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論文の内容の要旨

The structure and long-term variation of the stratospheric circulation

（　成層圏大循環の構造と長期変動　）

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The meridional circulation in the stratosphere called the Brewer-Dobson circulation (BDC) consisting of tropical upwelling and extratropical downwelling was found from the observations of ozone and water vapor distributions. Recent studies indicated that the BDC is composed of deep and shallow branches. The former extends up to the upper stratosphere and the latter is confined in the lower stratosphere. This circulation is approximately expressed by the residual circulation in the transformed Eulerian mean (TEM) system, although isentropic mixing is also important for the distribution of minor constituents. In the TEM framework, the BDC is driven by a body force associated with breaking/dissipation of the atmospheric waves. The deep branch is driven by the planetary wave forcing, while the shallow branch is driven by the synoptic-scale waves. Recent studies suggested the important role of the gravity wave on the BDC. However, because of their small scales, the estimation of the global distribution of the gravity wave forcing from observations is generally difficult and hence gravity wave parameterizations used in most climate models are based on uncertain assumptions. In this study, we first examine

the contribution of gravity waves to BDC by a diagnostic method using reanalysis data sets which include gravity wave effects in large-scale fields through assimilation of huge amount of observational data.

The gravity wave (GW) contribution to the BDC is indirectly estimated using the downward control principle under an assumption of the steady state. This method is applied to four analyses to examine the stratospheric residual mean circulation for the ERA-Interim reanalysis data. First, the GW contribution to the formation of the residual circulation is examined. The results show that the deep branch in the summer subtropics is mainly driven by GWs. Second, the GW contribution to the tropical upward mass flux in the lower stratosphere is investigated. GWs contribute to about 30¥% of the total mass flux, which is consistent with previous studies. Next, the GW effects are investigated on the determination of the turnaround latitude (TL) in the lower stratosphere, which is defined as a latitude of zero vertical velocity. The stream function contributed by the resolved wave forcing is not maximized near the TL, suggesting the importance of the GW for determining the location of TL. Finally, seasonal variations of the tropical upward mass flux are examined. The mass flux in the lower stratosphere exhibits annual cycle, while semiannual cycle is dominant in the middle stratosphere. It is considered that this difference between the two height regions is caused by three points. One is the GW contribution which increases with height. The other two are the interhemispheric differences in the planetary wave activity and in the persistency of westerly wind in the lower stratosphere. These results indicate the importance of the gravity waves for the formation and seasonal variation of the BDC even in the lower and middle stratosphere.

Long-term change of the meridional circulation in the middle atmosphere is another interesting topic. Recent studies focusing on the future climate change associated with increasing greenhouse gases and a decreasing trend of ozone depleting substances reported an acceleration of the BDC in the mid-21st century. In addition, dynamical response of the mesosphere-lower thermosphere (MLT) region to the ozone depletion trend in the polar stratosphere in the late 20th century was also examined. In this thesis, the remote dynamical responses to ozone recovery and CO$_2$ increase in the 21st century are examined using data from chemistry-climate model simulations.

In early summer, ozone recovery in the lower stratosphere results in a temperature increase in the polar lower stratosphere, leading to an easterly trend in the whole stratosphere. The change in the wind distribution allows propagation of more gravity waves into the mesosphere so that the mesospheric residual mean circulation is intensified by the gravity wave drag. The consequent polar temperature trend below the mesopause is negative due to the adiabatic response to the positive trend in the upwelling. This response is opposite to that of the ozone loss in the 20th century and hence the present study supports the mechanism proposed by previous studies. However, the temperature response in the lower thermosphere is not consistent with the expected adiabatic change. To examine the mechanism of the temperature response, other simulation data with three scenarios for the CO_2 variation in the 21st century are used. From comparisons of the positive CO_2 trend cases and no CO_2 trend case, the mesospheric temperature trend is mainly attributed to the ozone increase in the lower stratosphere, while the CO_2 trend largely affects the temperature response in the lower thermosphere. In addition, this result is supported by the multiple linear regression analysis.

In the equatorial atmosphere, unique oscillations called the quasi-biennial oscillation (QBO) and semiannual oscillation (SAO) are observed in the zonal mean zonal wind. It is known that the QBO affects the strength of the polar night jet (PNJ) and the frequency of the sudden stratospheric warming. However, dynamical connection between the SAO and PNJ has not been examined in detail so far. Thus, this study made an analysis from this view point using high resolution general circulation model (GCM) data and a reanalysis dataset. In particular, analysis was focused on the austral winter.

First, the GCM and reanalysis data are examined to investigate the seasonal march during austral winter. The PNJ core and easterly phase associated with the SAO descend with time. It seems that two descents are synchronized. Such a feature is also observed in several years in the reanalysis data. In addition, strong upwelling is located in the upper stratosphere and lower mesosphere, which is above and lower latitude side of PNJ core. This upwelling may affect the zonal wind distribution through the temperature change by adiabatic cooling. Next, long-term reanalysis data is used to examine the PNJ-SAO relation in the interannual variability focusing on July. All Julys are divided into two groups (strong SAO easterly Julys and weak SAO easterly Julys) and averaged for each group. From the comparison of two groups, more planetary waves tend to break around the SAO easterly and drive the strong poleward flow in the upper stratosphere in the mid-latitudes for the strong SAO easterly Julys than for the weak SAO easterly Julys. In addition, equatorial flow anomaly in the subtropical mesosphere is observed in the strong SAO easterly Julys. These two flow anomalies are combined into the strong upwelling in the mid-latitude upper stratosphere and lower mesosphere. This strong upwelling can affect the upper part of the PNJ through the temperature change. It is also found that the PNJ core height is located around the height of SAO easterly from the composite analysis based on the height of SAO easterly. On the other hand, composite analysis on the PNJ core height suggests that more planetary waves tend to propagate into the SAO easterly region in the lower PNJ core height Julys, which can enhance the easterly wind in the subtropics. These results indicate that the SAO variability affects the PNJ variability through the residual circulation change in the mid-latitudes, and the PNJ variability also affects the SAO variability through the control of the planetary wave propagation, which may adjust the location of the SAO easterly phase and the PNJ core.

The present study examined the variation and interaction of the residual mean circulation and various kinds of waves mainly in the meridional cross section in the two dimensional TEM framework. However, several recent studies indicate that the stratospheric circulation has longitudinally-dependent three-dimensional structure. It is also known from recent satellite observations that the stratopause and PNJ are not zonally uniform. Moreover, a three-dimensional TEM equation system has recently been developed, which treats both gravity waves and Rossby waves. For the future work, as an extension of the present study the three-dimensional aspects of the structure, seasonal variation, and long-term variation of the residual mean circulation in the middle atmosphere should be investigated.