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Ryosuke Shibuya

Dynamical Characteristics of Inertia-Gravity Waves in the Antarctic Mesosphere

Analyses Combining High-Resolution Observations and Modeling

Doctoral Thesis accepted by
The University of Tokyo, Tokyo, Japan

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Dedicated to my late father.

Supervisor's Foreword

Gravity waves, along with Rossby waves, are types of fundamental atmospheric waves. Through their potential to transport momentum upward, they contribute to the shape and position of the westerly jet in the upper troposphere and to the formation of a weak wind layer near the mesopause. Gravity waves are also one of the major drivers of quasi-biennial oscillations and semiannual oscillations in the equatorial stratosphere and mesosphere. Since large-scale phenomena affected by gravity waves are essential atmospheric elements that crucially affect daily weather and long-term forecasts, many climate models utilize parameterization methods to calculate momentum deposition by unresolved gravity waves. It is known, however, that current climate models using conventional parameterizations have serious problems, including significant cold bias in the winter stratosphere. Recent studies have also indicated that parameterized gravity waves in climate models are not realistic in the high latitudes of the Southern Hemisphere, including the Antarctic. In response to such recognition regarding the importance of gravity waves in the Antarctic, several observational campaigns have been performed to examine gravity waves in the lower Antarctic stratosphere.

However, in the Antarctic, it is still challenging to obtain observations of the mesosphere from the ground due to its harsh environment. Although gravity wave resolving models that cover the middle atmosphere have been recently utilized to elucidate the dynamics of mesospheric gravity waves, only a few studies have focused on the dynamical characteristics of gravity waves in the Antarctic mesosphere.

The purpose of Dr. Shibuya's study is to elucidate dynamical characteristics, such as wave parameters and propagation and generation mechanisms, by utilizing two novel research tools. One is the first Mesosphere-Stratosphere-Troposphere/Incoherent Scattering (MST/IS) radar in the Antarctic, which was recently installed at Syowa Station (39.6°E, 69.0°S) under a project named "Program of the Antarctic Syowa MST/IS radar (PANSY)." The PANSY radar is the only observational instrument that captures both fine vertical and temporal structures of mesospheric disturbances, including vertical wind. The other is the Non-hydrostatic Icosahedral Atmospheric Model (NICAM), which is used to examine the three-dimensional structures of mesospheric disturbances. In his study, the top of the NICAM is extended to an altitude of 87 km, with a vertical grid spacing in the middle atmosphere of approximately 400 m. This is the first non-hydrostatic simulation that tries to examine mesospheric gravity waves with a high-vertical-resolution model. Moreover, the largest advantage of his study is that the dynamical characteristics of gravity waves simulated by the NICAM can be validated by high-resolution PANSY radar observations.

However, such high-top and high-vertical-resolution settings require a large computational burden. Thus, he first developed regionally enhanced and quasi-uniform meshes in the Antarctic by a transformation method with icosahedral grids. The target region composed of fine meshes is connected to an outer region with coarse meshes, as transformed by the Schmidt transformation, to maintain isotropy in the grid shapes. The reason for selecting the uniform fine mesh, in contrast to the conventional approach, which gradually changes the mesh size, is that previous studies found that the momentum flux simulated by the model largely depends on the horizontal resolution. He showed that fine and quasi-uniform meshes in the target region are successfully generated using the new transformation.

The first observation by a complete system of the PANSY radar was performed on March 16–24, 2015. At heights of 70–80 km, large-amplitude disturbances were observed by the PANSY radar. Previous studies have suggested that disturbances with a period of 12 h in the mesosphere are mainly due to semidiurnal migrating tides or semidiurnal non-migrating tides. However, he noticed that the observed vertical wavelength is too short for semidiurnal tides. He then performed a simulation starting from the initial values given by the re-analysis data and succeeded in simulating waves with a quasi-period of 12 h, which was similar to those observed by the PANSY radar. The waves have a horizontal wavelength of approximately 2000 km, which is much shorter than that of the semidiurnal tide. Moreover, the parameters of the simulated waves well satisfy the dispersion relation of the linear inertia-gravity wave. These results strongly indicate that the disturbances with a quasi-period of 12 h observed by the PANSY radar are not planetary scale waves, such as tides, but are attributable to large-scale inertia-gravity waves. This is a remarkable finding showing the importance of gravity waves.

The generation and propagation processes of wave packets simulated at the location near Syowa Station are examined by backward ray tracing. In one case, the wave packet is likely generated by the spontaneous radiation mechanism around the tropospheric jet, as noted in a previous study. In another case, however, it is identified that the wave packet is generated around the core of the polar night jet at the stratopause, and it is suggested that the generation occurs with similar spontaneous radiation mechanisms.

He further carried out a long-term simulation using the high-top, non-hydrostatic, general circulation model to analyze mesospheric gravity waves in five months from April to August 2016, when continuous observations were made by the full system of the PANSY radar. Successive runs lasting 7 days were made with the initial condition from the MERRA re-analysis data, with an overlap of two days between the two consecutive runs, to maintain long-term simulations sufficiently close to the re-analysis data. Analyses were made for the last five days for each run. It was confirmed by comparison with the PANSY radar observation that mesospheric wind fields simulated by NICAM are realistic.

The statistical analysis of gravity waves is performed at latitudes from 30°S to 90°S, where the grid is sufficiently fine and uniform. First, the kinetic and potential energies of gravity waves and the momentum and energy fluxes associated with gravity waves are examined as a function of frequency. The power spectrum of the meridional wind fluctuations at a 70 km height has an isolated peak around frequencies slightly lower than the inertial frequency f at latitudes from 30°S to 75°S. On the other hand, there are isolated spectral peaks in the meridional wind fluctuations at frequencies of approximately ($2\pi/8$ h) from 78°S to 90°S. These results are consistent with the observations by the PANSY radar at 69°S and the lidar observations at McMurdo station at 78°S. It is found that gravity waves at lower latitudes, which constitute a broad peak at the inertial period and at slightly longer periods, have two origins: one is orographic origins propagating from the Antarctic Peninsula and Antarctic coast, and the other is non-orographic origins, such as convections and jet—front systems at approximately 45°S. Gravity waves from both origins propagate upward being concentrated at the latitude of the polar night jet. Statistical features and geographical features of the mesospheric gravity waves in the real atmosphere, which cannot be identified from observational data alone, are organized and clarified for the first time. These features include a long wavelength of more than 1000 km for the waves constituting the peak around the inertial period and a shorter wavelength of less than 1000 km for the peaks at other frequencies, with different signs of the momentum flux depending on the frequency, as well as the spatial distribution of gravity waves, which is non-uniform and variable depending on their period. Another important contribution of Dr. Shibuya's work is to show the high performance of his model for the shape of the frequency power spectrum of vertical wind fluctuations. High-resolution reproduction experiments of the troposphere and lower stratosphere with the conventional NICAM show good agreement of the horizontal wind frequency spectrum with the observed spectra, which follow the −5/3 to −2 power laws, respectively, but the vertical wind frequency spectrum, which shows a -6 power law, fails to reproduce the observed spectra, which follow −5/3 to 0 power laws. In contrast, his model of the revised high-resolution mesospheric NICAM succeeded in reproducing a spectrum consistent with the observations not only for the horizontal wind component but also for the vertical wind component. This result strongly supports the reliability of the reproduced gravity waves by the non-hydrostatic general circulation model and will largely contribute to the future of gravity wave studies.

Dr. Shibuya's presentations of these results have been highly regarded, and he has been awarded the Early Carrier Scientist Poster Award of the 6th SPARC General Assembly in 2018; the Outstanding Student Presentation Award from

Japan Geoscience Union in 2017; and the Student Presentation Award (Aurora Medal) from the Society of Geomagnetism and Earth, Planetary and Space Sciences in 2015. His Ph.D. thesis was awarded the Research Encouragement Award by the Graduate School of Science at The University of Tokyo in 2018.

Tokyo, Japan
June 2019

Prof. Kaoru Sato

List of Published Articles

Parts of this thesis have been published in the following journal articles:

Shibuya R., H. Miura and K. Sato, 2016: A grid transformation method for a quasi-uniform, circular fine region using the spring dynamic, Journal of the Meteorological Society of Japan, 94, https://doi.org/10.2151/jmsj.2016-022.

Shibuya R., K. Sato, M. Tsutsumi, T. Sato, Y. Tomikawa, K. Nishimura, and M. Kohma, 2017: Quasi-12h inertia-gravity waves in the lower mesosphere observed by the PANSY radar at Syowa Station (39.6 °E,69.0 °S), Atmos. Chem. Phys., 17, 6455–6476, https://doi.org/10.5194/acp-17-6455-2017.

Shibuya R., K. Sato, 2019: A study of the dynamical characteristics of inertia-gravity waves in the Antarctic mesosphere combining the PANSY radar and a non-hydrostatic general circulation model, Atmos. Chem. Phys, 19, 3395–3415, https://doi.org/10.5194/acp-19-3395-2019.

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