Vol. 4 No. 1 ADVANCES IN ATMOSPHERIC SCIENCES February 1987

MESOSCALE SPECTRA OF THE FREE ATMOSPHERIC MOTION IN MID-LATITUDE SUMMER——UNIVERSALITY AND CONTRIBUTION OF THUNDERSTORM ACTIVITIES

Lü Daren (吕达仁)

Institute of Atmospheric Physics, Academia Sinica, Beijing

T.E. VanZandt and *W.L. Clark*

NOAA/Aeronomy Laboratory, Boulder, CO. 80303 U.S.A.

Received August 24, 1985

ABSTRACT

Meridional and vertical wind velocities of the free atmosphere were observed continuously in mid-latitude summer of 1981 by using Platteville ST radar in the eastern Colorado plains in order to obtain the mesoscale spectra. Power spectra were obtained for both meridional and vertical components at heights of 3.3—7.9 km for meridional and 3.3—17.7 km for vertical. Results show that the "$-5/3$ law" is a good fit to "meridional" spectra for wave periods ranging from~3 hr to 2 days which are consistent with other published observations and give further evidence to the existence of a universal $-5/3$ law in mesoscale atmospheric motions. Results also show that for wave periods shorter than 3 hr (to about 10 min), the spectra obviously depart from the $-5/3$ law and reflect the significant contribution of thunderstorm activities which frequently happen in the mid-latitude summer. Mesoscale spectra of vertical velocity show some characteristics of gravity waves. The mechanism of the observed spectra is discussed.

I. INTRODUCTION

The research on statistical characteristics of atmospheric mesoscale motions (temporal scale ranges from several minutes to about 2 days, spatial scale ranges from several hundred meters to about 1000 km) is significant for understanding the interactions between atmospheric motions of large scale (planetary, synoptic) and small scale (cumulus, 3-D turbulence, etc). There have been some observations of the mesoscale atmospheric motions from radiosondes, aircraft, and recently by the newly-developed MST radars (*e.g.*, Vinnechenko, 1970; Balsley and Carter, 1982; Larsen et al., 1982; Gage and Nastrom, 1984). Some universality has been found from the observations (Gage, 1979; VanZandt, 1982). Two mechanisms have been proposed for interpreting the observed results. Gage, based on 2-D turbulence theory developed by Kraichnan (1967) and Batchelor (1969), interpreted the observed $-5/3$ law of atmospheric mesoscale spectra as an upscale 2-D turbulence. Recently, Lilly (1983) gave a more detailed theoretical discussion to this upscale 2-D turbulence mechanism. On the other hand, VanZandt (1982) interpreted the observed mesoscale motion as gravity wave activities and described the observed mesoscale spectra as a universal gravity wave spectrum which is a slight modification of Garrett-Munk's universal spectrum of the oceanic mesoscale fluctuations. To get a clear understanding of the mesoscale motion and determine the actual mechanism(s) of atmospheric mesoscale motion, further observations (from different latitudes, heights, seasons and different observation modes) are necessary.

This paper will present another set of mesoscale spectra, based on the observations made in the mid-latitude summer, which show the further evidence of the universal – 5/3 law over a part of the mesoscale frequency domain. However, our results also show an obvious discrepancy from the – 5/3 law over a wide frequency domain ranging from the wave period of about 3 hr to the short period limit of 10 min, which can be seen as a main energy source region for mesoscale spectra. We also obtained the mesoscale spectra of vertical velocities at wave periods of 6 days—10 min. As far as we know, these "vertical" spectra are the first published. We also discuss the mechanism of mesoscale atmospheric motion.

II. OBSERVATION AND ANALYSIS

Observations were made on July 27—August 8 of 1981 by using the Platteville ST radar (Platteville, Colorado, 40° 11' N, 103° 44'W) which is cooperatively operated by the Aeronomy Laboratory and the Wave Propagation Laboratory of NOAA. Parameters of the radar are listed in Table 1. Details of the Platteville radar can be found in Ecklund *et al* (1979). Time resolution was 307 s. Range resolution was 2.4 km. Vertical and meridional components of wind were observed simultaneously. Owing to the sensitivity limitations, we could only obtain the meridional data between 3.3—7.9 km above sea level while the vertical data were obtained between 3.3—17.7 km. From conventional Limon (~ 150 km south of the ST radar site) radar PPI maps, during the observations, we determined that local thunderstorms occurred in about half of the days, but no strong thunderstorm happened directly above the radar. Most thunderstorm cells moved away from the radar site. Nevertheless, the gravity waves generated by thunderstorms were still obvious in the wind observations by the Platteville radar, and are the topic of a companion paper (Lu *et al.,* 1982).

Table 1. Platteville Radar System Parameters

Latitude	40°11' N	Average Power	133 W
Longitude	103°44' W	Pulse Width	16 μs
Elevation	1536 m	Range Resolution,	2.4 km
Frequency	49.920 MHz	Antenna Area	100×100 m²
Peak Pulse Power	~15 kw	Beamwidth (two way)	~2°

The mean power spectra for each observed height (3.3, 5.7, 7.9 km for meridional and 3.3, 8.1, 12.9, 17.7 km for vertical) were obtained as follows. For spectra at wave periods of 10 min —12 hr, we calculated the spectra for each day from the raw data, then averaged the spectra for each day to get the mean spectra. For wave periods of about 2 hr—6 days, we calculated the usispectra by ng the mean of each 10 consecutive raw data points. The composite spectra have an overlapping wave period at about 2—12 hr.

III. RESULTS

Fig. 1 shows the meridional spectra for three tropospheric heights. It can be easily seen that these spectra are similar both for spectral shape and intensity in most part of wave period domain. These spectra have the following common features: (1) Several spectral peaks at wave periods of 24 hr (diurnal tide component) and about 16 hr (inertial wave period) can be easily identified. (2) At wave periods of about 3 hr—2 days the spectra can be well fitted by using a –5/3 power law, which is consistent with other published observations (Vinnechenko, 1970; Balsley and Carter, 1982; Larsen *et al.*, 1982). In Fig. 2 the comparisons of fitted spectra of different observations are given. The spectral intensities of our observations are a little higher than the high-latitude Poker Flat radar (65°17′58″ N, 147°27′30″W, Alaska) observations, but lower than Vinnechenko's results. The reason for the spectral intensity difference is not clear yet. (3) For those spectra at wave periods of 3 hr—10 min (the upper limit of present observations) the spectral shapes significantly departed from the – 5/3 law. The fitted power values are from – 2/3 (for 3.3 km height) to – 1/3 (for 7.9 km height), much more flattening than the – 5/3 law. The spectral intensities at these wave periods are about one order of magnitude larger than other published observations. In addition, there exists a spectral peak of about 20 min at 3.3 km height which does not exist at other heights. It should be pointed out that we used the same operational antenna mode (15° off vertical) to get meridional components as Balsley and Carter did in Poker Flat radar observations. In their observations, after the correction of "vertical contamination", the –5/3 can be fitted to the observational spectra down to the wave period below 10 min. For our observations, however, after correction of vertical contamination (subtracting the vertical spectral components at each corresponding wave period from observed slant spectral components), the spectral

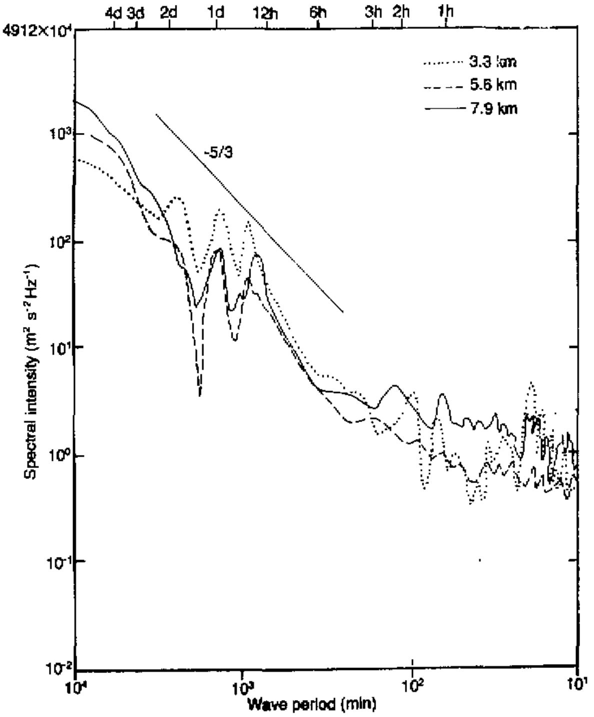

Fig. 1. Power spectra of atmospheric meridional motions at three tropospheric heights over Plateville radar site in the summer of 1981.

shape has no obvious change. The reason is that in our case, vertical spectral intensities are about half to one order of magnitude less than slant spectral intensities at the same wave periods.

Fig. 3 shows the vertical spectra for three tropospheric and one lower stratospheric heights. An obvious feature of these spectra, in comparison with meridional spectra, is their flatness. At wave periods of 24 hr to 10 min, the spectrum at each height can be approximately fitted by a two-segment power law. At wave periods of 10—60 min, the spectral shape for the three tropospheric heights is about $-3/4$. While from 1 to 24 hr, this spectral slope is about $-1/3$ to $-1/4$. For the lower stratosphere, the spectral slope for wave periods of 10—60 min and 1—24 hr are $\sim -1/8$ and $\sim -1/16$, respectively. The spectral intensities for the middle and upper tropospheric heights are stronger than those at the lower tropospheric and stratospheric heights. The spectral intensities for the lower stratosphere are about 5—10 times smaller than those from the middle tropospheric heights. As far as we know, the spectra of this paper are the first published spectra of vertical velocity in the whole mesoscale wave period. Comparing our results with Poker Flat observations (Balsley and Carter, 1982) at shorter wave periods *(10 min—2 hr), it is found that the spectral slope is similar (~3/4)*, but the spectral intensities of summer Platteville observations are much stronger than the Poker Flat observations (also summer).

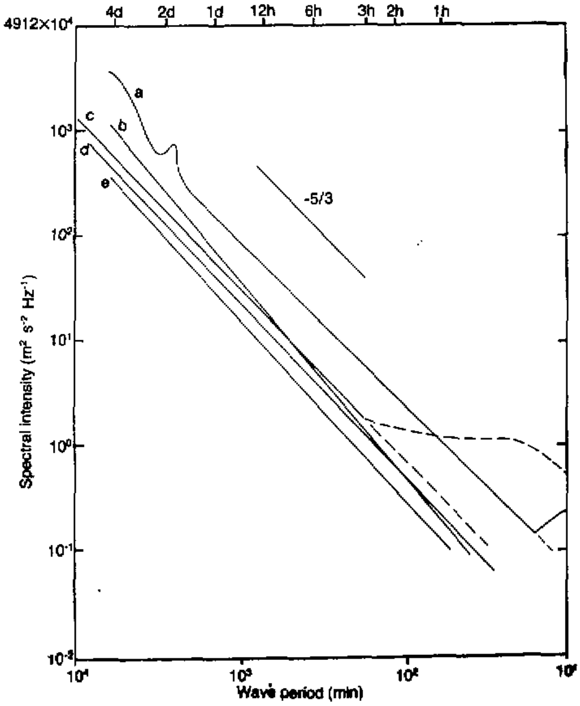

Fig. 2. Intercomparisons of atmospheric mesoscale spectra observed by different authors: a—Vinnechenko composite data; b—Larsen et al., meridional, 8 km; c—Lü *et al.*, present observations; d—Balsley and Carter, zonal, 8 km and e—Larsen et al., zonal, 8 km.

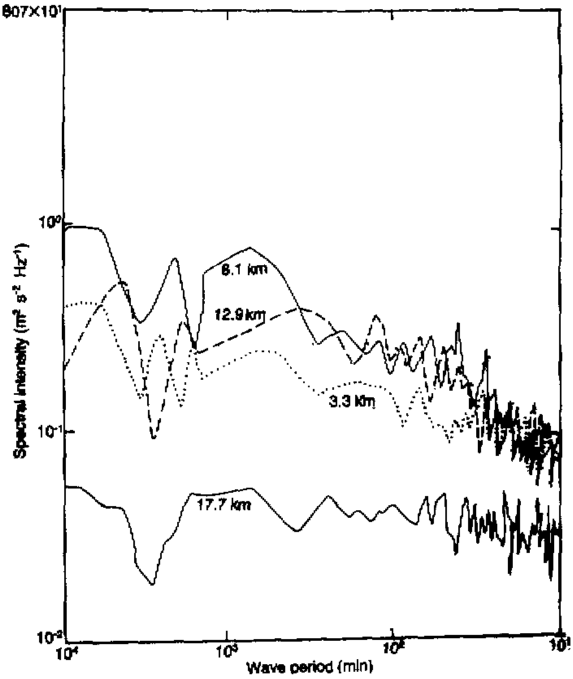

Fig. 3. Power spectra of atmospheric vertical motions at three *tropospheric heights and one stratospheric height over* Platteville radar in the summer (July 27—Aug. 8) of *1981.*

IV. DISCUSSION AND SUMMARY

The present results from mid-latitude summer observations of free atmospheric mesoscale motion give further evidence of the existence of a rather universal $-5/3$ law in the mesoscale spectra of atmospheric horizontal wind. In our case, the $-5/3$ law is applicable to wave periods of about 3 hr —48 hr. Spectral intensities of our observations are similar to Poker Flat radar observations (Balsley and Carter, 1982; Larsen *et al.*, 1982). The explanation for the difference of spectral intensities between MST radar (Poker Flat and Platteville) observations and Vinnechenko's observational summary (based on a variety of observation methods, sometimes using the Taylor hypothesis to convert spatial spectra to temporal spectra) is not yet clear.

An important difference of our spectra from other observed spectra is in the wave periods of 3 hr—10 min. In our mid-latitude summer spectra, the spectral shape at these wave periods is much flatter than the $-5/3$ law and spectral intensities are much stronger than other observations. Both spectra of Poker Flat results and Vinnechenko's results could be well fitted by the $-5/3$ law down to the wave period of about 10 min or less. Vinnechenko's mean spectra show the branching starting at the wave period of 10 min. Balsley and Carter's spectra show the $-5/3$ law fitting well down to the wave period of about 5 min (after correction of vertical contamination). Obviously, the above-mentioned difference could be caused by strong and frequent convective activities in mid-latitude summer. In a companion paper (Lu *et al.*, 1982) we have pointed out that the well-shaped and vertically coherent waves of periods of 30 min to a few hours exist and are related to regional thunderstorm activities. Statistics and case studies showed that these waves constituted the main part of the vertical spectral energy at these wave periods. Hence, in our mid-latitude summer case, thunderstorm activities (including the generated gravity waves) were the main contributor to mesoscale spectral energy at those wave periods.

The spectral peak at the wave period of ~20 min at 3.3 km might be due to the frequently occurring weak convection near the top of the mixed layer (planetary boundary layer) during summer time. Both convective cells and convection-induced gravity waves would have similar time scales. These clear air convections usually do not develop to higher heights (Kuo and Sun, 1976).

The relatively "flat" and two-segment (in log-log units) spectral shape of the vertical velocity spectra means that the spectral energy is concentrated in shorter wave periods, which is consistent with universal consideration (no stronger source at longer wave periods and main sources are in shorter time scale, Monin and Yaglom, 1975, P522). In mid-latitude summer, convection and convection-induced gravity waves (having wave periods up to a few hours) are important processes of the atmospheric vertical motion. The differences of spectral intensities at different heights (strongest at the upper troposphere and weakest at the lower stratosphere) are probably due to the fact that the upper troposphere is the region of strong vertical motion (both thunderstorm cells and the induced gravity waves), so the spectra in this region contain more characteristics of the energy source of mesoscale vertical motion. The spectrum from the lower stratosphere would be caused by propagating gravity waves which have a flatter shape (about zero slope) and smaller spectral intensities.

Whether the two-dimensional turbulence and/or nonlinear interactive gravity waves cause the observed mesoscale spectra is still unresolved and requires further theoretical and experimental investigation. Based on Gage's (1979) discussion about two-dimensional turbulence of atmospheric mesoscale motion, Lilly (1982) theoretically considered that this upscale (decascade) 2-D turbulence can be evolved from an originally 3-D turbulence (decaying convective clouds and thunderstorm anvil outflow). He pointed out that, in the presence of strong stratification, initially three-dimensional isotropic turbulence will transform equal energy into gravity waves and stratified (quasi-two-dimensional) turbulence. The gravity waves then propagate away from the generating region, leaving the quasi-two-dimensional turbulence moving in spectral space to larger scales (upscaling) and forming the $-5/3$ up-scale spectrum predicted by Kraichnan (1967). On the other hand, several authors (*e.g.*, VanZandt, 1982) described the mesoscale spectra as gravity wave spectra. Based on Garrett-Munk's empirical spectra of oceanic mesoscale motion, VanZandt summarized the observed mesoscale atmospheric spectra, both temporal and spatial, and suggested that there exists a universal spectrum of atmospheric gravity waves which can be used to interpret the observed spatial and temporal spectra. In addition, several authors have discussed the possibility of gravity energy transfer from smaller to larger scales and from higher to lower frequencies through weak and strong nonlinear wave-wave interactions (*e.g.*, Orlanski and Ceron, 1980, Yeh and Liu, 1981).

From our mid-latitude observation, we have found that in the spectral energy "source" region (wave periods about 3 hr—30 min analyzed in a companion paper, Lu *et al.*, 1984), the main contribution to the vertical motion came from thunderstorm-generated gravity waves. This GW-active periods are consistent with the spectral energy source region for the meridional motion. That means that the thunderstorm activities may contribute to both vertical and horizontal motions in these wave periods. We can not conclude the mechanism(s) from the present observation. Gravity waves may have their contribution, while the fact that the spectral intensity of meridional motion is larger than the expected values (in comparison with the spectral intensity of the vertical motion, particularly in those shortest wave periods) from the gravity wave theory means that there may be other contributing mechanism (s), *e.g.* 2-D turbulence. An important point of the present observation is that, although the universal $-5/3$ law is fitting to the observed spectra in wide frequency range, there exists the spectral range in which the spectra obviously have very flattening shape and much stronger spectral intensity. As no thunderstorm happened locally over the Platteville radar during the time period of observation, the present result should be representative of the mid-latitude summer situation. Further investigation of the possible mechanism (s) of the mesoscale spectra of "$-5/3$ law" is needed. In the meantime, we should find the reasonable mechanism (s) to explain the observed spectra in shorter wave periods, which will give us further information about the energy source and transfer of the atmospheric mesoscale motions.

Further observation is significant to a clear understanding of the atmospheric mesoscale motions. To this end, we should make MST and ST radars play an important role in continuous observations of the atmosphere.

We wish to thank W.L. Ecklund and B.B. Balsley for their assistance in planning the experiment; R.G. Strauch for conducting the experiment; A.C. Riddle for off-line data processing; and K.J. Ruth for performing the spectral analysis. One of the authors (Lü Daren) acknowledges NOAA and the Aeronomy Laboratory for providing the facilities for this research.

REFERENCES

Balsley, B.B. and Carter D.A. (1982), The spectrum of atmospheric velocity fluctuations at 8 km and 86 km, *Geophys. Res. Lett.* **2**:465—468.

Batchelor, G.K. (1969), Computation of the energy spectrum in homogeneous two-dimensional turbulence, *Phys. Fluids,* **12**: Suppl. 2, 233—239.

Ecklund, W.L., Carter, D.A. and Balsley, B.B. (1979), Continuous measurements of upper atmospheric winds and turbulence using a VHF Doppler radar: preliminary results, *J. Atmos. Terri, Phys.* **41**: 983-994

Gage, K.S. (1979), Evidence for a $K^{-5/3}$law inertial range in mesoscale two-dimensional turbulence., *J. Atmos. Sci.,* **36** 1950—1954.

Gage, K.S. and Nastrom, G.D. (1984), On the interpretation of the variance spectrum of velocity observed by ST/MST radars, 22nd Conf. on Radar Met. No. 15.2, 10—13, Sept. 1984, Zurich, Switzerland.

Kraichnan, R.H. (1967), Inertial range in two-dimensional turbulence, *Phys. Fluids,* **10**:1417—1423.

Kuo, H.L., and Sun, W.Y. (1976), Convection in the lower atmosphere and its effects, *J. Atmos. Sci.,* **33**: 21—39.

Larsen, M.F., Kelley, M.C. and Gage, K.S. (1982), Turbulence spectra in the upper troposphere and lower stratosphere between 2 hours and 40 days, *J. Atmos. Sci.,* **39**:1035—1041.

Lilly, D.K. (1983), Stratified turbulence and the mesoscale variability of the atmosphere, *J. Atmos. Sci,* **40**:749—761.

Lü Daren, VanZandt, T.E. and Clark, W.L. (1984), VHF Doppler radar observations of buoyancy waves associated with thunderstorms, *J. Atmos. Sci,* **41**:272—282.

Monin, A.S. and Yaglom, A.M. (1975), *Statistical Fluid Mechanics: Mechanics of Turbulence* Vol. 2, MIT Press.

Nastrom, G.D., Gage, K.S. and Jasperson, W.H. (1984), Kinetic energy spectrum of large and mesoscale atmospheric processes, *Nature* **310**: No 5972, 36—38.

Orlanski, L., and Cerosoli, C.P. (1981), Energy transfer among internal gravity modes: weak and strong interactions, *J. Geophys. Res.,* **86**(C5): 4103—4124.

VanZandt, T.E. (1982), A universal spectrum of buoyancy waves in the atmosphere, *Geophys. Res. Lett.*, **2**:575—

578.

Vinnichenko, N.K. (1970), The kinetic energy spectrum in the free atmosphere-1 sec. to 5 yrs., *Tellus*, **22**:158—166.

Yeh, K.C., and Liu C.H. (1981), The instability of atmospheric gravity waves through wave-wave interaction, *J. Geophys. Res.*, **86**(C10): 9722—9728.