論文の内容の要旨

Roles of Rossby wave and gravity wave generation in the middle atmosphere in the interhemispheric coupling
（南北半球間結合における中層大気でのロスビー波および重力波発生の役割）

氏　名　安井　良輔

Stratospheric Sudden Warmings (SSWs) often occur at the polar region in the winter northern hemisphere (NH). This is a phenomenon in which a Lagrangian mean meridional circulation in the NH stratosphere is driven by forcing of stationary Rossby waves (RWs) originating from the troposphere, resulting in adiabatic heating (cooling) in the Arctic (equatorial) stratosphere. It has been reported using satellite observations that warming at high latitudes in the summer mesosphere and lower thermosphere (MLT) of the southern hemisphere (SH) appears during an Arctic SSW. This phenomenon has also been confirmed using numerical model simulations. Based on these results, a scenario of interhemispheric coupling of temperature anomaly through the regions from the NH stratosphere and mesosphere to the SH MLT region has been proposed. This scenario describes that the interhemispheric coupling occurs due to the modulation of mesospheric meridional circulation driven by forcing of gravity waves (GWs) originating from the troposphere. On the other hand, when the warm anomaly is formed at NH high latitudes in the stratosphere, a cold anomaly is formed over the region across the equator to SH low latitudes in the stratosphere. Moreover, the quasi 2-day waves (QTDWs), which are identified as Rossby-gravity normal mode with $(s,\ n-s)$ = (3, 0) and give strong wave forcing in the SH mesosphere, develop during an SSW, resulting in warming at SH mid-latitudes in the upper mesosphere. These features show that the previous scenario of the interhemispheric coupling may not be complete. Recently, it is also shown that RWs and GWs are respectively generated from the barotropic (BT) and/or baroclinic (BC) instability in the winter mesosphere and from the shear instability in the summer mesosphere. These RWs and GWs generated in-situ in the mesosphere may largely influence the momentum budget in the MLT region. This study revisits the interhemispheric coupling following the NH SSWs from a viewpoint of wave forcing not only by GWs and RWs originating from the troposphere but also by GWs, RWs, and Rossby-gravity waves (RGWs) generated in-situ in the middle atmosphere. This study also elucidates causes of the warm anomaly in the SH MLT region that occurs in the interhemispheric coupling.

In this study, data for the neutral atmosphere from simulations by a whole atmosphere model called Ground–to–topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) are analyzed. The model resolution is T42L150. Orographic and non-orographic GW parameterizations are included. The model is nudged by the Japanese 25-year Reanalysis (JRA-25)/Japan Meteorological Agency Climate Data Assimilation System (JCDAS) data below about a height of 30 km. The analyzed time period is 19 boreal winter seasons in the time period of December 1996 to March 2015. The analyzed height region is from the surface to 120 km. To validate the reality of the model fields in the stratosphere and lower mesosphere, Aura Microwave Limb Sounder (MLS) observation and Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) data are also analyzed.

The interhemispheric coupling events are extracted as cold equatorial stratosphere events: first, a temperature anomaly from the climatology is calculated. A 90-day running mean is removed from the temperature anomaly (hereafter referred to as "anomaly") to exclude the effects of 11-year solar activity cycle. Second, the time period of the cold equatorial stratosphere events is defined as that during which the temperature anomalies at (0 °N, 5 hPa) and (20 °S, 5 hPa) are lower than twice of the standard deviation ($\sigma_{0\,°\mathrm{N}}$ and $\sigma_{20\,°\mathrm{S}}$), and the day with the coldest anomaly is defined as the central day (Day = 0). A composite analysis is performed for the anomaly of the temperature, wind, potential vorticity, wave activity flux, and wave forcing. The disturbances are divided into three as follows: first, migrating tides with zonal wavenumber 1–3 are extracted from the original data as a tidal component. Second, using Fourier analysis, the remaining component is divided into RWs/RGWs with wave periods longer than 24 hours and (resolved) GWs with wave periods shorter than or equal to 24 hours. The contribution of each wave forcing to the momentum budget is examined.

First, the temperature, wind, wave activity, and wave forcing are analyzed from a viewpoint of zonal mean fields. The cold anomaly in the equatorial stratosphere extends latitudinally to about 40 °S. This is caused by a strong wave forcing in the NH stratosphere. When the cold equatorial stratosphere occurs, a warm anomaly first appears at SH high latitudes in the lower thermosphere (Day = +4). Subsequently, the warm anomaly region moves down to the SH upper mesosphere (Day = +9).

Compared with the wave forcing anomaly due to GWs and RWs/RGWs, these warm anomalies in the SH MLT region are caused by resolved GWs for the lower thermosphere and by RWs/RGWs, especially QTDWs, for the upper mesosphere. Therefore, the interhemispheric coupling seems to occur through a different mechanism from that proposed by the previous studies. Furthermore, it is also revealed that QTDWs and resolved GWs that cause the warm anomalies in the SH MLT region are radiated respectively from BT/BC instability and from shear instability in the mesosphere. These instabilities are formed by parameterized GW forcing, namely, GWs originating from the SH troposphere. It is suggested that the parameterized GW forcing is modulated by the westward wind anomaly in the SH stratosphere.

Previous observations and numerical simulations showed that there is a wide range of time lag of ~5–10 days between the appearance of the temperature and wave forcing anomalies in the NH stratosphere and that of the temperature anomaly in the SH MLT region and that the time lag depends on the season. In this study, there is a long-time lag of ~5 days between the date of the warm anomaly maximum in the SH lower thermosphere and that in the SH upper mesosphere on average. This result is consistent with the time lag shown in the previous observational studies. This may be because QTDWs need a longer time (several days) to develop in the mesosphere and propagate to the upper mesosphere than resolved GWs (approximately 1 day). As shown by the previous studies, the seasonality of the growth rate of the QTDWs is large, and the QTDWs hardly develop in the first half of December and the second half of February. Thus, it is considered that the wide range of the time lag and its seasonality of the time lag reported in the previous studies are due to the fact that the two types of waves (i.e., GWs and QTDWs) play important roles in the interhemispheric coupling.

Next, causes of the cold anomaly in the equatorial stratosphere are examined by comparing strong cold events with weak cold events. This cold anomaly is important to form the westward wind anomaly at SH low and mid-latitudes in the stratosphere and mesosphere. A negative wave forcing anomaly in the NH upper stratosphere and lower mesosphere is extended to NH low latitudes during the strong cold equatorial stratosphere events. The negative wave forcing anomaly strengthens the middle atmosphere Hadley circulation. The strengthened middle atmosphere Hadley circulation causes upward flow anomaly in the equatorial stratosphere. The negative wave forcing anomaly at NH low latitudes is caused by the breaking of the stationary RWs with zonal wavenumber $s = 1$ originating from the troposphere and by the generation of secondary RWs with zonal wavenumber $s = 4$–10 and periods $\tau = 1$–5 days from the BT instability related to the stationary RW breaking.

Last but not the least, the longitudinal structure of the interhemispheric coupling is analyzed. First, the polar vortex largely shifted to a lower latitude around 340 °E and 70 °N associated with the development of the Aleutian high, and the southwestern edge of the polar vortex is collapsed. The latitudinal gradient of angular momentum becomes small over 150 °E–340 °E. A strong meridional flow anomaly is formed in the longitude region, which leads to a strong cold anomaly at 290 °E–350 °E in the equatorial stratosphere.

In the SH mesosphere, the occurrence frequency of shear instability increases in a longitude region of ~-60 °E–~60 °E, where the parameterized GW forcing anomaly is observed. More GWs propagating upward and westward are radiated from the shear instability area. Therefore, likely due to the westward propagation of the GWs from the shear instability and their breaking in the lower thermosphere, the warm anomaly at SH high latitudes in the lower thermosphere appeared to the west of the cold anomaly in the equatorial stratosphere. The negative latitudinal gradient of potential vorticity, which is a necessary condition of BT/BC instability, is enhanced over 80 °E–200 °E. In addition, an anomaly of QTDW activity is positive in the same longitude region. These longitudinal characteristics are consistent with the scenario obtained from the analysis of the zonal mean field in this study.

Many previous studies considered that interhemispheric coupling is caused mainly by waves originated from the troposphere. However, the mechanism revealed by this study indicates that waves generated in the middle atmosphere make a significant contribution to the meridional circulation, especially in specific events such as SSWs.

Because the model used in this study has a relatively low resolution, resolved GWs may be different from those in the real atmosphere. Therefore, it is necessary to statistically revisit the scenario presented in this study using a GW-resolving model. Moreover, it is necessary to analyze the stationary wave development observed in the SH stratosphere during the cold equatorial stratosphere events in the future since the stationary waves modulate the parameterized GW forcing and make its longitudinal structure in the SH stratosphere. Furthermore, it is recently suggested that there is a correlation between the tropospheric Arctic oscillation and the Antarctic oscillation. This correlation could be related to the change in the zonal winds in the SH stratosphere during the cold equatorial stratosphere events shown in this study. In addition, the effect of the tidal forcing is small in the altitude region examined in this study. However, its amplitudes are large above 120 km. The tides generate an electric field in the ionosphere, which is a significant parameter of the ionized atmosphere. The waves generated in the middle atmosphere may affect the momentum and energy budget not only of the neutral atmosphere but also of the ionized atmosphere. It is necessary to study the effects of tide modulation on the ionosphere in addition to the impact of GWs, RW, and RGWs generated in the SH MLT region.