

## Comparison of Global Distributions of Zonal-Mean Gravity Wave Variance Inferred from Different Satellite Instruments

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### Abstract.

Gravity wave temperature fluctuations acquired by the CRISTA instrument are compared to previous estimates of zonal-mean gravity wave temperature variance inferred from the LIMS, MLS and GPS/MET satellite instruments during northern winter. Careful attention is paid to the range of vertical wavelengths resolved by each instrument. Good agreement between CRISTA data and previously published results from LIMS, MLS and GPS/MET are found. Key latitudinal features in these variances are consistent with previous findings from ground-based measurements and some simple models. We conclude that all four satellite instruments provide reliable global data on zonal-mean gravity wave temperature fluctuations throughout the middle atmosphere.

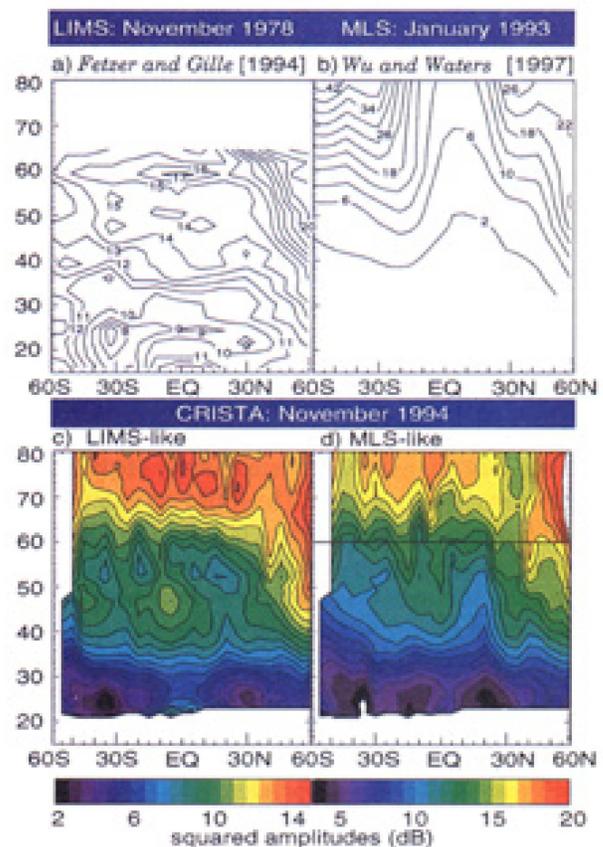
### Introduction

Remote-sensing instruments on satellites have revolutionized our understanding of the synoptic-scale dynamics and chemistry of the middle atmosphere. Since the structure of the middle atmosphere is controlled in large part by gravity wave breaking, global measurements of gravity wave activity are needed to further our understanding of this region of the atmosphere [McLandress, 1998]. This requires satellite measurements of high precision and high spatial resolution in all three dimensions, which most previous instruments have not provided. Thus, comparatively little global information on gravity wave activity exists.

Recent advances in remote-sensing technology have produced instruments capable of measuring gravity waves. To date, gravity wave signals have been analyzed on global scales using temperature data acquired by the Limb Infrared Monitor of the Stratosphere (LIMS) [Fetzer and Gille, 1994], 63 GHz limb radiances measured by the Microwave Limb Sounder (MLS) [Wu and Waters, 1996; Wu and Waters, 1997; McLandress et al., 2000], temperature data from the Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) [Preusse et al., 1999; Eckermann and Preusse, 1999], and temperature retrievals from the Global Positioning System Meteorological Experiment (GPS/MET) [Tsuda et al., 2000].

Puzzling differences among these data sets have emerged. An example is given in the top row of Figure 1, which shows zonal mean gravity wave variances from LIMS and MLS in the northern winter. The MLS radiance variances (Figure 1b) should be closely related to temperature variance [Wu and Waters, 1997], and so should resemble the LIMS temperature variances in Figure 1a. However, substantial differences between the two are evident. Since gravity waves are near the detection limits of each instrument, these discrepancies might call some or all of these data into question.

Using a theoretical model, Alexander [1998] argued instead that the MLS variances in Figure 1b are reliable, but



**Figure 1.** Top row: zonal-mean latitude-height distributions of small-scale variances in data from LIMS (a) and MLS (b), after Fetzer and Gille [1994] and Wu and Waters [1997], respectively. LIMS contours are temperature variances in dB over  $1 \text{ K}^2$  ( $10 \text{ dB} = 10 \text{ K}^2$ ,  $20 \text{ dB} = 100 \text{ K}^2$ ). MLS contours are relative radiance variances, with contour labels in multiples of  $10^{-7}$ . Bottom row: corresponding squared temperature amplitudes from corrected CRISTA MEM/HA data. See text for details of the filters used in each case for comparison with LIMS (c) and MLS (d).

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that the vertical weighting functions of this instrument play a pivotal role in controlling the global distributions. She went on to argue that meaningful comparisons of gravity wave data from different satellites requires careful consideration of the spatial sensitivities of each instrument. These ideas were used by *McLandress et al.* [2000] to argue that longitudinal variations in MLS variances at  $\sim 38$  km can provide information on sources. These ideas have not been tested on other satellite data sets.

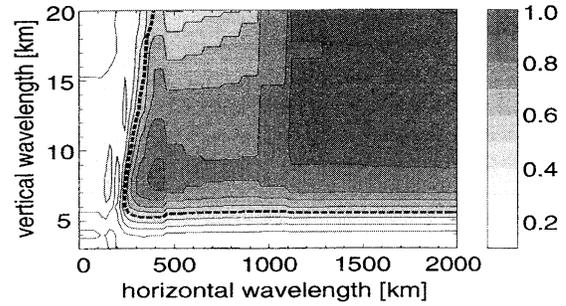
Here, we test Alexander's hypothesis by applying it in an intercomparison of zonal-mean gravity wave variances from the aforementioned satellite instruments. In section 2, we present updated calculations of the spatial sensitivity of the CRISTA temperature data to gravity waves, and use them to apply approximate corrections to these data. In section 3, we apply additional filters to the corrected CRISTA gravity-wave data that mimic the LIMS, MLS and GPS/MET vertical weighting functions, and compare the resulting zonal mean variances with actual data from LIMS, MLS and GPS/MET.

## Gravity Wave Data from CRISTA Temperatures

In this study, we use gravity wave data derived from temperatures measured by CRISTA during the first CRISTA-SPAS mission in November, 1994 [*Offermann et al.*, 1999]. We use a two-day subset of these data which scanned the largest range of altitudes [*Riese et al.*, 1999]. To isolate short scales, the large-scale global background was removed using a 0-6 zonal wavenumber Kalman filter (see also *Fetzer and Gille* [1994]). Separate daytime and nighttime fits were used to remove tidal structures as well. The resulting temperature residuals contain gravity wave fluctuations [*Preusse et al.*, 1999; *Eckermann and Preusse*, 1999].

To characterize these waves, individual vertical profiles were analyzed using the Maximum Entropy Method (MEM) and harmonic analysis (HA). The MEM spectrum was calculated using the complete height profile. The MEM peaks were used to constrain harmonic fits to the profile within a 13 km altitude window that was moved upwards in 1.5 km increments to span the full height range. This MEM/HA analysis provides height profiles of the amplitudes, phases and vertical wavelengths of the two largest oscillations in any given profile, and allows these values to vary with height (see also *Eckermann and Preusse* [1999]).

Sensitivity of CRISTA temperatures to gravity waves can be estimated from high spatial resolution radiative transport calculations using two-dimensional sinusoidal temperature perturbations of varying vertical wavelength  $\lambda_z$  and horizontal wavelength  $\lambda_h$  [*Preusse et al.*, 1999]. Updated calculations, using the BANDPAK libraries [*Marshall et al.*, 1994] and postprocessing through CRISTA retrieval algorithms, are summarized in Figure 2. The contours show the fraction of the gravity wave temperature amplitude recovered by CRISTA,  $\epsilon(\lambda_h, \lambda_z)$ , hereafter called the "visibility." We note  $\gtrsim 50\%$  visibility for waves of  $\lambda_z \gtrsim 5$  km and  $\lambda_h \gtrsim 200$  km. These are worst case scenarios in which



**Figure 2.** Sensitivity, or "visibility"  $\epsilon(\lambda_h, \lambda_z)$ , of CRISTA temperature data to gravity wave temperature oscillations of different horizontal and vertical wavelengths ( $\lambda_h$  and  $\lambda_z$ ). The 0.5 contour is highlighted (thick dashed line). Here, the waves propagate horizontally parallel to the CRISTA line of sight. Values were derived from high spatial resolution radiance calculations (see text).

CRISTA scans across the wave phase fronts. Waves with horizontal wavevectors rotated by  $\pm 90^\circ$  present phase fronts that CRISTA scans along. For these waves, the shortest visible  $\lambda_h$  is much shorter [*Fetzer and Gille*, 1994; *Wu and Waters*, 1997].

For  $\lambda_h \lesssim 1000$  km, typical of most gravity waves in the middle atmosphere [*Reid and Vincent*, 1987], Figure 2 shows that  $\epsilon(\lambda_h, \lambda_z)$  reaches a maximum at  $\lambda_z \sim 10$  km and depends weakly on  $\lambda_h$  for  $\lambda_h \gtrsim 200$ –300 km. Hence we derive a one-dimensional visibility  $\hat{\epsilon}(\lambda_z)$ , averaged over the  $\lambda_h = 300$ –800 km range for each  $\lambda_z$ . We use  $\hat{\epsilon}^{-1}(\lambda_z)$  to scale measured CRISTA amplitudes and compensate to some extent for observational degradation. These corrected CRISTA data contain gravity waves roughly in the range  $\lambda_z = 3$ –25 km.

## Effective Visibilities of LIMS, MLS, and GPS/MET

Next we choose simple boxcar visibility functions  $\hat{\epsilon}(\lambda_z)$  for the LIMS, MLS and GPS/MET instruments, following *Alexander* [1998]. However, rather than applying them to model data, here we apply them to the corrected CRISTA MEM/HA data to derive gravity wave temperature data that are "LIMS-like," "MLS-like," and "GPS/MET-like."

In isolating temperature fluctuations from LIMS, *Fetzer and Gille* [1994] applied only a wavenumber 0-6 Kalman filter at each level. This involves no vertical filtering, so only observational degradation affects the range of resolved vertical wavelengths. Calculations by *Bailey and Gille* [1986] suggested that LIMS should measure gravity waves of  $\lambda_z \gtrsim 6$  km with roughly equal sensitivity: however, these calculations were based on vertical weighting functions that did not take into account the two-dimensional spatial structure of the waves [*Preusse et al.*, 1999]. Because LIMS and CRISTA had nearly the same viewing geometry, we assume here that their visibility characteristics were broadly similar. To test this, we computed latitude-height temperature variances from CRISTA using the same method as *Fetzer and*

Gille [1994], and compared them to latitude-height distributions of filtered forms of the corrected CRISTA MEM/HA data. Best agreement was found using a pass band of  $\lambda_z = 3\text{--}15$  km on the corrected CRISTA MEM/HA data. This result is consistent with diminished LIMS visibility to long vertical wavelengths, as was inferred for CRISTA in Figure 2.

MLS radiance fluctuations were analyzed by Wu and Waters [1997]. They argued that MLS could not resolve waves of  $\lambda_z \lesssim 10$  km and had greatest sensitivity to waves of  $\lambda_z \gg 10$  km. The MLS weighting functions at high altitudes were even broader, and could not resolve  $\lambda_z \lesssim 15$  km. Thus, we approximate MLS visibilities using boxcar passbands of  $\lambda_z = 10\text{--}25$  km below 60 km and  $\lambda_z = 15\text{--}35$  km above 60 km. The sliding HA window was increased to 17 km to yield more reliable long-wavelength data for the latter pass band. While these filters capture the first-order effects, actual MLS visibility functions are more complex [Wu and Waters, 1997; McLandress et al., 2000].

In isolating gravity waves from GPS/MET temperature profiles, Tsuda et al. [2000] used a high pass filter which eliminated  $\lambda_z > 10$  km. Thus, we generate GPS/MET-like data from the corrected CRISTA MEM/HA data using a  $\lambda_z = 3\text{--}10$  km pass band.

The total error estimates are 0.7 dB for the LIMS-like CRISTA data, 1.5 dB for the MLS-like data, and  $\sim 30\%$  for the GPS/MET-like data.

### Intercomparison of Zonal Mean Variances

Zonal-mean gravity wave variances during winter are shown in Figure 1. The LIMS data in Figure 1a [after Fetzer and Gille, 1994] show small-scale temperature variance in dB over  $1\text{ K}^2$ , averaged from 6–12 November, 1978. Notable features are the strong tropical maximum and midlatitude minima in the lower stratosphere ( $z \sim 16\text{--}30$  km) and enhanced activity throughout the stratosphere and lower mesosphere at high northern latitudes. Variances grow with height over the  $z \sim 25\text{--}40$  km range. Above 40–45 km, however, amplitudes remain relatively constant with height, apart from a weak tropical maximum at  $\sim 60$  km.

Many of these features can be seen in the LIMS-like CRISTA MEM/HA data in Figure 1c. At the lowest heights, the midlatitude minima and equatorial maximum are reproduced. Enhanced variance occurs at high northern latitudes. Variances grow with height up to  $\sim 40\text{--}45$  km, but show little growth with height from 45–60 km. Interestingly, the LIMS-like CRISTA variance grows with height from  $\sim 60\text{--}75$  km before growth abates again at the uppermost heights  $\sim 75\text{--}80$  km (there are no LIMS data above 65 km for comparison).

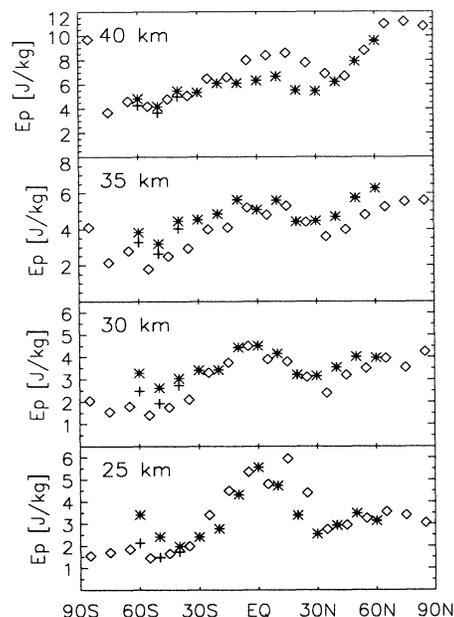
One large difference exists, however. The absolute values in Figures 1a and 1c should agree, whereas we find a mean offset between the two of  $\sim 5$  dB. The same offset occurs when we compute CRISTA temperature variances using the same procedure as Fetzer and Gille [1994]. Substantially stronger background winds during the LIMS period may have contributed by allowing more waves of longer wave-

length into the middle atmosphere. In addition, differences between the two instruments may also be implicated.

Figure 1b shows normalized MLS radiance variances, averaged from 20 December, 1992 to 29 January, 1993 [after Wu and Waters, 1997]. The latitude-height distribution differs from the LIMS data at heights where the measurements overlap ( $\sim 33\text{--}64$  km). For example, a column of attenuated MLS variance at  $\sim 0\text{--}20^\circ\text{N}$  extends throughout the middle atmosphere. MLS variances at high northern latitudes are largest at the lowest altitudes only: at upper altitudes, largest values occur in the midlatitude southern hemisphere. There is also no variance “plateau” above 40–45 km: MLS variances grow with height throughout the altitude range.

Since the MLS-like CRISTA data are temperature variances and the MLS data are radiance variances, Figures 1b and 1d can be compared qualitatively only. Nevertheless, the agreement in latitude-height morphology below 60 km is quite good. Both variances grow with altitude up to  $\sim 70$  km. There is also a column of reduced variance at  $\sim 0\text{--}20^\circ\text{N}$  and of enhanced variance at  $\sim 10\text{--}20^\circ\text{S}$  and  $60^\circ\text{N}$ . At mesospheric heights, the agreement is less impressive. It appears that the waves resolved by each instrument have such different vertical and horizontal wavelengths at these altitudes that corrected CRISTA MEM/HA data still cannot adequately reproduce the MLS data.

GPS/MET variances from Tsuda et al. [2000] are plotted with diamonds in Figure 3, while the GPS/MET-like CRISTA MEM/HA variances are plotted with asterisks. These values have been converted into potential energies per unit mass,  $E_{pot} = \frac{1}{2} (g/N)^2 \langle T'/\bar{T} \rangle^2$ , where  $\langle T'/\bar{T} \rangle^2$  is



**Figure 3.** Zonal mean potential energy per unit mass,  $E_{pot}$ , as a function of latitude and height, derived from GPS/MET data (diamonds) [after Tsuda et al., 2000] and the GPS/MET-like CRISTA MEM/HA data (stars). Crosses replot the CRISTA MEM/HA data at  $50\text{--}60^\circ\text{S}$  after removal of large values over South America due to mountain waves.

the relative temperature variance,  $T$  is local background temperature,  $g$  is gravitational acceleration and  $N$  is background Brunt-Väisälä frequency. Even though GPS/MET data were acquired and analyzed in a quite different way from CRISTA and are averages for three winter months and different years, the agreement between the two is excellent, both in absolute terms and in latitudinal variations.

Slight differences at low altitudes at 50–60°S can be explained by strong mountain wave activity excited over South America during November, 1994 [Eckermann and Preusse, 1999]: Omitting CRISTA data from this region yields variances (crosses in Figure 3) that agree much better with the GPS/MET data. These data also compare well with the LIMS data in Figure 1a: for example, we see clear evidence of a tropical maximum and midlatitude minima at lower heights in Figure 3.

## Summary and Conclusions

Differences among zonal-mean gravity wave variances inferred from four different satellite instruments that measured middle atmosphere temperatures during northern winter are shown here to result in large part from the different “visibilities” to gravity waves. Once these observational effects were taken into account, using a method where we scaled CRISTA gravity wave data, good comparisons were found with results from the other three instruments. The resulting zonal-mean latitude-height variance distributions in Figures 1 and 3 also have much in common with ground-based measurements from this region [Alexander, 1998; Tsuda et al., 2000]. For instance, the lack of growth in LIMS temperature variances from 45–60 km (Figure 1a) is also seen in rocketsonde data [Eckermann et al., 1995; Eckermann, 1995].

Thus, our analysis shows that gravity wave signals in all four satellite instruments are reliable and yield reproducible zonal-mean structures. This work provides direct experimental support for similar arguments made by Alexander [1998] using model data. While it now appears that basic zonal-mean features noted here can be explained without invoking sources [Eckermann, 1995; Alexander, 1998], recent work has shown that longitudinal variability can often be source related [Eckermann and Preusse, 1999; McLandress et al., 2000].

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