JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D4, PAGES 4685-4687, FEBRUARY 27, 2000

A comparison of gravity wave energy observed by VHF radar and GPS/MET over central North America

G.D. Nastrom and A.R. Hansen

Department of Earth Sciences, St. Cloud State University, St. Cloud, Minnesota

T. Tsuda and M. Nishida

Radio Atmospheric Science Center, Kyoto University, Kyoto, Japan

R. Ware

GPS/MET Project, GPS Science and Technology Program, University Corporation for Atmospheric Research Boulder, Colorado

Abstract. Monthly mean values of the kinetic energy at frequencies associated with gravity waves based on wind observations made with the VHF radar at White Sands Missile Range, New Mexico, are compared with potential energies determined using GPS/MET soundings. The monthly mean curves of E_k and E_p are highly correlated, and both show minimum values in the summer season with summer to winter increases of about a factor of 2. The observed ratio E_k/E_p agrees very closely with the prediction of a linear gravity wave model. These observations support previous comparisons of E_k with E_p made using the middle and upper atmosphere radar in Japan.

1. Introduction

The purpose of this note is to compare indicators of the intensity of gravity wave activity based on observations from the radar wind profiler at White Sands Missile Range (WS), New Mexico, and based on vertical temperature profiles in an area around New Mexico from the Global Positioning System (GPS/MET). This effort follows the same procedures as used by *Tsuda et al.* [2000], who based their comparisons on observations from the middle and upper atmosphere (MU) radar wind profiler near Shigaraki, Japan. While the values from the MU radar and the GPS/MET compare favorably, comparison at another radar site is warranted since the number of GPS/MET soundings over any region of the globe is relatively small and the mean values based on them correspondingly uncertain. The relatively large quantity of radar data available at WS makes it especially well suited for a comparison of climatological values.

MU (34.85°N, 136.01°E) and WS (32.41°N, 106.35°W) are located at similar latitudes, although they are in quite different climatic and geographic regimes. MU is located in locally hilly terrain with no very high mountains (over 1000 m) within 100 km west of MU [*Sato*, 1990]. MU is subject to synoptic weather events associated with the active bai-u front, as well as occasional tropical storms and typhoons and the effects of land/sea contrasts. The east Asian jet stream over MU is among the strongest in the world and averages over 50 ms^{-1} during winter months [*Murayama et al.*, 1994]. By contrast, WS is in the desert southwest in locally flat terrain with nearby mountain ridges oriented north-south, approximately perpendicular to the prevailing winds. A peak at 2704 m is located in the Organ Mountains only about 20 km from WS. Most frontal passages are relatively weak, and summer convective storms are often high-based. The mean jet stream over WS is less than 35 ms^{-1} during all months [*Nastrom and Eaton*, 1995].

Tsuda et al. [2000] compared the gravity wave kinteic energy (E_k) derived from MU wind observations with the gravity wave potential energy (E_p) derived from GPS/MET soundings. For convenience their procedure is sketched here, and their results are summarized in Figure 1. The GPS/MET data consist of vertical profiles of temperature obtained from occultation of the GPS satellite as described by others [e.g., *Ware et al.*, 1996; *Feng and Herman*, 1999]. The vertical wavenumber spectrum of the temperature perturbations over the wavelength range 2–10 km is used to estimate E_p at 15–20 km altitude. The E_p values in Figure 1 are based on 106 profiles in the area around the MU radar during 1995–1997.

The E_k values in Figure 1 are based on the analysis of MU radar data by *Murayama et al.* [1994]. Observation periods 4 or 5 days long each month during December 1985 to December 1989 were used. They integrated the frequency spectrum from 5 min to a 21-hour period (approximately the buoyancy period

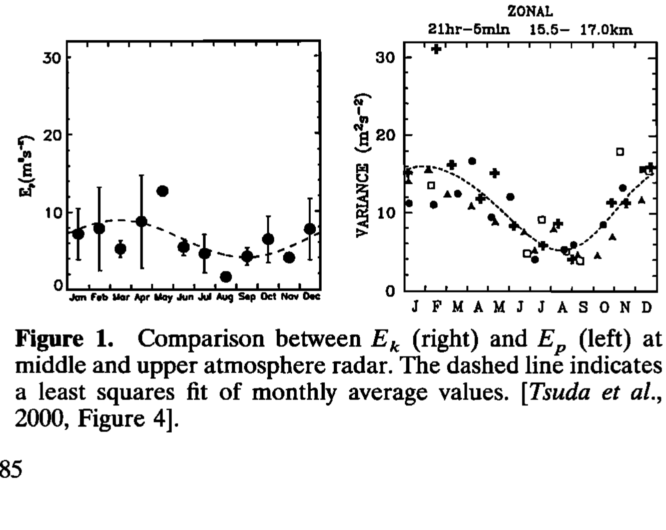

Figure 1. Comparison between E_k (right) and E_p (left) at middle and upper atmosphere radar. The dashed line indicates a least squares fit of monthly average values. [*Tsuda et al.*, 2000, Figure 4].

Paper number 1999JD901164.
0148-0227/00/1999JD901164$09.00

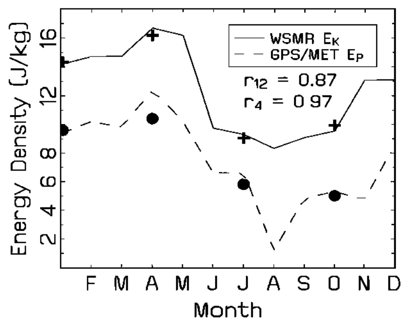

Figure 2. Similar to Figure 1 except comparing E_k and E_p at White Sands (WS); also, the circles (pluses) show the seasonal means of E_p (E_k). The correlation of the monthly (seasonal) mean values is given by r_{12} (r_4).

to the inertial period) at all heights from 15.5 to 17 km altitude and averaged the values with respect to height. Figure 1 contains the amplitude for only the zonal velocity since Murayama et al. show that the values for the zonal and meridional winds are approximately equal and are much larger than the value for the vertical wind component, and thus the vertical component can be neglected.

Tsuda et al. [2000] used the gravity wave model given by *Fritts and VanZandt* [1993] to relate estimates of E_p and E_k. The numerical value of the ratio E_k/E_p in this model is the same as the slope of the frequency spectrum, believed to be between 5/3 and 2. The observed ratio in Figure 1 is about 2. *Tsuda et al.* [2000] point out that E_p may be slightly underestimated because the vertical wavenumber spectrum is truncated at a 2 km wavelength.

2. Results

Figure 2 shows the corresponding results at WS of E_k at 14.9–19.1 km and of E_p from GPS/MET soundings. The monthly means, standard deviations, and number of data used are given in Table 1. The estimates of E_k were made following the procedure described by *Murayama et al.* [1994] using all 96-hour segments during January 1991 to September 1996 with more than 60% complete data. The frequency spectrum was integrated from 6 min to 21 hours, and vertical averages of the individual levels at 1.5 km intervals from 14.9 to 19.1 km were formed. The number of segments available varies slightly among beams and levels; the average number used each month for the four levels and three beams is given in Table 1. The GPS/MET values for E_p over the height range 15–20 km were taken from *Tsuda et al.* [2000] for all soundings falling within the area 24°–46°N, 96°–116°W; their geographical distribution is shown in Figure 3.

Table 1. Monthly Values of E_p and E_k for White Sands

Month	E_p (J/kg)	s.d.	$N_{profiles}$	E_k (J/kg)	s.d.	$N_{segments}$
January	9.4	5.1	7	14.19	6.18	8.6
February	10.2	6.2	14	14.71	5.71	16.3
March	9.8	8.0	6	14.74	4.90	8.2
April	12.4	···	2	16.68	5.77	17.4
May	10.2	3.3	2	16.18	5.88	12.3
June	6.6	···	1	9.74	3.31	15.6
July	6.6	3.2	11	9.30	3.01	13.5
August	1.2	0.7	2	8.32	2.05	16.2
September	4.8	2.6	8	9.08	2.48	13.0
October	5.3	1.9	14	9.54	3.62	14.8
November	4.7	1.3	4	13.07	4.04	6.1
December	8.6	4.2	9	13.10	6.09	5.7

The annual mean value of E_k is 12.4 J kg^{-1}, and the mean value of E_p is 7.5 J kg^{-1}. Their ratio, E_k/E_p = 1.66, compares very well with the range of values expected from gravity wave theory. However, note that the standard deviations associated with the monthly values in Table 1 imply some uncertainty in the estimate of this ratio. Also, when the analysis is limited to segments with more complete data coverage, the mean value of E_k, and of the ratio E_k/E_p, decreases (e.g., when only segments with 70% complete data are used, the ratio is 1.5). The

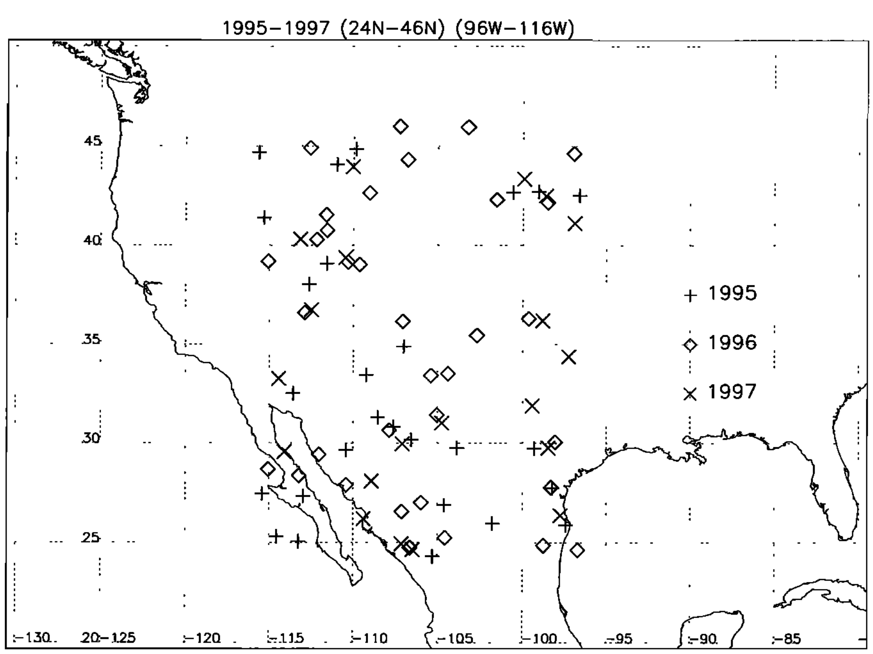

Figure 3. A map of GPS/MET sounding locations in the area around WS.

Table 2. Seasonal Mean Values of E_p and E_k for White Sands

Season	E_p (J/kg)	s.d.	$N_{profiles}$	E_k (J/kg)	s.d.	$N_{segments}$
DJF	9.6	5.5	30	14.33	5.95	30.6
MAM	10.4	6.5	10	16.17	5.74	37.9
JJA	5.8	3.4	14	9.04	2.83	45.2
SON	5.0	2.1	26	9.94	3.43	33.9

correlation of the monthly values in Table 1, $r = 0.87$, is statistically highly significant. When the individual values are combined to form seasonal means (listed in Table 2 and plotted as solid symbols in Figure 2) the correlation rises to 0.97, although the statistical significance is essentially unchanged because there are only four seasonal data pairs. The close correlation of these results is especially remarkable considering that the observing periods and observing regions of the radar and the satellite are not coincident.

Murayama et al. [1994] found that the kinetic energy in the lower stratosphere at periods from 5 min to 2 hours at the MU radar correlates closely with the amplitude of the mean winds at 12.6 km, an index of the jet stream intensity. They suggest that at MU the jet stream is a principal source of gravity wave excitation. By contrast, Figure 4 shows that at WS, E_k in this period range is not so closely correlated with the mean wind speed near the jet stream level as with that in the midtroposphere (5.6 km). This correlation pattern suggests that at WS, flow over the local rough terrain is a major source of excitation of gravity wave activity. Further, since the values of E_k (radar) and E_p (satellite) agree well at both MU and WS, and since the radar and satellite techniques have different observational "filters" [e.g., *Alexander*, 1998], this is evidence that the wave source fields are fundamentally different in Japan and New Mexico.

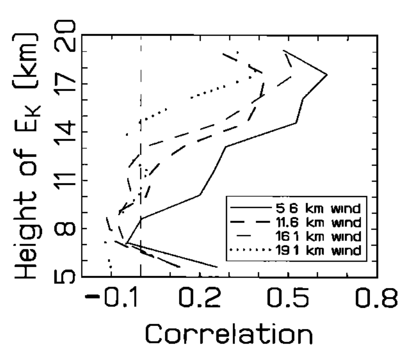

Figure 4. Correlation of E_k at heights on the ordinate with wind speed at the height indicated for each curve. Note that the largest correlation at all levels is with wind speed at 5.6 km.

Acknowledgments. The effort by GDN and ARH was partially funded by the Air Force Office of Scientific Research.

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A.R. Hansen and G.D. Nastrom, Department of Earth Sciences, St. Cloud State University, 720 4th Avenue South, St. Cloud, MN 56301-4498. (nastrom@stcloudstate.edu)

M. Nishida and T. Tsuda, Radio Atmospheric Science Center, Kyoto University, Uji Kyoto 611-0011 Japan.

R. Ware, GPS/MET Project, GPS Science and Technology Program, UCAR, Boulder, CO 80307.

(Received February 5, 1999; revised November 8, 1999; accepted November 17, 1999.)