論文内容の要旨

A study of dynamical characteristics of inertia-gravity waves in the Antarctic mesosphere by combination of high-resolution observations and modeling

（高解像度観測と数値モデルを組み合わせた

南極中間圏重力波の力学特性に関する研究）

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Abstract

Gravity waves are atmospheric waves with a restoring force of buoyancy that transport momentum upward from the troposphere to the middle atmosphere. Since horizontal wavelengths of a significant part of gravity waves are shorter than typical resolutions of the present climate models, many climate models utilize parameterization methods to calculate momentum deposition by the unresolved gravity waves. All of these gravity wave parameterizations are based on several simplifications and assumptions on dynamics of gravity wave characteristics. However, owing to complex nature of gravity waves, it is still challenging to represent the effects of gravity waves by parameterizations correctly. Therefore, observational constraints on dynamical characteristics of gravity waves to the parameterizations are inevitably required. Recent studies indicate that parameterized gravity waves in climate models are not realistic in the Antarctic. In response to such recognitions for the importance of gravity waves in the Antarctic, several observational campaigns to examine the gravity waves in the lower Antarctic stratosphere have been performed.

In the Antarctic, on the other hand, it is still challenging to perform observations of the mesosphere from the ground under its harsh environment. Although gravity-wave resolving models which cover the middle-atmosphere have been recently utilized to elucidate the dynamics of the mesospheric gravity waves, only a few studies focus on dynamical characteristic of the gravity waves in the Antarctic mesosphere.

The purpose of this study is to elucidate the dynamical characteristics such as wave parameters, 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) as a project named “Program of the Antarctic SYowa MST/IS radar”. The PANSY radar is designed to observe three-dimensional winds at high

time and vertical resolutions in the troposphere, stratosphere and mesosphere, which is the only observational instrument to capture both fine vertical and temporal structures of mesospheric disturbances including vertical wind. Furthermore, a Non-hydrostatic ICosahedral Atmospheric Model (NICAM) is also used to examine three dimensional structures of mesospheric disturbances. In this study, the top of the NICAM is extended to an altitude of 87 km with a vertical grid spacing in the middle atmosphere of about 400 m. This is the first non-hydrostatic simulation which tries to examine the mesospheric gravity waves with a high-vertical-resolution model, since currently most mesospheric gravity wave permitting models are the hydrostatic general circulation model. Moreover, the largest advantage of this study is that dynamical characteristics of gravity waves simulated by the NICAM can be validated by the high-resolution PANSY radar observation.

However, such a high-top and high-vertical-resolution setting requires a large computational burden. Thus, as a preparation of the mesospheric gravity wave permitting simulations, regionally enhanced and quasi-uniform meshes in the Antarctic by a transformation method with icosahedral grids are newly developed. The target region composed of fine meshes are connected to an outer region with coarse meshes transformed by the Schmidt transformation in order to maintain an isotropy of grid shapes. To realize these requirements, the characteristic lengths of the spring connecting grid nodes are analytically determined. It is shown 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 from March 16–24, 2015. Over this period, strong polar mesosphere winter echoes were detected, which likely resulted from a quite strong magnetic storm event. At heights of 70-80 km, large-amplitude disturbances are observed by the PANSY radar. Estimated vertical wavelengths, wave periods and vertical phase speeds of the disturbances are approximately 13.7 km, 12.3 h and −0.3 m s^{-1}, respectively. Previous studies suggested that disturbances with a period of 12 h in the mesosphere are mainly due to the semi-diurnal migrating tides or the semi-diurnal non-migrating tides. However, the wave parameters obtained in this study are quite different from those of the semi-diurnal tides.

To examine spatial structures and generation mechanisms of the wave disturbances, a model simulation using the Non-hydrostatic Icosahedral Atmospheric Model (NICAM) is performed in which the newly developed grid configuration in Chapter 2 is applied. The target region is a region south of 30°S centered at the South Pole with a horizontal resolution of 36 km. The vertical grid spacing is 400 m at heights from 2.4 km to 80 km with a 7 km thick sponge layer above 80 km.

The NICAM successfully simulates the large-amplitude disturbances and with a period of quasi 12 h, which is consistent with the observations. By using time and spatial filters, amplitudes of the diurnal and semi-diurnal migrating tides and small-scale gravity waves are examined in the simulated wind fields. The small-scale gravity waves are defined as components with horizontal wavelengths smaller than 1000 km, as frequently examined by previous studies. Their amplitudes are much smaller than observations, suggesting that dominant wave structures in the mesosphere are not due to the migrating tides nor the small-scale gravity waves. The remaining component has quite a similar structure and amplitudes to those by the observations. Wave parameters, such as vertical wavelengths and wave periods, simulated by the model agree well with those estimated by the observations. Moreover, the parameters of the simulated waves are consistent with the dispersion relation of the linear inertia-gravity wave. These results indicate that the disturbances with a period of quasi 12 h observed by the PANSY radar are attributable to large-scale inertia-gravity waves.

The generation and propagation processes of wave packets simulated at Syowa Station are examined by a backward ray tracing. The first case is a wave packet which appears at 0600 UTC 21 March at Syowa Station at a height of 70 km and propagates from the location of (~100°E, ~40°S) at a height of 23 km for 48 hours. It seems that the wave packet is captured over the tropospheric jet core at 0600 UTC 19 March. Moreover, it is shown by examining a residual from the nonlinear balanced equation that the tropospheric jet is significantly imbalanced around the region. Thus, the wave packet is likely generated by the spontaneous radiation mechanism around the tropospheric jet. The second case is a wave packet which appears at 0000 UTC 19 March at Syowa Station at a height of 70 km and whose amplitude becomes significantly weak around a height of 55 km. This feature indicates an existence of a wave source at this height. A longitude-height cross-section of the wave packet shows symmetric features above and below the core of the polar night jet at a height of 55 km. The energy flux diverges from the core of the polar night jet, suggesting that the wave packet is generated around the core of the polar night jet. For the spontaneous radiation of the inertia-gravity waves around the polar night jet, a generation mechanism associated with the semi-diurnal migrating tides is newly proposed. As vertical winds associated with a semi-diurnal migrating tide at the height of the core of the polar night jet are adiabatically present along the modulated θ surface, quasi 12 h inertia-gravity waves with $s = 2$ can be radiated by the spontaneous radiation. In addition, because of the horizontal shear of the background wind including the migrating tides, the deformation process can occur which causes the horizontal wavelength of the radiated quasi 12 h inertia-gravity waves shorter than that of the semi-diurnal migrating tide.

Furthermore, a long-term simulation using the high-top non-hydrostatic general circulation model is carried out 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 are made with the initial condition from the MERRA reanalysis data with an overlap of two days between the two consecutive runs to maintain long-term simulations sufficiently close to the reanalysis data. Analyses are made for the last five days for each run. It is confirmed by comparing with the PANSY radar observation that mesospheric wind fields simulated by NICAM are realistic, although the amplitudes of the wind disturbances seem to be slightly larger than radar observations. The latitude-height structure of the zonally-averaged zonal winds is also comparable to the MERRA reanalysis data.

Next, the frequency spectra of zonal, meridional and vertical wind fluctuations and temperature fluctuations are obtained for the period from June to August 2016. The power spectra of zonal and meridional wind fluctuations obey a power law with an exponent of approximately -5/3 in higher frequency region than the inertial frequency f (corresponding to $(2\pi/12.7$ h)), while that of vertical wind fluctuations has a flat structure (i.e., $\propto \omega^0$) at frequencies from $(2\pi/2$ h) to $(2\pi/5$ days). The power spectrum of the meridional wind fluctuations without the migrating tides has an isolated peak around frequencies slightly lower than f at latitudes from 30°S to 75°S. On the other hand, there are isolated spectral peaks of meridional wind fluctuations at frequencies of about (2π/8 h) for 78°S to 90°S. Moreover, the frequency power spectra of zonal and meridional components of the vertical momentum fluxes ($\mathrm{Re}[U(\omega)V(\omega)]$, $\mathrm{Re}[V(\omega)V(\omega)]$) are obtained for the period of JJA 2016 at altitude regions of 70-75 km by the zonal average (using 1280 time series data at each grid point). It seems that $\mathrm{Re}[U(\omega)V(\omega)]$ is mainly negative in the examined frequency region with an isolated peak at a frequency slightly lower than f. On the other hand, $\mathrm{Re}[V(\omega)V(\omega)]$ is positive at frequency regions higher than the inertial frequency f, while that is negative at frequency regions lower than f. Assuming upward energy propagating gravity waves, this result suggests that disturbances with frequencies higher than f propagate equatorward, while those with frequencies lower than f propagate poleward.

Last, the spatial structures of the kinetic and potential energies, momentum and energy fluxes of gravity waves defined by components with frequencies higher than (2π/30 h) are examined. The distribution of the momentum fluxes in the lower stratosphere are consistent with those shown by previous studies. In the upper stratosphere and the mesosphere, large kinetic and potential energies are distributed along the axis of the polar night jet. The zonal components of the vertical momentum fluxes are mainly negative and have maxima slightly poleward of the axis of the polar night jet. This fact indicates that the gravity waves propagate westward relative to the mean wind. The meridional components of the vertical momentum fluxes are negative along and equatorward of the jet axis and positive or almost zero poleward of the jet axis, suggesting the propagation of the gravity wave into the regions slightly poleward of the axis of the polar night jet.

Previous studies suggested that disturbances with a period of quasi 12 h are due to the semi-diurnal migrating/non-migrating tides. This study shows the possibility that such disturbances are due to quasi-inertial-period gravity waves with horizontal wavelengths larger than 1000 km. By comparing the frequency spectra in NICAM to observations, it is indicated that the statistical behaviors of the mesospheric disturbances simulated in NICAM are quite realistic in the high latitudes of the Southern Hemisphere. Moreover, it is shown that the quasi-inertial-period gravity waves have a large negative zonal momentum flux in the mesosphere.

For future studies, statistical analyses about parameters of the mesospheric gravity waves including intermittencies are interesting by combination of the PANSY radar observations and the high-top NICAM simulations. The origins of the spectral peaks around the quasi inertial frequency should be elucidated using the outputs by the high-top NICAM simulations. Further model development is needed for simulations for the period when the polar mesosphere summer echoes are detected by the PANSY radar for an altitude range of 80-95 km than the current available model top of NICAM. Such a very high top model can cover the whole mesosphere and provides invaluable data to understand momentum budgets in the Antarctic mesosphere where gravity waves are expected to play a significant role and affect the momentum and energy budgets in the themosphere/ionosphere by propagating further upward.