論文の内容の要旨

A study of the hierarchical structure in the Antarctic atmosphere based on PANSY radar observations and high-resolution general circulation model simulations

（PANSY レーダー観測と高解像度大気大循環モデル再現実験に基づく南極大気の階層構造の研究）

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It is well known that atmospheric Rossby waves (RWs) and gravity waves (GWs) excited mainly in the troposphere, propagate upward, and drive the general circulation in the middle atmosphere by transporting momentum. The momentum transports by GWs and RWs have conventionally been investigated separately. However, several studies using a high-resolution general circulation model (GCM) that explicitly resolves GWs have reported that GWs are radiated from a distorted RW in the stratosphere. Furthermore, studies using a high-top GCM permitting GWs which covers from the ground to the upper mesosphere and above have shown that in-situ RW generation in barotropic and/or baroclinic instability is maintained by the GW forcing in the mesosphere. Thus, we have glimpsed the interplay between RWs and GWs, which is a part of relations between atmospheric phenomena having different temporal and spatial scales within a hierarchical structure of the middle atmosphere including RWs and GWs. A few studies have attempted to elucidate the hierarchical structure of the atmosphere composed of various phenomena having different scales.

Recent studies that compared satellite observations and GCM simulations suggested that GWs generated around the Antarctica significantly contribute to the middle-atmosphere general circulation, but the observation of the Antarctic atmosphere was a challenge due to the harsh environment. In, 2011, the Program of the Antarctic Syowa (PANSY) radar, which is the first Mesosphere-Stratosphere-Troposphere/Incoherent Scatter (MST/IS) radar in the Antarctic, was installed at Syowa Station (69.0°S, 39.6°E) and it enables to examine RWs and GWs in the Antarctic regions using direct measurements with a fine vertical resolution. The purpose of this study is to elucidate the hierarchical structure in the Antarctic atmosphere over broad spatial and temporal ranges from Kelvin-Helmholtz (KH) billows to the polar vortex, based on the observations by the PANSY radar and radiosondes with high accuracy and resolution at Syowa Station as well as numerical simulations using GW-permitting GCMs. In particular, this study focuses on the atmospheric phenomena observed at Syowa Station during the observational campaigns performed in 2019.

In Chapter 2, we focus on the dynamical relations among relatively small-scale phenomena from KH billows to synoptic-scale waves. During 14–24 March and 2–12 August 2019, observation campaigns targeting atmospheric turbulence in the troposphere and lower-stratosphere were performed using the PANSY radar and radiosondes. The PANSY radar performed the observation with the frequency radar interferometric imaging technique, which provides the data with high resolutions in time and range. A total of 73 'S-shaped' structures, which are characteristic of KH billows, were detected in the time-height section of echo power during the campaigns. Numerical simulations using the Non-hydrostatic Icosahedral Atmospheric Model (NICAM) were also carried out in order to investigate the spatial structure of the atmospheric phenomena related to the generation of the observed KH billows in these periods.

First, a detailed analysis for the observed KH billows was performed. Since the height and time regions where clear KH billow structures were found were limited, we focused on two representative examples out of all observed KH billows. The first case is the KH billow with the longest duration, likely excited by a strong vertical shear associated with orographic GWs according to the analysis based on the observation as well as the NICAM simulations. The theoretically infinite wave periods and steadily maintained phase structure of orographic GWs are consistent with the long duration of this KH billow. The second case is the KH billow with the deepest vertical structure. The KH instability of this case was likely caused by upper-tropospheric jet associated with a cyclone. These results indicate that there are at least two excitation mechanisms of KH billows in the Antarctic region. These two excitation mechanisms reflect the characteristics in the Antarctic: steep coastal topography and well-developed synoptic-scale cyclones.

We also examined the most unstable modes expected from a two-dimensional linear stability theory applied for the idealized background field of the two cases mentioned above. The most unstable modes have horizontal wavelengths and depths that roughly match those of observed KH billows. These results suggests that the observed KH billows are consistent with the maximum growth mode expected from linear stability theory.

This study also showed the dynamical statistical characteristics of KH billows in the Antarctic for the first time. The mean and probability density function of the horizontal wavelength, thickness, and aspect ratio of all 73 observed KH billows waves are almost the same as those estimated by the mid-latitude observations. It means that the dynamical properties of KH billows in the Antarctic are found to be similar to those in mid-latitudes. On the other hand, the magnitude of vertical shear of the background wind is about 60 % of that estimated at mid-latitudes. Moreover, the wave period of the KH billows is about twice as long as that at mid-latitudes. This result probably likely reflects that the tropospheric jets over the Syowa Station are not as strong as those over Japan.

In Chapter 3, we focused on the dynamical relations among relatively large-scale phenomena from GWs to the polar vortex. Specifically, we examined the time evolution of the dynamical properties of GWs and RWs during the Southern Hemisphere stratospheric sudden warming in September 2019 (SSW-SH 2019). Simultaneous measurements using the PANSY radar and radiosondes were made from 26 August to 2 October 2019, targeting disturbances in the lower stratosphere during the SSW-SH 2019. In addition, short numerical simulations using a high-resolution (T639L340) Japanese Atmospheric General circulation model for Upper Atmosphere Research (JAGUAR) were performed to investigate the dynamical properties of GWs and RWs especially quasi-6-day waves (Q6DWs) below the lower thermosphere. Some previous studies reported that Q6DWs in the mesosphere and above were enhanced during the SSW-SH 2019.

First, using the PANSY radar and radiosonde observation data, the high-resolution JAGUAR simulations were verified. It was shown that the high-resolution JAGUAR reproduced GWs in the lower stratosphere well, but the amplitude of the simulated vertical wind disturbances associated with the GWs was about one-fifth of that observed.

Next, we examined the spatial distribution and time variation of GWs during the SSW-SH 2019. We found large negative momentum fluxes associated with GWs in the stratosphere above the Andean Mountains and the Antarctic Peninsula before the SSW onset (7 September) and above and leeward of the Ross Sea after the onset. On the other hand, in the mesosphere (especially above

z = 75 km), largely negative momentum flux was observed to the south of 40°S before 3 September. During 3–10 September when the polar vortex became obscure, positive momentum flux was seen around 60°S. After 10 September when the polar vortex reappeared, negative momentum flux was observed again to the south of 40°S, although its magnitude was smaller than that before 3 September.

We also investigated the dynamical characteristics of Q6DWs using the JAGUAR-Data Assimilation System (JAGUAR-DAS) analysis data and high-resolution JAGUAR simulations for SSW-SH 2019. The JAGUAR-DAS analysis data which can be used for analysis of waves with low wavenumbers enable us to analyze RWs for longer time periods. There were two types of Q6DWs, one with eastward phase velocity (Q6DW-E) and the other with westward phase velocity (Q6DW-W). It was found that Q6DW-Es were dominant to the south of 50°S before 10 September, and Q6DW-Ws were dominant in both hemispheres after that in the mesosphere. The Q6DW-E and Q6DW-W have a baroclinic structure in the vertical, which is different from a barotropic structure of normal mode 5-day Rossby wave.

Excitation mechanisms of the Q6DW-E and Q6DW-W were investigated in terms of Eliassen-Palm fluxes (EP fluxes) and modified potential vorticity (MPV). It was suggested that the Q6DW-E is an unstable wave due to baroclinic-instability, which is conditioned by a pair of the meridional gradient of MPV: a negative gradient in high-latitude mesosphere and a positive gradient in the stratosphere. This inference is supported by the fact that the Q6DW-E was no longer observed after the negative MPV gradient in the mesosphere disappeared. On the other hand, the Q6DW-W is likely to be an internal RW generated from barotropic/baroclinic instability in the upper stratosphere over 60°–80°S. This dynamical instability was associated with the MPV maximum due to the maximum of the static stability broadly existing over 40°–70°S in the upper stratosphere. We showed that the static stability maximum was caused by a downward residual flow from z = 50 km at 80°S to z = 70 km at 40°S. This downward residual flow was partly driven by a combination of the positive RW forcing (eastward acceleration) expanding from z = 50–80 km at 80°S to z = 70 km at 40°S due to the Q6DW-E and the negative wave forcing (westward acceleration) in the region from z < 50 km at 80°S to z < 60 km at 40°S due to the convergence of RWs propagating from the mid- and high-latitudes troposphere. In addition, a pair of the positive GW forcing in the polar mesosphere and the negative GW forcing in the stratosphere contribute similarly to the downward residual flow atalmost the same magnitude. It was also suggested that the Q6DW-W originated from the Southern Hemisphere and spread the Northern Hemisphere. We suggested that the positive GW forcing in the region where the polar vortex shifted to the lower latitudes due to the SSW play an important role in the excitation of Q6DW-W in September 2019. This is consistent with the most obvious dominance of Q6DW-W in September 2019 during 2015 and 2020.

In this thesis, we examine the relations between phenomena with different scales in the atmospheric hierarchy structure. In the first half, we suggested that orographic GWs and cyclones having the enhanced upper-tropospheric jets likely excited KH billows in the Antarctic coastal region. They are characteristic phenomena in the Antarctic coastal region. In the second half, we confirmed that RW and GW forcings weakened the polar vortex and eventually led to the SSW-SH 2019. We also showed how the GW distribution varies with the shift of the polar vortex during the SSW-SH 2019. For Q6DWs, we indicated that the mesospheric RW and GW forcings contribute to the excitation of Q6DW-E and that the Q6DW-E forcing and the GW forcing distribution associated with the shifted polar vortex likely contributed to the excitation of internal RWs, namely Q6DW-W, from the barotropic and/or baroclinic instability. However, the relations among atmospheric phenomena with different temporal and spatial scales shown in this study are only a part of the hierarchical structure in the Antarctic atmosphere. More studies based on both high-resolution observations and numerical simulations utilizing GW-permitting GCMs are necessary to understand the hierarchical structure further. By extending the analysis period longer, it will be possible to examine seasonal and year-to-year variations in the relationships within the hierarchical structure.

In particular, an accumulation of case studies is essential for elucidating whether there are other new excitation mechanisms of KH billows and for statistical significance for the mean values and probability density function of characteristics of KH billows in the Antarctic. It is also interesting to confirm the robustness of the excitation mechanism of Q6DW shown in this study. The examination of the interannual variation of Q6DW is necessary in terms of the Q6DW-E and GW forcing, which are a key for the excitation mechanism of Q6DW-W. The investigation what determines the time lag between the appearance of the barotropic/ baroclinic instability and the onset of Q6DW-W dominance is also future work.