論文の内容の要旨

Climatology and interannual variability of stratospheric planetary waves in the Southern Hemisphere and their connection to the troposphere

（南半球成層圏におけるプラネタリー波のクライマトロジー及び年々変動とその対流圏との関係）

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Planetary-scale Rossby waves in the wintertime polar stratosphere and associated dynamical phenomena are introduced in chapter 1. The wintertime polar stratosphere is dominated by planetary waves propagating from the troposphere. Amplitudes of stratospheric planetary waves in winter are generally smaller in the Southern Hemisphere (SH) than in the Northern Hemisphere (NH) due to differences in amplitudes of the geographical asymmetries. As a result, significant interhemispheric differences in dynamical phenomena associated with planetary waves are observed in the wintertime polar stratosphere. For example, the stratospheric final warming (SFW), which is the breakdown of the polar vortex, occurs approximately one month later in the SH than in the NH.

Planetary waves with large amplitudes in the SH polar stratosphere are quasi-stationary waves with zonal wavenumber 1 ($s = 1$ QSWs; s is zonal wavenumber) and transient waves with zonal wavenumber 2 ($s = 2$ TWs). Climatological seasonal evolution of the planetary-wave amplitudes in the SH stratosphere is already shown by previous studies using data for a limited time period. However, cause of the seasonal variation of stratospheric planetary-wave amplitudes is still not clear. Moreover, although it has already been confirmed by previous studies that SFWs occur earlier when stratospheric wave activity is larger, detailed tropospheric conditions leading to earlier SFWs are still not elucidated well. The present study investigates climatology and interannual variability of planetary waves in the SH stratosphere and their connection to the troposphere. The analysis is focused on planetary waves in the troposphere and wave transmission properties of the mean flow through which planetary waves propagate. Refractive index (n) squared is used to diagnose the wave transmission properties of the mean flow. Reanalysis dataset (MERRA-2) for 38 years from 1980 to 2017 is mainly used.

In chapter 2, climatological seasonal evolution of planetary-wave amplitudes in the SH stratosphere is shown. The climatology for 38 years obtained in this study is compared to that shown by the previous studies. This is because the time period of data used for climatology by previous studies is relatively short, which may lead to spurious climatology affected by a certain phase of the interannual variability. Cause of the climatological seasonal variation of planetary-wave amplitudes in the stratosphere is examined in terms of the climatological seasonal variation of planetary-wave amplitudes in the troposphere and distribution of n^2 in the stratosphere. In addition, the relation of the distribution of n^2 with the structure of the polar night jet is investigated. Results of the analysis for $s = 1$ QSWs and $s = 2$ TWs are shown.

For $s = 1$ QSWs, seasonal evolution of the stratospheric wave amplitudes is different between above and below 3 hPa. The wave amplitudes above 3 hPa attain a local maximum in autumn, a local minimum in midwinter, and a maximum in spring. On the other hand, the wave amplitudes below 3 hPa gradually increase from early winter and are maximized in spring. A local maximum in the middle stratosphere in early winter observed in climatology shown by previous studies is not seen. The midwinter maximum in the middle stratosphere shown by the previous studies reflects significantly large amplitudes of $s = 1$ QSWs in a year during time period analyzed by previous studies.

Possible cause of the climatological seasonal evolution of $s = 1$ QSW amplitudes in the stratosphere is examined. A region which is largely occupied by negative n^2 is observed in midwinter. This is consistent with the local minimum of the wave amplitudes in midwinter. On the other hand, in the lower stratosphere, n^2 is largely positive from early winter to spring. The wave amplitudes in the troposphere gradually increase from early winter and are maximized in spring. Thus, it is suggested that the gradual increase of the stratospheric wave amplitudes below 3 hPa is due to that of tropospheric wave amplitudes. The maximum of the wave amplitudes in spring in the whole stratosphere is likely caused by the maximum in tropospheric wave activity.

For $s = 2$ TWs, stratospheric wave amplitudes gradually increase from early winter and attain a maximum in late winter. This is almost the same as climatology shown by a previous study. It is suggested that the gradual increase in stratospheric wave amplitudes from early to mid-winter is caused by both gradual increase in tropospheric wave activity and latitudinal widening of lower stratospheric positive n^2. The maximum of stratospheric wave amplitudes in late winter is likely associated with tropospheric wave activity which attains the maxima twice in mid- and late winter, and larger areas of positive n^2 in the middle and upper stratosphere in late winter than in midwinter.

In chapter 3, interannual variability of SFW date in the SH is investigated in terms of difference in stratospheric wave activity between early and late SFW years. The analysis is focused on $s = 1$ QSWs because their amplitudes are the largest among extratropical planetary waves in the SH stratosphere, and attain a maximum during the austral spring. Stratospheric $s = 1$ QSW activity is larger in early-SFW years than in late-SFW years in late winter and spring before SFW. Larger wave forcing due to $s = 1$ QSWs is observed in early-SFW years in the stratosphere. This likely leads to advanced seasonal evolution of the polar night jet, and hence early SFWs. The larger $s = 1$ QSW activity in early-SFW years is also observed in the troposphere. From the troposphere to the stratosphere, larger upward Eliassen-Palm flux is observed in early-SFW years. These results indicate that the larger stratospheric $s = 1$ QSW activity originates in the troposphere. It is shown by examining the distribution of n^2 that more favorable conditions for $s = 1$ stationary waves to propagate from the troposphere into the stratosphere in early-SFW years than in late-SFW years are found at high latitudes. This indicates contribution of the difference in wave transmission properties of the mean flow to the larger stratospheric $s = 1$ QSW activity. In addition, it is suggested that the difference in wave transmission properties of the mean flow between early- and late-SFW years comes from advanced seasonal evolution of the polar night jet in early-SFW years.

Next, cause of the larger amplitudes of tropospheric $s = 1$ QSWs in early-SFW years is explored. The analysis is focused on Rossby wave source (RWS) at low latitudes and the background flow in the troposphere because they may mainly affect the amplitudes of tropospheric $s = 1$ QSWs. Significant differences in the RWS at low latitudes and the background flow between early- and late-SFW years are observed. Difference in $s = 1$ steady response to the RWS at low latitudes and the background streamfunction is calculated using a linear barotropic model. The difference in $s = 1$ response is compared to difference in $s = 1$ stationary waves in MERRA-2 at high latitudes. Their longitudinal phase structures are similar. It is indicated that the cause of the larger amplitudes of $s = 1$ response in early-SFW years is different between late winter and spring seasons. Difference in RWS at low latitudes matters in late winter, while difference in background wind with zonally asymmetric structure is important in spring.

The above results indicate that the larger amplitudes of $s = 1$ QSWs in early-SFW years are caused by stationary Rossby waves which originate in low latitudes. It is shown that synoptic-scale waves may also contribute to the larger amplitudes of $s = 1$ QSWs in early-SFW years.

In chapter 4, summary and concluding remarks are given.