves to the BDC is diagnosed using the "downward control principle (DC)" in terms of the residual mean mass stream function and the net upward mass flux. The drag due to model-resolved-waves, mainly planetary waves, is important to form the BDC in the high latitudes of the middle stratosphere. On the other hand, orographic gravity wave drag has a great influence on the BDC in the lower stratosphere. To confirm the reality of these model results, similar analysis was performed by using the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim) data. The effect of the gravity wave drag using ERA-Interim can be evaluated as the difference between the directly-estimated stream function of the residual circulation and the stream function due to the resolved wave calculated using DC theory. The result is consistent with that from the CCM data analysis. Thus, it is very likely that the gravity waves play an important role to maintain the BDC.

According to recent studies, most CCM predictions indicate acceleration of the BDC in response to the climate change in the 21st century. In this study, linear trend of each parameter describing the BDC is calculated using CCM data in the time period of 2005-2070. The orographic gravity wave drag largely contributes to the positive trend of the stream function in the middle latitudes and then to the increase in the net upward mass flux on the 70 hPa surface. This is caused by the upward shift of the orographic gravity wave drag near the 70 hPa surface rather than by the change of the momentum flux of the orographic gravity waves at the ground surface.

On the other hand, recent observational studies suggest that there is no evidence of the BDC acceleration based on the analysis of the ``age'' of air (AOA). The AOA is another parameter characterizing the strength and shape of the BDC. In this study, AOA is older in the polar region and younger in the equatorial region, as expected from the structure of the BDC. The difference in AOA between 2085 and 2005 is negative throughout most of the lower stratosphere, implying the

acceleration of the BDC. On the other hand, the AOA difference between 2005 and 1985 in the polar regions is significantly positive in the middle stratosphere and negative in the lower stratosphere while that in the low and middle latitudes is not clear. This result suggests the BDC was decelerated or changed its transport paths in the recent past and may give us a hint to explain the observational evidence as above.

Keywords: The downward control principle, the Brewer-Dobson circulation, wave forcing, age of air, CCM