学位論文 （要約）

A study of climatology and intraseasonal-to-interannual variability of atmospheric gravity waves in the stratosphere based on high-resolution satellite data

高解像衛星観測データに基づく成層圏大気重力波のクライマトロジー、季節内変動および年々変動の研究

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Abstract

Since the importance of the horizontal propagation of gravity waves in the climatology and its relevance to model biases is recently recognized, the horizontal propagation characteristics of gravity waves are investigated by using observations. The climatology and the intraseasonal-to-interannual variability of gravity waves in the summer subtropics are also investigated because they play a dominant role in driving the meridional circulation in the stratosphere in the summer subtropics. In order to investigate gravity waves in the summer subtropics, an instrument that can detect gravity waves with short horizontal wavelengths is used because gravity waves generated by convection could have a broad range of horizontal wavelengths including short one.

Recently, on-board satellite instruments with high horizontal and vertical resolution have been developed and they allow us to detect gravity waves in a broader wavenumber-frequency range, which has not been observed yet. Atmospheric Infrared Sounder (AIRS) is one of such satellite instruments. The highest horizontal resolution of 13.5 km is suitable to study gravity waves in the stratosphere. Although the operational temperature product of AIRS was degraded to coarser horizontal resolution, new data was developed by using an updated temperature retrieval algorithm to allow original high horizontal resolution of AIRS. In the present study, the characteristics of gravity waves at an altitude of 39 km that is corresponding to the middle stratosphere are described by using high resolution temperature data made by this new retrieval algorithm and their climatology and intraseasonal-to-interannual variability over nine years from 2003 to 2011 is also investigated.

Since AIRS is a nadir-view instrument, it is sensitive to gravity waves with vertical wavelengths longer than about 15 km. Because vertical group velocities of those gravity waves are large, gravity wave packets probably stay in an altitude range in a short time period and be localized horizontally. Thus, in the present study, the S-transform is used, which is a wavelet analysis and is suitable for the detection of localized gravity wave packets, in order to estimate the amplitudes of temperature fluctuations, the horizontal wavelengths, and the direction of the horizontal wavenumber vector of gravity waves. Before the analysis, the random noise originating from the temperature retrieval process was estimated in the location versus wavelength space using the S-transform analysis to extract meaningful signals. It is found that the noise spectra are mainly distributed in the range of horizontal wavelengths shorter than about 70 km, and thus the temperature perturbations with horizontal wavelengths longer than 70 km were regarded as meaningful signals of gravity waves.

The results of the present study are follows. The seasonal variation and latitudinal dependence of the zonally averaged gravity wave amplitudes, horizontal wavelengths, and direction of the horizontal wavenumber vector are investigated. Gravity waves have larger amplitudes at the winter high latitudes and in the summer subtropics. These peaks are likely due to the significant Doppler shift by strong mean winds. Gravity waves tend to have vertical wavelengths that are longer enough to be detected by AIRS. This effect is usually called as the observational filter. These latitudinal and temporal variations of observed gravity wave variance are consistent with previous studies that used data from Microwave Limb Sounder (MLS), which was also sensitive to longer vertical-scale fluctuations. The horizontal wavelengths are large in the solstice season and latitudes where gravity waves have large amplitudes. It is interesting that the mean meridional component

of horizontal wavenumber vector near the polar night jet in the Southern Hemisphere is northward (southward) at latitudes higher (lower) than 60°S. This distribution may imply that gravity waves propagate into the polar night jet axis. Although such the propagation of gravity waves toward the polar night jet has been suggested by a general circulation model simulation that resolved gravity waves and also by several observational studies that analyzed mountain waves from satellite data, the present study is the first that reports an existence of gravity waves that focus to the jet axis in a climatological sense using global observations.

The seasonally averaged gravity wave amplitudes have a clear longitudinal dependence in the summer subtropics, while the mean zonal wind does not change much longitudinally. This longitudinal dependence of gravity waves is similar to that of precipitation, and this feature is consistent with previous studies. Interestingly, the maxima of the gravity wave amplitudes are shifted southward from the South Pacific Convergence Zone (SPCZ) by about 3°. If a typical horizontal wavelength of 225 km is used as an estimation, theoretical considerations suggest that there are three possible mechanisms that can explain this latitudinal difference at least partly. The first one is the stronger excitation of gravity waves due to the existence of the islands. The second one is the selective excitation of gravity waves due to the wind shear. The last one is the refraction of gravity waves due to the meridional gradient of the zonal wind. It is noted that the total distance of gravity wave propagation explained by the selective excitation and refraction mechanisms is 375 km in maximum, which is marginally equivalent to the latitudinal propagation of 3° if and only if a gravity wave has a horizontal wavelength of 700 km, although such gravity waves are rarely observed.

The author focused on the interannual variability of gravity wave amplitudes in the austral summer subtropics because the year-to-year variation of gravity wave

amplitudes is larger in the austral summer subtropics than in the boreal summer subtropics. The DJF-mean time series of gravity wave amplitudes and of precipitation are regressed to that of sea surface temperature anomalies in the NINO.3 region. Precipitation around the SPCZ shifts northwestward (southeastward) in the El Niño (La Niña) phase and gravity wave amplitudes show similar change depending on the El Niño-Southern Oscillation (ENSO) phase. Moreover, it is shown that the interannual variability of the regional mean precipitation in the equatorial central South Pacific and to the east of the SPCZ are positively correlated with the NINO.3 time series, while that to the west of the SPCZ shows negatively correlations with NINO.3. Mean gravity waves exhibit a similar interannual variability to the precipitation in all three regions. It is also shown that such regional dependence of the interannual variability of gravity wave amplitudes cannot be explained by the observational filter effect. It is emphasized that there are no previous studies showing a clear relation of the longitudinal dependence of interannual variability of gravity wave amplitudes to the ENSO.

The intraseasonal variability of gravity wave amplitudes is examined. Gravity wave amplitude averaged over the latitudes of 0°S to 20°S is compared with the precipitation and the zonal wind at 100 hPa, which is corresponding to the altitude of the tropopause. It is found that large gravity wave amplitudes move eastward as precipitation maximum moves eastward. Moreover, it is also found that gravity wave amplitudes are weaker in regions where the zonal wind is eastward at the tropopause level. Thus, gravity wave amplitudes in the middle stratosphere have some relations with the precipitation maximum and the zonal wind at the tropopause. The eastward wind works as critical level filtering upward and eastward propagating gravity waves.

These results strongly indicate that the momentum transport from the tropo-

sphere to the summer mesosphere by gravity waves has significant interannual and intraseasonal variabilities that depend on the convective activity in the troposphere and the zonal wind at the tropopause in the subtropics in the austral summer.

要旨

近年、重力波の水平伝播が中層大気のクライマトロジーやモデルバイアスの改善に重要であることがわかってきた。そこで、重力波の水平伝播特性を観測データから明らかにすることが求められている。また、成層圏亜熱帯夏季における子午面循環の駆動源が重力波であることが指摘されている。亜熱帯夏季においては、重力波は短い水平波長を含む広い帯域を持つと考えられているため、水平解像度の良い測器で観測されたデータを用いる必要がある。

衛星搭載測器は、その解像度の向上により、大気重力波の広い波数・周波数帯域の一部を検出できるようになってきた。Atmospheric Infrared Sounder (AIRS) は、現在大気重力波の研究に用いられている衛星搭載測器の中でも最高水平解像度（13.5 km）を持つ。公開されている従来の AIRS の温度データは測器の持つ本来の解像度より粗く設定されていたが、最近、AIRS 本来の高解像度で成層圏における温度プロダクトを作成するアルゴリズムが開発された。本研究の目的は、このアルゴリズムにより作成された 2003 年から 2011 年までの 9 年間の AIRS 高解像度温度データのうち、最も信頼度の高いとされる高度 39 km における一層のデータを用いて、重力波の伝播特性を明らかにし、成層圏中層における重力波振幅のクライマトロジー及び季節内変動や経年変動を明らかにすることである。

AIRS は天底観測であるため、鉛直波長の長い重力波に感度を持っている。そのような重力波の鉛直群速度は一般に大きいため、解析対象とする高度にとどまっている時間が短い。したがって、温度の水平分布には、重力波はパケットとして局在化していると考えられる。そこで、局在化した重力波の位相構造を検出し、振幅、水平波長、水平波数ベクトルを推定するため、一次元ウェーブレット解析の一種である S 変換を観測データに適用した。まず、有意なシグナルを検出するため、温度推定の過程で与えられるランダムノイズの特徴を調べた。位置と波長の空間におけるウェーブレットスペクトル

を描くと、ノイズに由来するスペクトルの分散は、水平波長が約 70 km よりも短い帯域に現れることを確認した。そこで、水平波長 70 km 以上の擾乱を解析対象とすることにした。

次に、重力波の振幅と水平波長、水平波数ベクトルの方向を東西平均して、9 年間の平均季節進行を調べた。重力波振幅は風速の強い冬季高緯度で最も強く、夏季亜熱帯にも振幅のピークが存在した。このような分布は、背景風速が強い領域では、重力波のドップラーシフトによって鉛直波長が長くなり、AIRS で検出されやすくなる観測フィルターと呼ばれる効果で説明できる。実際、同様の分布は、AIRS と同様に鉛直波長の長い重力波に感度をもつ Microwave Limb Sounder (MLS) を用いた先行研究によっても報告されている。一方、重力波の水平波長は、重力波振幅が大きな季節・緯度で長い傾向がみられる。重力波の水平波数ベクトルは、南半球冬季の極渦周辺で特徴的な分布をしている。すなわち、波数ベクトルの南北成分に着目すると、60°S より高緯度では北向き、低緯度では南向きの卓越がみられた。これは、重力波が極夜ジェットの中心に向かって伝播していることを示している。このような南北伝播特性は、重力波を解像可能な気候モデルによる研究や、衛星データを用いた山岳起源の重力波の事例解析により示されていたが、統計的なクライマトロジーとして、実観測データを用いた解析により示したのは本研究が初めてである。

季節平均した重力波振幅の地理分布を調べると、夏季亜熱帯に明瞭な経度依存性がみられた。この経度分布は降水量の分布に似ていたものの、南太平洋において、重力波振幅最大の緯度は、降水量最大の緯度で定義した南太平洋収束帯 (SPCZ) より約 3 度高緯度側に位置することがわかった。これは MLS を用いた先行研究でも指摘されている。降水量は重力波の主要な励起源の一つである強い対流の指標と考えられる。そこで、降水量分布より重力波振幅が高緯度側に位置する原因について考察したところ、海上に比べ島域で重力波がより多く励起されること、南北風の鉛直シアが南向き伝播する重力波の選択的励起を起こす特徴を持つこと、及び背景風の緯度勾配により重力波の屈折することによって定性的に説明可能であることがわかった。典型的な水平波長である 225

km の重力波について簡単な理論計算を行うと、南北風の鉛直シアによる南向き伝播する重力波の選択的励起の効果と背景風の緯度勾配による重力波の屈折効果の和は、緯度 3 度に及ぶ伝播を部分的にしか説明しないことがわかった。ただし、観測可能な帯域のうち最も長い 700 km の水平波長を持つ重力波を仮定すると、二つの効果による伝播距離の和は 375 km に達することも確かめた。

夏季亜熱帯における重力波振幅の年々変動を調べてみると、北半球に比べ南半球で大きいことがわかった。そのため、南半球夏季亜熱帯における重力波振幅の経年変動を調べた。この領域で年々変動を引き起こす可能性の高い現象として、エルニーニョ・南方振動（ENSO）に着目し、NINO.3 海域の海面水温（SST）偏差時系列に、降水量と重力波振幅の季節平均時系列を回帰した。その結果、SPCZ における降水域は El Niño 期に北東に、La Niña 期に南西に移動していた。重力波振幅の偏差も ENSO の位相に依存して、降水量と似たパターンの変化があることが確かめられた。また、領域平均した重力波振幅と降水量、及び成層圏中層における背景東西風の時系列も調べた。降水量は SPCZ の西側で NINO.3 SST 時系列と逆位相の変動を、赤道南太平洋中央部と SPCZ の東側で同位相の変動をするが、重力波振幅の変動も降水量と同様であった。このような重力波振幅の空間分布の時間変動は、観測フィルターの影響ではないことも確かめられた。このような、重力波振幅の空間分布の経年変動と ENSO の関係を明瞭に示した研究は過去には存在しない。

最後に、季節内スケールの変動を調べるために、成層圏中層における重力波振幅、降水量と熱帯対流圏界面付近に対応する 100 hPa の東西風を南緯 0°から 20°で平均し、東西時間断面を作成して比較した。すると、降水域のマッデン・ジュリアン振動に伴う東向き移動と同時に、重力波振幅が大きい場所も移動していることがわかった。また、対流圏界面において東向きの風が強いほど成層圏中層において重力波振幅が弱いこともわかった。

夏の成層圏・中間圏の東向き運動量の鉛直フラックスは、主に、南半球夏季亜熱帯における重力波によることが先行研究で記されている。本研究は、中間圏への運動量輸

送に、対流活動の経年変動、季節内変動に伴う変動が存在することを示唆している。

Chapter 1

General introduction

1.1 Role of gravity waves in the meridional circulation

The temperature structure in the middle atmosphere is significantly different from that expected from the radiative equilibrium. In the mesosphere, the vertical gradient of temperature is opposite to that derived from the radiative equilibrium. Such structure is maintained by the wave-driven meridional circulation (Holton, 1983). It is considered that the meridional circulation in the mesosphere is mainly driven by gravity waves (e.g., Andrews *et al.*, 1987). Thus, it is impsrtant to estimate the amount of the gravity wave forcing in order to understand the momentum budget in the middle atmosphere.

Besides its importance, the direct detection of gravity waves is difficult because the typical scale of gravity waves is small. Because of this feature, the gravity wave forcing has been indirectly diagnosed from large-scale flows and temperature. The gravity wave forcing in the mesosphere can be estimated from the momentum and thermodynamic equations by using large-scale temperature data observed from satellites (e.g. Hitchmann and Leovy, 1986; Fetzer and Gille, 1996).

On the other hand, the meridional circulation in the stratosphere, which is called as the Brewer-Dobson circulation (Brewer, 1949; Dobson, 1956), was considered to be mainly driven by the planetary and synoptic scale waves (Plumb, 2002). The gravity wave forcing is, however, also important in driving the Brewer-Dobson circulation. Okamoto *et al.* (2011) made estimation of respective contributions of planetary wave forcing, synoptic-scale wave forcing, and gravity wave drag to the stream function of the meridional circulation. It is well known that the lower cells in the winter and summer hemispheres are maintained by the synoptic-scale wave forcing and the upper cell in the winter hemisphere is maintained by the planetary waves. In addition to those, Okamoto *et al.* (2011) showed that the gravity wave drag drives the upward branch of the upper winter cell, which is located in the summer subtropics. Thus, the direct detection of the gravity waves by observations in the summer subtropics is important.

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Figure 1.1: Typical visibility limits as functions of horizontal and vertical wavenumber for (green) limb viewing satellite (CRISTA), (red) sub-limb viewing satellite (MLS), (pink) nadir viewing satellite (AIRS), (blue) balloon, and (purple) radiosonde measurement technique. Shaded regions are not visible to any of the techniques. Adopted from Alexander *et al.* (2010).

One of the observational instruments that can detect gravity waves directly is Mesosphere-Stratosphere-Troposphere (MST) radars. Previous studies investigated the momentum flux by gravity waves using MST radar observations in the continuous altitude range. The forcing was derived by the vertical divergence of the gravity wave momentum flux (Vincent and Reid, 1983; Fritts, 1984; Sato, 1990; Tsuda *et al.*, 1990). Data is limited at only several single stations because the MST radar is expensive. Recently, satellite observations become to provide global data of gravity waves, although the momentum flux estimation is still indirect.

1.2 Range of gravity waves

1.2.1 Broadness of the gravity wave spectrum

The range of horizontal and vertical wavelengths of gravity waves is broad; their ranges are from several kilometers to several hundred kilometers horizontally and from several hundred meters to the infinity vertically. However, the relative importance of gravity waves with respective wavelengths is still unknown. Gravity waves with shorter horizontal wavelengths transport larger amount of momentum upward even if temperature amplitudes are the same. These gravity waves with shorter horizontal wavelengths are considered to be important for the momentum budget at upper altitudes. When gravity waves reach their critical levels, the vertical wavelengths are expected to become shorter. Near the critical level, gravity waves are attenuated and deposit the momentum to the background wind field. Because of the critical level filtering, gravity waves with shorter vertical wavelengths are considered to be important at the observed altitude. This is the reason why the whole range of gravity waves should be investigated.

The vertical wavelengths of gravity waves are largely altered due to the change in background wind speed. This mechanism can be understood by the dispersion relation of linear gravity waves: $\hat{c} = (c - U) \fallingdotseq N/m$, where $\hat{c}$, c, U, N, and m are the intrinsic phase speed, the ground-based phase speed, the background zonal wind, the Brunt-Väisälä frequency, and the vertical wavenumber, respectively. Assuming that c is small as observed, the vertical wavelength $|2\pi/m|$ is roughly proportional to $|U|$. Thus, for stronger (weaker) background winds, the vertical wavenumber becomes smaller (larger), that is, the vertical wavelength becomes longer (shorter). Thus, for the study of gravity waves, satellite instruments need to have fine resolution both horizontally and vertically. However, there is a limitation in the wavelength range that can be observed by any single instrument (Alexander, 1998).

1.2.2 Observational filter

Figure 1.1 shows the visible ranges of various observations, which are called an observational filter (Alexander *et al.*, 2010). Atmospheric Infrared Sounder (AIRS) is the best in observing the shortest horizontal wavelength range. AIRS has the highest horizontal resolution (13.5 km across the satellite orbit and 18 km along the orbit at nadir), although the vertical resolution is relatively coarser (AIRS is sensitive to gravity waves with vertical wavelength larger than 9 km). The gray shaded region in Figure 1.1 shows the wavelength range where any instruments cannot detect gravity waves. Thus, to detect gravity waves with shorter horizontal wavelengths, it is reasonable to use AIRS data. The background wind speed makes the vertical wavelengths within or without the range of observation of AIRS. In this study, we examine the change in gravity wave amplitudes which is not largely contaminated by the background wind speed.

Microwave Limb Sounder (MLS), which has provided the climatology of gravity waves with long vertical wavelengths as will be shown later, is one of the earlier satellite instruments that observed gravity waves globally. The range of MLS observation is narrower than that of AIRS because the weighting function for temperature of MLS across the line of sight is relatively narrow (about 15 km), but that along the line of sight is wider than 200 km (Wu and Waters, 1996a). On the other hand, AIRS scans across the satellite orbit within the angle of $\pm 49.5°$ from the nadir. Thus, the detectable temperature in phase line direction of gravity waves by MLS largely depends on the satellite orbit but recent AIRS observation does not.

1.3 Gravity wave activities in the subtropics

It is considered that a main source of gravity waves in the subtropics is convection. The importance of convection for the generation of gravity waves is also inferred from the climatology of gravity waves. Wu and Waters (1996b) investigated the climatology of gravity waves with long vertical wavelengths using MLS data, which is one of the earlier satellite observations. They showed that large variances of gravity waves at the altitude of 38 km were observed at the winter high latitudes, where the polar night jet was located. They also showed that moderately large gravity wave variances were observed in the summer subtropics. The gravity wave variances in the summer subtropics have clear longitudinal dependence, which correlates with the outgoing longwave radiation (OLR). Thus, it is reasonable to consider that the longitudinal dependence of gravity wave variances reflects variations of wave sources such as deep convection (McLandress *et al.* 2000, Jiang *et al.*, 2004). The enhancement of the gravity wave activity in the subtropical summer monsoon season was also observed by High Resolution Dynamics Limb Sounder (HIRDLS) satellite, which can detect gravity waves with shorter vertical wavelengths (Wright and Gille, 2011).

As discussed later, the generation mechanism of gravity waves by convection is complicating. The spectrum of gravity wave amplitudes generated by convection in the horizontal phase speed or wavelength space is controversial (Alexander *et al.*, 1995). In addition, it is very difficult to clarify the climatology of the amplitudes of gravity waves emitted from convection in the whole range of gravity wave spectrum because of the observational filter. As will be shown later, the range of horizontal wavelengths of gravity waves from convection is very wide. Since AIRS can detect gravity waves with shorter horizontal wavelengths, AIRS data is used to investigate gravity waves from convection in the present study.

1.4 Variability of gravity waves

The variability of gravity waves is also important. Although the importance of convection as a dominant mechanism that determines the climatology of gravity waves is known, its contribution for the time variations of gravity waves has not fully been examined. The change in gravity wave activities is affected by the change in the generation process and the change in the background wind for the propagation condition of gravity waves. Because the upward decrease in gravity wave amplitudes (more strictly speaking, pseudo-momentum) implies the forcing to the background wind fields of the gravity waves, many studies have focused on the change in gravity wave amplitudes or the momentum flux during the propagation process.

1.4.1 Variability of gravity wave propagation characteristics

The change in the gravity wave propagation characteristics related to the quasi-biennial oscillation (QBO) has received much attention in many previous studies. In the subtropics, it is expected that small change in zonal winds associated with the QBO is observed because the latitudinal half width of the zonal wind of the QBO is about 12°. Thus, the modulation of the propagation condition of gravity waves by the background wind is considered in the present study.

From the 1990s, studies using radiosonde observations showed that the QBO is driven mainly by the momentum transport by gravity waves, not by equatorial Kelvin and Rossby-gravity waves. Sato *et al.* (1994) showed that gravity waves have large energy that is comparable to or larger than that of equatorial Kelvin waves both in eastward and westward wind shear phases. Sato and Dunkerton (1997) showed that the total momentum flux by gravity waves observed by radiosondes can be about ten-times larger than that by Kelvin waves. The importance of gravity waves for driving the QBO was also shown theoretically by Haynes (1998) and numerically by Takahashi (1996) and Kawatani *et al.* (2010). Thus, the interannual variability of gravity waves is investigated about the amplitude change through the propagation in relation to the QBO using satellite observations.

Gong *et al.* (2012) analyzed AIRS data which is sensitive to gravity waves with longer vertical wavelengths and showed that amplitudes of eastward propagating gravity waves decrease in the eastward wind phase of the QBO although the decrease in the westward propagating gravity waves in the westward wind phase of the QBO is rather unclear. Using Challenging Minisatellite Payload (CHAMP) Global Positioning System (GPS) occultation data which enables us to detect gravity waves with shorter vertical wavelengths, de la Torre *et al.* (2006) showed an enhancement of gravity and equatorial Kelvin wave amplitudes in time and altitude where the zonal wind is close to zero especially in the eastward wind shear phase of the QBO. Consistent results were also obtained using Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) observation (Zhang *et al.*, 2012; John and Kumar, 2012), which is sensitive to gravity waves with shorter vertical wavelengths.

The discussions of the former studies listed above are both devoted to the background wind speed and the filtering of gravity wave amplitudes. In stronger westward background winds, gravity waves with eastward phase speeds are selectively detected by the AIRS observation because their vertical wavelengths are longer. In the eastward background winds, the vertical wavelengths of gravity waves with eastward phase speeds become shorter. Since the upper troposphere wind is easterly in general, eastward propagating gravity waves are expected to dominate

(Gong *et al.*, 2012). It is considered that these waves tend to be filtered out by the eastward winds. If such filtering occurs, the gravity wave amplitudes in the middle stratosphere are also expected to be smaller in the eastward wind phase of the QBO in the lower stratosphere. In this study, the influence of the QBO to the gravity wave amplitude change in the middle stratosphere will be discussed.

On the other hand, the results using CHAMP were examined in terms of the critical level filtering. It is expected that the majority of gravity waves has slow phase speeds, reflecting the characteristics of sources such as topography and convection, even if gravity waves are generated spontaneously from the jet-front system (Yasuda *et al.*, 2013a and 2013b). Thus, gravity waves tend to have shorter vertical wavelengths in weaker background wind and can be detected selectively by CHAMP and SABER. Furthermore, such gravity waves may be filtered in the weak background wind region which acts as their critical levels (Zhang *et al.*, 2012). Thus, the gravity wave amplitudes may be smaller above the weaker wind region. Because Kelvin waves have an eastward phase speed, the enhancement of the wave activity is clearer in the eastward wind shear than in the westward wind shear.

The gravity wave activity in the subtropical regions can be affected by the change in the filtering effect by the zonal wind at the tropopause level and below and at the lower stratosphere modulated by the QBO.

It is considered that the eastward winds at the tropopause level at the subtropics tend to filter out gravity waves. Sato *et al.* (2009) used gravity wave-resolving general circulation model data (Watanabe *et al.*, 2008) and showed that the momentum flux in the subtropics is large in the monsoon convective region where there are westward winds associated with the monsoon circulation located around 100 hPa. Thus, in order to clarify the effect of the conductivity of gravity waves on the gravity wave variability, the variability of the zonal wind at the tropopause level should be considered.

The latitudinal half width of the zonal wind of the QBO is about 12°. Thus, in the subtropics, small change in zonal winds associated with the QBO is expected. Vincent and Alexander (2000) analyzed long-term radiosonde observations at Cocos Island (12°S, 97°E) and investigated the interannual change in the energy and momentum flux of gravity waves in relation to the QBO. Krebsbach and Preusse (2007) and Ern *et al.* (2011) performed the spectral analysis of the time series of SABER observation data. They indicated the influence of the QBO on the interannual variability of the subtropical gravity wave and convective activities.

1.4.2 Variability of gravity wave sources

The gravity waves from convection have a broad spectrum. Three simplified mechanisms were proposed about the generation of gravity waves by convection.

The first one is the generation by thermal forcing (Beres *et al.*, 2002), which is related to a diabatic heating term in the linearized thermal equation. Most dominant vertical and horizontal wavelengths of gravity waves generated by this mechanism are considered to be twice the depth and the horizontal scale of heating (Salby and Garcia, 1987; Alexander *et al.*, 1995; Piani *et al.*, 2000). The second is an obstacle effect (Pfister *et al.*, 1993). The heating changes the isothermal surface, which makes a form drag analogous to topographic wave generation. The horizontal wavelength is expected to be determined by the horizontal scale of isothermal surface. The last is a mechanical oscillator effect (Fovell *et al.*, 1992), which is regarded as a periodic and localized source term for the momentum equation. Gravity waves generated by this mechanism tend to have wave frequencies equal to the oscillation frequencies. The expected horizontal wavelengths are in a broader range. All these mechanisms can generate gravity waves with various horizontal wavelengths. Thus, in the subtropics, it is essential to study gravity waves with shorter horizontal wavelengths as well as longer ones. AIRS is suitable for studying such gravity waves. In the present study, precipitation is used as a rough index of convection to describe source of gravity waves because all these mechanisms are directly and/or indirectly related to the latent heat release associated with water vapor condensation. The expected vertical wavelengths vary depending on the mechanisms above (Alexander *et al.*, 1995). It should be noted that the vertical structure of convection cannot be investigated using precipitation data. Thus, the vertical wavelength distribution of gravity waves is not discussed in the present study.

It is well known that convective activities have clear variability in intraseasonal-to-interannual time scales. In the interannual time scale, the geographical distribution of precipitation is largely modified by the El Niño-Southern Oscillation (ENSO). Many studies reported that precipitation in the equatorial central Pacific increases in the El Niño phase (e.g., Wallace *et al.*, 1998) and that precipitation in the South Pacific convergence zone (SPCZ) shifts northeastward in the El Niño phase (Vincent, 1994). In the intraseasonal time scale, it is well known that the eastward migration of large scale convective systems is observed in association with the Madden-Julian oscillation (MJO, Madden and Julian, 1972). These variations are characterized by the temporal change in the longitudinal distribution of convection.

Some studies showed the correlation between the gravity wave activity and convective activity using the long term radiosonde observations (e.g. Vincent and Alexander, 2000; Gong *et al.*, 2010). However, no previous study of gravity waves has investigated the relationship between the longitudinal distributions of gravity waves and convection. Because AIRS provides continuous observation data from May 2002 up to now, interannual variability can be examined from AIRS data. Thus, in the present study, the longitudinal distributions of intraseasonal and interannual variability of gravity waves are revealed. Because the AIRS observation has a long duration over ten years, it is usable to investigate interannual variability of gravity waves.

1.4.3 Strategy for the analysis

The present study will discuss the causes of the variability of gravity waves in a following manner. At first, the interannual to intraseasonal variability of gravity wave amplitudes is detected. Next, the correlation between the variability of gravity waves and the variability of the wave sources is revealed. Finally, the filtering effect due to the change in the zonal winds at the tropopause level and the lower stratosphere is investigated.

1.5 Relation to gravity wave parameterizations

Effects of gravity waves need to be parameterized in most general circulation models. The conventional gravity wave parameterizations (e.g., Hines, 1997) were based on quite simplified assumptions such as the uniform distribution of non-orographic gravity wave sources. This is only a first approximation of such sources, which change their location depending on weather conditions. Some studies have tried to extend gravity wave parameterizations by including the observational features of gravity waves (Song and Chun, 2008; Richter *et al.*, 2010). The results from the present study provide observational characteristics of the intraseasonal-to-interannual variability of gravity waves, which needs to be expressed in the model results using such parameterizations.

1.6 Propagation characteristics of gravity waves

In the present study, the climatology of the meridional propagation of gravity waves is examined by using AIRS data and compared with the results from the studies using the gravity wave-resolving general circulation model. This is motivated by the recently recognized importance of the horizontal propagation of gravity waves in improving model biases. This point is described in detail below.

The climatology of gravity waves has been examined using a gravity-wave resolving general circulation model (Watanabe *et al.*, 2008; Sato *et al.*, 2009). The zonal winds, the temperature structure, and a QBO-like zonal wind oscillation in the equatorial lower stratosphere were simulated well in their model. Thus, the characteristics of simulated gravity waves are expected to be similar to the characteristics of observed gravity waves. The reality of their results needs to be confirmed in comparison with the real atmosphere using observations, however. AIRS is useful to provide such information even though AIRS can only detect gravity waves with longer vertical wavelengths.

Sato *et al.* (2009) showed that the momentum flux characteristics of simulated gravity waves; negative (positive) $\overline{u'w'}$ is dominant in eastward (westward) background zonal wind, where u' and w' are zonal and vertical wind components of gravity waves, and the over bar shows the time mean. The horizontal propagation direction corresponds to the direction of momentum flux of gravity waves, if they propagate energy upward. It is implied that the propagation direction relative to the background winds is westward (eastward) in the winter (summer) hemisphere in the middle atmosphere where the dominant background wind direction is eastward (westward). They also showed that both dominant momentum fluxes originating from the subtropics in summer and those from the middle to high latitudes in winter are focused toward the mesospheric jet axis of the respective hemispheres. In their Figure 2 (a), the axis of the maximum positive momentum flux is at about 15°N at 200 hPa and at 20°N at 3 hPa in summer and that of the negative momentum flux is at about 45°S (75°S) at 200 hPa and at 55°N (65°N) at 3 hPa in winter.

Such meridional propagation is considered as a result of the refraction and/or advection of gravity waves. Sato *et al.* (2009) conducted the ray tracing calculation and showed that the meridional gradient of the background zonal wind refract gravity waves so as to generate a meridional component of the wavenumber vector pointing to the jet axis. Sato *et al.* (2012) showed that the gravity waves generated by mountains are advected by the background winds which have a component perpendicular to the horizontal wavenumber vector of generated gravity waves. In addition, some observational case studies (e.g., Preusse *et al.*, 2002; Eckermann *et al.*, 2007; Jiang *et al.*, 2013) showed the evidence of wide distribution of gravity waves at the middle to high latitudes originating from Andes, Antarctic Peninsula, and Scandinavia.

Recently, it is considered that the meridional propagation of gravity waves is important for the reduction of the bias of the climate models. For example, McLandress *et al.* (2011) suggested that a bias of a significant delay of about 20 days of the polar vortex breakdown in the Southern Hemisphere in late spring is likely due to the missing gravity wave drag at 60°S in the gravity wave parameterization employed in climate models.

1.7 Overview of this thesis

In the present study, the new dataset of AIRS observation with a fine horizontal resolution, which is the same as the original footprint size, is used to clarify the climatology and intraseasonal-to-interannual variability of gravity waves in the stratosphere. A wavelet analysis is applied to AIRS data, which allows us to estimate the amplitudes, horizontal wavelengths, and direction of the horizontal wavenumber vector of gravity waves locally. In Chapter 2, details of the high-resolution AIRS observation data and the method of analysis are described. The climatology of gravity waves is shown in Chapter 3. In Chapter 4, the interannual variability of gravity waves related to ENSO is investigated in terms of the longitudinal distribution. The intraseasonal variability of gravity waves is clarified and its relation to the MJO is discussed in Chapter 5. In Chapter 6, the possible mechanisms that explain the difference in the maximum latitudes between gravity wave amplitudes and precipitation are discussed in terms of lateral propagation and selective generation of gravity waves. Summary and concluding remarks are given in Chapter 7.

Chapter 2

Data description and analysis method

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Chapter 3

Climatology

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Chapter 4

Interannual variability

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Chapter 5

Intraseasonal variability

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Chapter 6

Discussions

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Chapter 7

Summary and concluding remarks

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