MLS observations of atmospheric gravity waves over Antarctica

Dong L. Wu and Jonathan H. Jiang
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

Received 28 March 2002; revised 12 June 2002; accepted 3 July 2002; published 21 December 2002.

[1] Stratospheric gravity waves over Antarctica are studied with the radiance variances observed by Upper Atmosphere Research Satellite Microwave Limb Sounder (UARS MLS). Strong wave activities are found during August and September in 1992–1994 over the Drake Passage region (290°–315° longitude and 50°S–70°S latitude), where the enhancement seems associated with the topography of both South America and Antarctic Peninsula tips. During the same period, significant gravity wave activities are also evident along the Antarctic coastal region. The vertical growth of the wave variance shows a scale height of ~14 km at low altitudes for both Drake Passage and the coastal regions but reduces substantially at high altitudes. The growth rate transition occurs at a lower altitude in the Drake Passage region where the variance is larger. The gravity wave activities observed near the Antarctic may contribute significantly to the formation of polar stratospheric clouds (PSC) because of the overlapping with the vortex edge and with the PSC activities as observed by CLAES (Cryogenic Limb Array Etalon Spectrometer). *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 6969 Radio Science: Remote sensing; *KEYWORDS:* Gravity waves, Antarctica, polar stratospheric cloud, circulation, ozone depletion

Citation: Wu, D. L., and J. H. Jiang, MLS observations of atmospheric gravity waves over Antarctica, *J. Geophys. Res.*, *107*(D24), 4773, doi:10.1029/2002JD002390, 2002.

1. Introduction

[2] Gravity wave (GW) drag is recognized as one of the essential forcings that control transport/circulation and thermal structure in the middle atmosphere. The scales of most GWs are too small to be resolved by general circulation models (GCMs), and parameterized GW drag is needed for the models to reproduce observed atmospheric structures. Without the small-scale wave forcing, the stratospheric polar vortices would be too strong and the polar temperature in the upper stratosphere would be too cold [*Hamilton et al.*, 1994; *Pawson et al.*, 2000; *Shepherd*, 2000]. In the lower atmosphere, including appropriate GW drag parameterizations has been shown to help improve model score of forecasting [*Milton and Wilson*, 1996]. However, more studies are still needed for understanding of wave dynamics and sources as well as formulating adequate GW parameterization.

[3] GWs also play a considerable role in the ozone depletion problem as a mechanism to enhance polar stratospheric cloud (PSC) formation [*Carslaw et al.*, 1998]. PSCs have been thought as a key agent in/near the polar vortex that helps efficiently destroy ozone via heterogeneous reactions. *Cariolle et al.* [1989] reported a large PSC event over Antarctica in early September while severe ozone depletion occurred in the region. The event started with some short-scale features over the Antarctic Peninsula and quickly (within 30 hours) spread to a synoptic-scale area inside the vortex. Although PSC formation is attributed to both GWs [*Carslaw et al.*, 1998] and synoptic-scale tropospheric forcing [*Teitelbaum et al.*, 2001], the clouds appearing near the vortex edge are thought critical to ozone loss due to early exposure to sunlight. *Lee et al.* [2001] recognized the importance of ozone loss in the vortex-edge region and argued that more PSC appearance on the edge could cause a delay in the ozone recovery.

[4] Antarctica is unique for its strong nearly axisymmetric flow in the wintertime stratosphere with fewer orographic gravity wave sources compared to the Arctic. Antarctic circulation produces mean sinking motion throughout the troposphere in the interior of the continent and ascent motion near the coastline. Large elevation changes (2 km in 100–200 km) along the coastal region provide most of orographic sources for the GWs around Antarctica. The Antarctic Peninsula stretches out north from the Antarctic continent for 1300 km. It is separated from South America by the Scotia Sea and the Drake Passage (290°–315° in longitude and 55°S–65°S in latitude), a ~500-km-wide water channel connecting the South Atlantic Ocean and the South Pacific Ocean. Rugged offshore islands and glaciers crowd in the Peninsula with a long and narrow land on which mountains rise to 1–2 km. Exposure to open-water winds, which is often stronger than those near the coastline, the tips of the Peninsula and the South American can be very effective orographical sources for GW generation [*Bacmeister*, 1993].

[5] Observations of GW activities remain limited comparing to what needed to understand wave sources and

0148-0227/02/2002JD002390$09.00

generation mechanisms. In particular, validation and constraint of GW forcing in GCMs require global observations of GW activities, which are not readily available with ground-based techniques. In the lower atmosphere GW observations over Antarctica are mainly provided by radiosondes [*Allen and Vincent*, 1995; *Pfenningner et al.*, 1999; *Yoshiki and Sato*, 2000], but little study has been given to overall morphology of GW activities in the region. Satellite observations are now able to measure GW-scale fluctuations in the stratosphere with global coverage [*Fetzer and Gille*, 1994; *Wu and Waters*, 1996; *Preusse et al.*, 1999]. *Wu and Waters* [1996] analyzed GW-induced radiance fluctuations from Upper Atmosphere Research Satellite Microwave Limb Sounder (UARS MLS) and found good correlation between GW activities and the background winds in the stratosphere. Such correlation is thought mostly due to effects of the background winds on GW propagation [*Alexander*, 1998]. *Jiang et al.* [2002] studied the MLS data over the Andes and showed that orographic GWs are detectable with MLS-like instruments even though the wave amplitudes are weak in the lower stratosphere. In that study, they also found much stronger wave activities over the Drake Passage region that are associated with the topography around the tips of the South America and the Antarctic Peninsula.

[6] In this paper we present further observational studies with the MLS GW measurements over the Drake Passage region as well as elsewhere around Antarctica. Our analyses are focused on three years of MLS limb-scan data in August of 1992–1994 when the stratospheric polar vortex and GW activities are strong. The paper is organized to have description of the data and analysis methods in section 2, observational results in section 3, and discussion and conclusion in the end.

2. Data Analysis

[7] The data used in this study are the mesoscale variances from MLS 63-GHz O_2 radiance measurements. Similar to the approach used by *Wu and Waters* [1996], the variances are computed from the saturated limb radiances at the bottom of each scan. The difference in this study is that we use three radiances instead of six for the variance calculation to assure sufficient radiance saturation in all spectral channels. In the 6-point variances, the radiances from the wing channels (1 and 15) are not well saturated at high latitudes and hence contaminate the atmospheric variances. By restricting the radiance measurements to lower tangent heights, we find that the 3-point truncation from the bottom of each scan will guarantee saturation at all latitudes. Nevertheless, there will be a difference in the horizontal wavelength truncation between the 3-point and 6-point variances. Because of the satellite motion (7.5 km/s) and measurement time (2 s), the 3-point variances filter out most waves of horizontal scales greater than ~50 km whereas the 6-point method truncates at ~100 km. Hence, the 3-point variances are smaller than the 6-point variances for the same GW features because wave power generally increases with horizontal wavelength. In addition, MLS radiance variances are limited to waves of vertical scales greater than ~10 km for channels 1–7 and 9–15 (~15 km for channel 8) due to smearing of the antenna field-of-view.

[8] The variance analysis is carried out such that the variances derived from each scan and spectral channel are independent from each other. For UARS MLS, two consecutive scans are separated by ~500 km and therefore they cannot be used to infer the timescale of the GWs without assumptions about wave spectra and dispersion relations. There are 15 spectral channels (symmetric about channel 8) in MLS 63-GHz radiometer, which feature 8 altitude layers at about 28, 33, 38, 43, 48, 53, 61, and 80 km. We may combine those variances from the symmetric channels for a better signal-to-noise ratio.

[9] The derived radiance variance is composed of instrument noise and an atmospheric component. The atmospheric variance is proportional to the temperature fluctuation at the layer of saturation since saturated radiances provide a good measure of the atmospheric temperature. MLS radiance noise is relatively low and stable throughout the entire mission, which allows detection of very weak (e.g., 3.3×10^{-4} K^2 for ch.1) atmospheric variances on a monthly map.

[10] To properly interpret the observed variances, we need a comprehensive understanding of the temperature weighting functions of MLS radiances, which exhibit a cigar-like shape oriented along the line-of-sight (LOS) and tilted from local horizontal plane [*Wu and Waters*, 1997; *McLandress et al.*, 2000]. In addition to the filtering on vertical wavelength, these weighting functions provide a very selective filtering on horizontal wavelength. They tend to filter out waves propagating in the directions perpendicular to the LOS and accept the propagation components transverse to the LOS. Because MLS LOS directions are tilted differently, the measurements from ascending and descending orbits filter out waves that propagate in nearly opposite directions. For the same reason, we need to analyze the ascending- and descending-orbit variances separately such that GWs are sampled in similar viewing geometry.

[11] UARS MLS latitude coverage is biased on a given day between 34° in one hemisphere to 80° in the other because the instrument views 90° from the satellite moving direction and the orbital inclination angle is 57°. UARS makes 10 yaw maneuvers in a year, allowing alternating views of high latitudes in the two hemispheres. MLS radiance variance data are available for the period of September 1991–June 1997, and we choose to use the data in 1992–1994 when MLS employed the same scan scheme (i.e., from top to bottom). MLS changed the scan order to the bottom-to-top operation since 1995 and introduced the so-called limb-tracking mode where the antenna points at a fixed tangent height. Because these changes in sampling are critical to the variance analysis and comparison, the observations in 1995–1997 need to be treated separately from those in 1991–1994.

3. Results

[12] Shown in Figure 1 are the maps of MLS GW activity observed during August of 1992–1994. Despite variability in GW amplitudes and distributions, the salient feature over the Drake Passage region appears to be consistent and repeatable from year to year. The variances in 1992 and 1994 are higher at ~28 km than that in 1993 but the year-to-year differences are less prominent at altitudes greater than

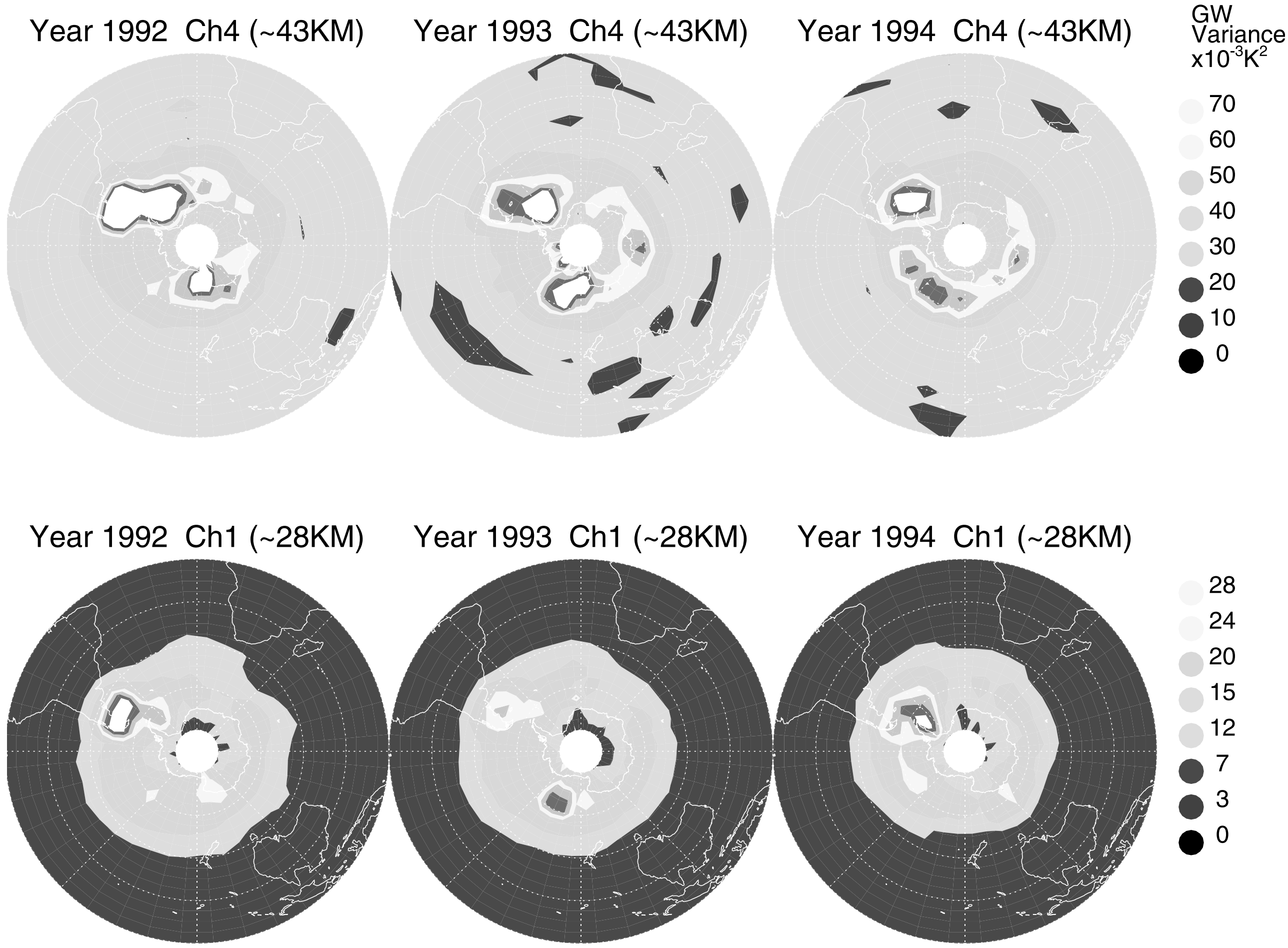

Figure 1. GW variances as observed with MLS during August of 1992–1994. Only data from ascending orbits are used to make the maps. The bottom row is the variances from channel 1 at ~28 km whereas the top row is from channel 4 at ~43 km. These monthly maps are made on 10° × 5° longitude-latitude grids and no data are at latitudes of 80° poleward. The instrument noise has been removed from the total radiance variance. Latitude grids are labeled at intervals of 20° from the equator. See color version of this figure at back of this issue.

~43 km. The peak variance over the Drake Passage region is associated more closely to the tip of the South America at ~28 km. As height increases, the center shifts slightly toward the Antarctic Peninsula and spreads over to a larger area. The contrast between the Drake Passage feature and the surrounding activities also reduces at higher altitudes as the amplitude growth of the surrounding GWs outpaces that over the Drake Passage region. The variances from the descending orbits (not shown) exhibit similar patterns but the amplitudes are smaller, as expected for westward propagating waves in the eastward background winds.

[13] Elsewhere, the GW activity follows the Antarctic coastline quite well, especially at the lowest altitude, with enhanced regions at longitudes between 90°–220°. Unlike the feature over the Drake Passage region, the locations of these enhancements vary from year to year but are correlated between low and high altitudes within the same year. In 1992 and 1993 the GW activities at longitudes between 90°–220° appears higher than other coastal regions at 43 km. In 1994 the coastal patterns at 43 km reveal enhanced activities over a larger area between 45° and 270° in longitude. As found in early MLS variance observations [*Wu and Waters*, 1996], the enhanced coastal variances reside mostly in the vortex-edge region in the stratosphere and exhibit good correlation with the stratospheric jet stream. However, the variation of the stratospheric jet stream around the vortex edge is not large enough to explain the modulation of the GW variances, and the GW source distribution must be taken into consideration.

[14] To study temporal and height variations of the GW activity, we define the Drake Passage region as an area between 290°–315° in longitude and 50°S–70°S in latitude and average all the variances within the area. Figure 2 shows the time series of daily GW variances over the Drake Passage region from the ascending orbits. During the period when the instrument viewed SH high latitudes, there are typically 4–7 measurements falling into the region each day from the ascending orbits. Low statistics and GW variability apparently cause large fluctuations in the daily variances. A 21-day smoothing, therefore, is applied to remove the large daily variability and the smoothed curve is superimposed on the time series. Throughout the stratosphere, the GW variations over the Drake Passage region are dominated by an annual cycle with the peak activity in August and

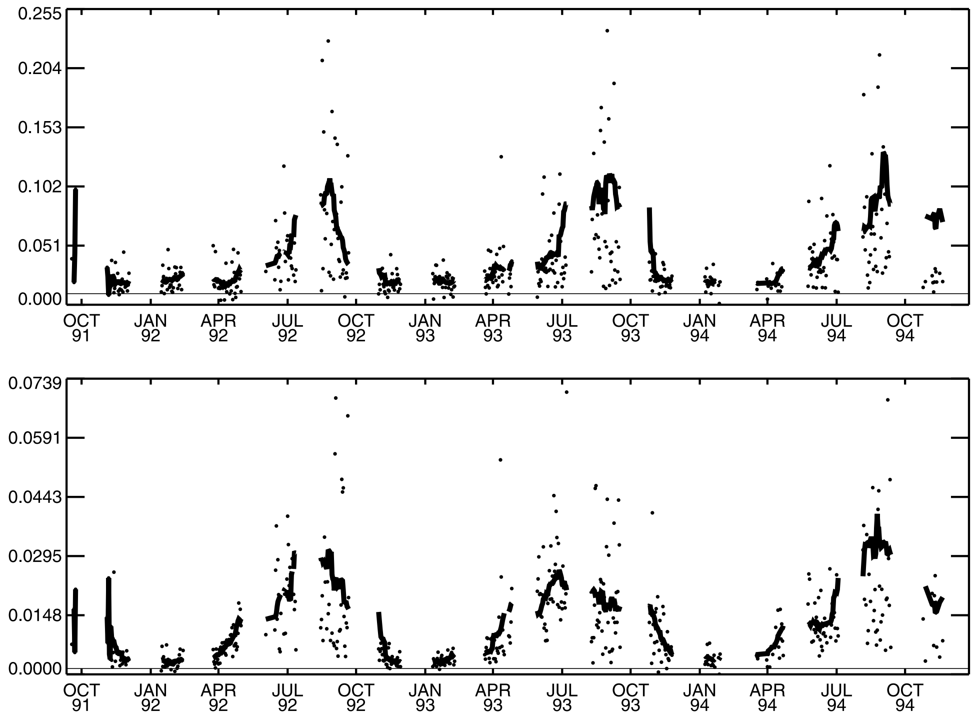

Figure 2. Time series of channel 1 (bottom) and 4 (top) variances over the Drake Passage region. The instrument noise is not removed and indicated with the horizontal line. Large gaps are the missing data while MLS viewed the Northern Hemisphere high latitudes.

September. During January–March, wave activities are so low that the variances are not significantly above the noise level. The year-to-year variability is evident in low-altitude channels but becomes less prominent at higher altitudes.

[15] Figure 3 summarizes the variance growth with height over Antarctica during August. The variances are grouped into the Drake Passage and coastal regions, where the coastal region is defined as 0°–215° in longitude and

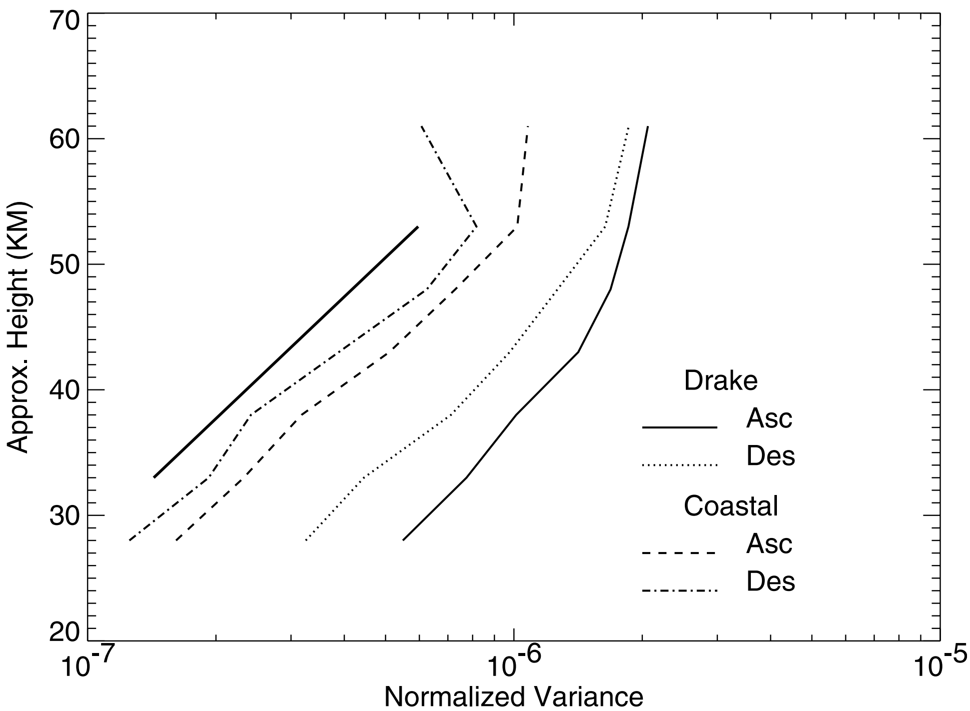

Figure 3. Vertical growth of the normalized GW variance, $(\Delta T_b/T_b)^2$, over the Drake Passage and coastal regions for ascending and descending orbits. All measurements during August in 1992–1994 are averaged to produce the growth profiles. A reference (14 km scale height) is shown as the straight line on the left.

50°S–70°S in latitude, and all the variances are normalized by the saturated radiance. Both ascending and descending variances reveal a similar growth trend between 28 and 61 km showing an exponential increase in amplitude. Characterized by the exponential scale height, the growth rate shows clear dependence on altitude. In the Drake Passage region, the scale height is close to 14 km at altitudes below ~43 km and gradually increases with altitude. Above the stratopause, the variances begin to show the sign of saturation. There are some differences between ascending and descending observations, showing that the descending growth slows down at a somewhat higher altitude. Moreover, the variances in the coastal region, starting with a much weaker amplitude, show a similar scale height (~14 km) up to 53 km before the slowdown occurs. This is interesting because the slowdown altitude moves to a higher level for the variances that start with a smaller value at low altitudes.

4. Discussions and Conclusions

[16] Mesoscale radiance fluctuations observed with MLS can be used to infer GW activities over Antarctica although the derived variances are limited to waves of long (>10 km) vertical and short (<~50 km) horizontal scales. MLS variances are not suitable for deriving total potential energy of the GWs because one needs to assume horizontal and vertical wave number spectra, which can be highly varying with space and time. However, based on the part of wave spectrum where MLS is sensitive, one may obtain important information on GW activity distributions and sources. In this study, the Drake Passage region shows up as a strong source for the GWs entering into the stratosphere and mesosphere during August and September. It is unclear though how these GWs are generated and how they are connected to the topography nearby. More studies are needed to identify and understand the mechanism(s) through GW modeling and observations in the lower atmosphere.

[17] Apart from unclear causes of the GW activity over the Drake Passage region, we have been interested in the potential GW effects on atmospheric dynamics and chemistry in the polar region. Strong GW activities have been observed often near the vortex edge in the stratosphere in both ground-based and satellite measurements [*Whiteway et al.*, 1997; *Wu and Waters*, 1996]. The Drake Passage feature is of interest because it is enhanced often when the vortex center leans toward the region. Is the synoptic-scale motion related to the strong GW activity in the region? To explore this further, we compared MLS GW observations to the constituent measurements (not shown here) from CLAES (Cryogenic Limb Array Etalon Spectrometer) N_2O and from MLS O_3 and HNO_3. These constituent measurements have been found very useful to infer information about dynamical as well as chemical processes of synoptic scales [*Santee et al.*, 1995]. Preliminary results indicate that there is an ascent air of synoptic scales in the lower stratosphere in the east of the Drake Passage during August, which produces high N_2O, low O_3 and low HNO_3 at 100 hPa. We also examined MLS upper tropospheric H_2O measurement and found the similar synoptic-scale ascent at 310 hPa in the east of Drake Passage. In addition, we also found an interesting zone of descent air just west of the Drake Passage with the H_2O data. Altogether, these observations certainly suggest some connections between the GW activity and synoptic-scale tropospheric forcing over the Drake Passage region. More work, however, is required to quantify these connections or interactions between synoptic-scale and mesoscale dynamics in the polar region.

[18] It remains puzzling what makes the variance vertical growth deviate from the free-propagating rate (~7 km in scale height) over the Drake Passage region as well as other enhanced activities along the Antarctic coastal region. Wave breaking/saturation may be part of causes for the slow growth rates observed in the stratosphere (scale height of ~14 km) and mesosphere (scale height $\gg$ 14 km). These breaking/saturating processes, depending on wave amplitude, scale, and phase velocity, may occur at different altitudes. Since MLS variances consist of waves in different scales and propagation directions, some waves experience breaking/saturation while some remain growing exponentially in amplitude, which may yield a variance scale height greater than 7 km.

[19] To examine possible GW impacts on PSC formation, we compared GW activities observed by MLS to the PSC distribution observed during the same period by CLAES with the 780 cm^{-1} aerosol extinction data [*Mergenthaler et al.*, 1997, Plate 3b]. During August and September 1992, the polar vortex was elongated stretching out toward the Antarctic Peninsula, which caused frequent occurrence of PSCs in the region. The PSC distribution was confined mostly poleward from the tip of the Peninsula and showed some overlaps with the GW activities in the Drake region (Figure 1). In the vicinity of the Drake Passage region, a significant fraction of CLAES PSCs occurred at temperatures greater than the 195 K contour on the synoptic map, suggesting possible contributions of GWs to the PSC formation. Note that the 195 K threshold from synoptic scale analyses is often used as the limit of Type I PSC formation [*Toon et al.*, 1986]. In reality, local temperature can fluctuate substantially around the synoptic-scale temperature in the presence of strong GW activities, which allows PSCs to occur even when the synoptic-scale temperature is near or slightly greater than 195 K. As a result, the simultaneous observations of CLAES PSCs and MLS GW activity near the Drake Passage region suggest strongly that GW may take part of PSC formation around the vortex edge [*Carslaw et al.*, 1998]. Unfortunately, CLAES was only able to operate for 18 months during the early UARS mission and no comparisons can be drawn for 1993 and 1994. It would be interesting to know if PSCs have the same distribution preference over the Drake Passage during these years when temperatures are around 195 K.

[20] In conclusion, we find a strong and repeatable GW activity pattern over the Drake Passage region during 1992–1994 with UARS MLS radiance variances. The GWs generated in this region are able to propagate up to the mesosphere with the variance scale height close to 14 km in the stratosphere. The comparison between the simultaneous MLS GW and CLAES PSC observations suggests that the GWs over the Drake Passage region likely play a significant role in PSC formation in the vortex edge region.

[21] **Acknowledgments.** We thank Drs. Stephen Eckermann, Michelle Santee, and Joe Waters for helpful discussions during development of this study. We also thank two reviewers for helping improve the

manuscript. This work was performed at Jet Propulsion Laboratory, California Institute of Technology, under contract with National Aeronautics and Space Administration, and sponsored by NASA.

References

Alexander, M. J., Interpretations of observed climatological patterns in stratospheric gravity wave variance, *J. Geophys. Res.*, *103*, 8627–8640, 1998.

Allen, S. J., and R. A. Vincent, Gravity wave activity in the lower atmosphere: Seasonal and latitudinal variations, *J. Geophys. Res.*, *100*, 1327–1350, 1995.

Bacmeister, J. T., Mountain-wave drag in the stratosphere and mesosphere inferred from observed winds and a simple mountain-wave parameterization scheme, *J. Atmos. Sci.*, *50*, 377–399, 1993.

Cariolle, D., S. Muller, and F. Cayla, Mountain waves, stratospheric clouds, and the ozone depletion over Antarctica, *J. Geophys. Res.*, *94*, 11,233–11,240, 1989.

Carslaw, K. S., et al., Increased stratospheric ozone depletion due to mountain-induced atmospheric waves, *Nature*, *391*, 675–678, 1998.

Fetzer, E. J., and J. C. Gille, Gravity wave variance in LIMS temperatures, Part I, Variability and comparison with background winds, *J. Atmos. Sci.*, *51*, 2461–2483, 1994.

Hamilton, K., R. J. Wilson, J. D. Mahlman, and L. J. Umscheid, Climatology of the SKYHI troposphere-stratosphere-mesosphere general circulation model, *J. Atmos. Sci.*, *52*, 5–43, 1994.

Jiang, J. H., D. L. Wu, and S. D. Eckermann, Upper Atmosphere Research Satellite (UARS) MLS observation of mountain waves over the Andes, *J. Geophys. Res.*, *107*(D20), 8273, doi:10.1029/2002JD002091, 2002.

Lee, A. M., et al., The impact of the mixing properties within the Antarctic stratospheric vortex on ozone loss in spring, *J. Geophys. Res.*, *106*, 3202–3211, 2001.

McLandress, C., M. J. Alexander, and D. L. Wu, MLS observations of gravity waves in the stratosphere: A climatology and interpretation, *J. Geophys. Res.*, *105*, 11,947–11,967, 2000.

Mergenthaler, J. L., J. B. Kumer, A. E. Roche, and S. T. Massie, Distribution of Antarctic polar stratospheric clouds as seen by the CLAES experiment, *J. Geophys. Res.*, *102*, 19,161–19,170, 1997.

Milton, S. F., and C. A. Wilson, The impact of parameterized subgrid-scale orographic forcing on systematic errors in a global NWP model, *Mon. Weather Rev.*, *124*, 2023–2045, 1996.

Pawson, S., et al., The GCM-reality intercomparison project for SPARC (GRIPS): scientific issues and initial results, *Bull. Am. Meteorol. Soc.*, *81*, 781–796, 2000.

Pfenninger, M., A. Z. Liu, G. C. Papen, and C. S. Gardner, Gravity wave characteristics in the lower atmosphere at South Pole, *J. Geophys. Res.*, *104*, 5963–5984, 1999.

Preusse, P., B. Schaeler, J. T. Bacmeister, and D. Offermann, Evidence for gravity waves in CRISTA temperatures, *Adv. Space Res.*, *24*, 1601–1604, 1999.

Santee, M. L., et al., Interhemispheric differences in polar stratospheric HNO_3, H_2O, ClO, and O_3, *Science*, *267*, 849–852, 1995.

Shepherd, T. G., The middle atmosphere, *J. Atmos. Sol. Terr. Phys.*, *62*, 1587–1601, 2000.

Teitelbaum, H., M. Moustaoui, and M. Fromm, Exploring polar stratospheric cloud and ozone minihole formation: The primary importance of synoptic-scale flow perturbations, *J. Geophys. Res.*, *106*, 28,173–28,188, 2001.

Toon, O. B., P. Hamill, R. P. Turco, and J. Pinco, Condesation of HNO3 and HCL in the winter polar stratosphere, *Geophys. Res. Lett.*, *13*, 1284–1287, 1986.

Whiteway, J. A., et al., Measurements of gravity wave activity within and around the Arctic stratospheric vortex, *Geophys. Res. Lett.*, *24*, 1387–1390, 1997.

Wu, D. L., and J. W. Waters, Satellite observations of atmospheric variances: A possible indication of gravity waves, *Geophys. Res. Lett.*, *23*, 3631–3634, 1996.

Wu, D. L., and J. W. Waters, Observations of gravity waves with the UARS microwave limb sounder, in *Gravity Wave Processes and Their Parameterization in Global Climate Models*, *NATO ASI Series*, vol. 50, edited by K. Hamilton, pp. 404, Springer-Verlag, New York, 1997.

Yoshiki, M., and K. Sato, A statistical study of gravity waves in the polar regions based on operational radiosonde data, *J. Geophys. Res.*, *105*, 17,995–18,011, 2000.

J. H. Jiang and D. L. Wu, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop: 183-701, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. (jonathan@mls.jpl.nasa.gov)

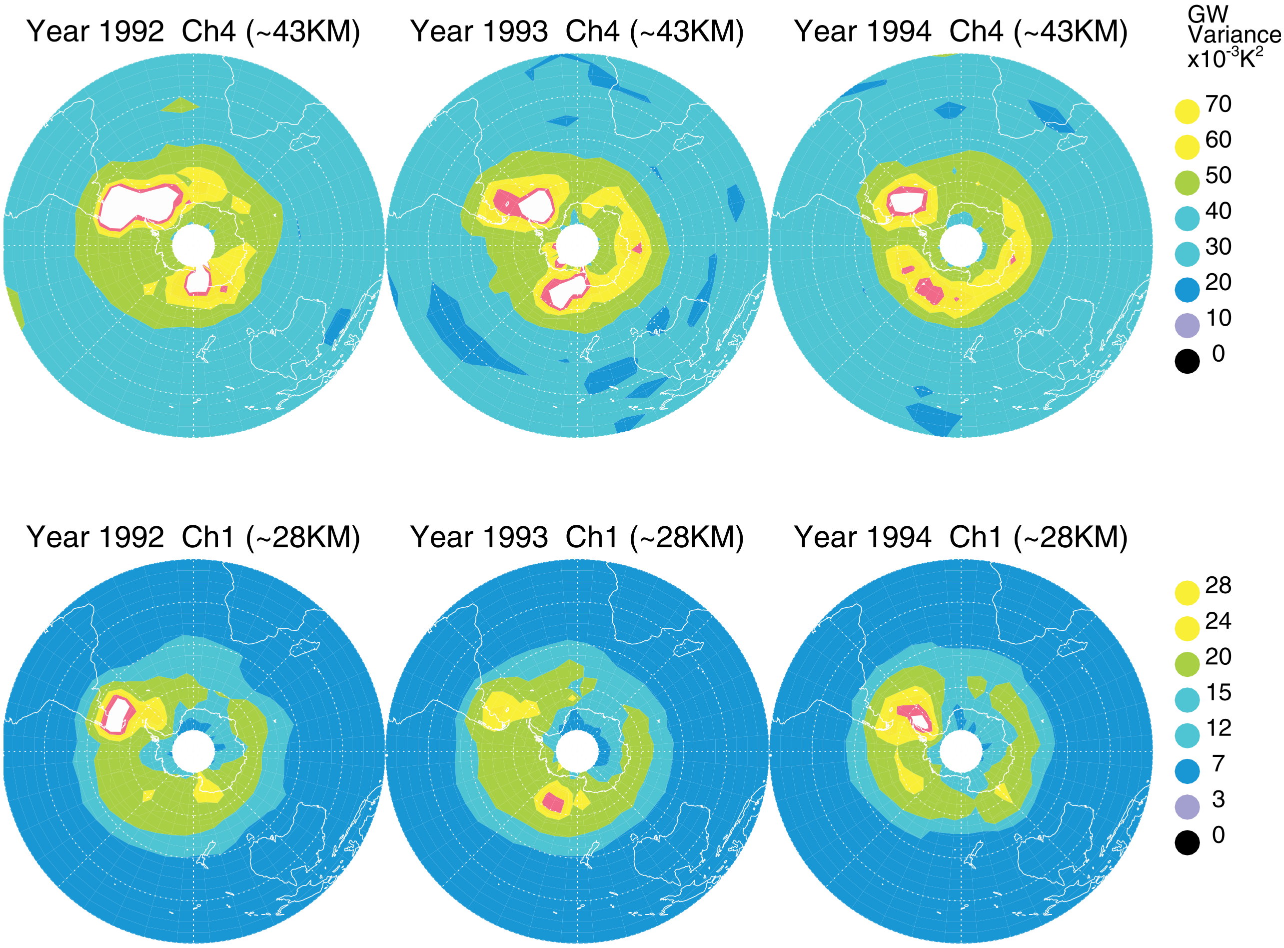

Figure 1. GW variances as observed with MLS during August of 1992–1994. Only data from ascending orbits are used to make the maps. The bottom row is the variances from channel 1 at ~28 km whereas the top row is from channel 4 at ~43 km. These monthly maps are made on 10° × 5° longitude-latitude grids and no data are at latitudes of 80° poleward. The instrument noise has been removed from the total radiance variance. Latitude grids are labeled at intervals of 20° from the equator.