The Scales of Variation of Turbulent Kinetic Energy Dissipation in Hurricanes

FRANCIS J. MERCERET

National Hurricane and Experimental Meteorology Laboratory, NOAA, Coral Gables, FL 33124

28 June 1978 and 18 September 1978

ABSTRACT

Conventional techniques for determining which features of hurricanes govern their distribution of kinetic energy dissipation rate (ϵ) fail to yield significant correlations because of the high random variability of ϵ. Spectral analysis of the time series of the logarithm of ϵ, however, shows several distinct features which may be tentatively identified with specific aspects of the storm circulation. In particular, cloud-scale, cloud-cluster-scale and rainband-scale peaks occur in the power spectrum of $\log_{10}\epsilon$.

1. Introduction

During 1975 Hurricanes Caroline, Eloise and Gladys, a hot-film anemometer aboard the NOAA Research Facilities Center (RFC) DC-6 aircraft measured the streamwise wind velocity fluctuations along the flight track. The measurements covered frequencies from 2 to 2500 Hz corresponding to scales from 50 m to 4 cm which include the inertial subrange of the turbulence. From these spectra time series of dissipation were generated covering scales from 100 m to about 20 km. Detailed discussion of the instrumentation, the experiments and of the specific storms is found elsewhere (Merceret, 1976a, b; Moss and Merceret, 1976, 1977; Moss, 1978). The variable of concern in this paper is the turbulent kinetic energy dissipation rate ϵ determined from the inertial subrange at a wavelength of 15 cm as described by Merceret (1976b).

The study of Hurricane Caroline showed little correlation between ϵ and altitude from 100 to 3000 m or local wind speed from less than 7 m s^{-1} to above 35 m s^{-1}, but it did suggest that the probability distribution of ϵ was log-normal. A more extensive study of the data from all three storms confirmed that ϵ is a log-normal random variable and also that it is essentially uncorrelated with local bulk variables. The standard deviation of the logarithm of ϵ was similarly uncorrelated. The mean of the logarithm was correlated with wind speed but only at the 5% level and only 25% of its variance was accounted for (Merceret, 1978). This negative result led to the adoption of another approach to investigating what features of the hurricane determine the dissipation rate.

The alternate approach is an intercomparison of scales. This paper presents results from computations of the power spectrum of $\log\epsilon$ and compares these with the scales of known features of hurricanes.

2. Selection and analysis of data

The 1975 hurricane turbulence data were examined along with the corresponding bulk meteorological data and aircraft parameters. Sections of record were selected which met the following criteria:

1) Turbulence data quality excellent.
2) Straight and level flight.
3) Homogeneous meteorological environment.
   (a) Mean[1] wind speed constant within ±3 m s^{-1}
   (b) Mean temperature constant within ±2°C
   (c) Mean wind direction constant within ±20°
4) Record length $\geq$2 min.

There were 23 such records processed for spectra as described below. Of these, 20 were from altitudes between 150 and 300 m. The remaining three were from 400, 450 and 3150 m. Wind speeds ranged from near calm to more than 30 m s^{-1}. Regions of the storm examined included those near the eye, the rainbands and the spaces between bands. Distances from the storm center ranged from less than 30 km to more than 200 km. Fifteen of the records are taken between 50 and 150 km from the center, three are from within 50 km of the center and the remaining six are from beyond 150 km.

The turbulence signal (velocity) was put into a Spectral Dynamics model SD 330 real-time analyzer,[2] having a full scale range of 2 kHz and a bandwidth of 12 Hz. An exponential running average of the power spectral density at 648 Hz was computed with the averaging time constant equal to 1 s. The logarithm of this quantity, which is proportional

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[1] Averages taken over 10 s.

[2] Mention of a commercial company or product does not constitute an endorsement by NOAA or the Environmental Research Laboratories. Use of information from this publication for publicity or advertising purposes relating to proprietary products or the tests of such products is not authorized.

TABLE 1. Scales corresponding to statistically significant spectral peaks for each spectrum of log ε. A peak is significant if it rises at least one standard error (41%) above its surroundings on a log spectral density versus log frequency plot. This is equivalent to an 80% confidence limit of about 1.5 dB.

Time (GMT)	Altitude (m)***	Wind speed (m s⁻¹)	Direction**	Notes	Approximate scales of significant spectral peaks (km)								
Caroline 750830A													
1827–1830	450	15	S	Poor data	4	2	0.09						
2000–2003	300	25	A		7.7*	1.4	0.43	0.22	0.19				
2004–2007	300	25	A		7.7*	1.4	0.42	0.22	0.11	0.07			
2015–2019	300	23	A		7.7*	0.71	0.42	0.25	0.20	0.16			
2056–2059	3150	23	S		7.7*	0.42	0.31	0.26	0.20	0.17	0.11		
2322–2333	300	19	S	Fig. 3	21*	5.3	1.1	0.56	0.50	0.24	0.16		
Eloise 750916A													
1910–1914	150	11	S		7.7*	0.5	0.38	0.23	0.16				
1922–1926	150	13	S		4.2	1.4	0.56	0.45	0.22	0.18	0.12	0.10	
2039–2051	250	33	A	Fig. 1	21*	4.4	2	1.3	1	0.63	0.5		
2054–2059	250	35	A		6.7	0.56	0.28	0.24	0.21				
2150–2154	250	35	S		7.7*	0.71	0.21						
2208–2212	300	30	S		7.7*	0.26	0.21						
Eloise 750917A													
1827–1830	250	15	S		5	1.2	0.53	0.42	0.36	0.21			
1830–1833	250	15	S		0.77	0.4	0.33						
2033–2037	250	25	P		2.5	0.71	0.43	0.3	0.25	0.2	0.16	0.13	
2108–2112	400	20	A		7.7*	0.29	0.20	0.14	0.10				
2125–2130	250	25	S		7.7*	2	0.71	0.42	0.2				
Gladys 750916A													
2036–2043	150	25	X		21*	3	1.6	1.1	0.77	0.56			
2043–2050	150	25	X		21*	5.3	2	1.4	0.67	0.5			
2051–2059	150	30	S		21*	3.6	1.4	1.1	0.91	0.59			
2126–2130	300	30	P		4	1.9							
2139–2143	300	25	A	Fig. 2	7.7*	0.91	0.71	0.5	0.4	0.29	0.21	0.16	0.09
2146–2153	300	25	A		21*	4	1.7	1	0.53				

* Low end frequency limit. Actual peak may be at larger scale.

** Key: X denotes crosswind run; P = parallel to wind; A = antiparallel; S = Skew.

*** Rounded to nearest 50 m.

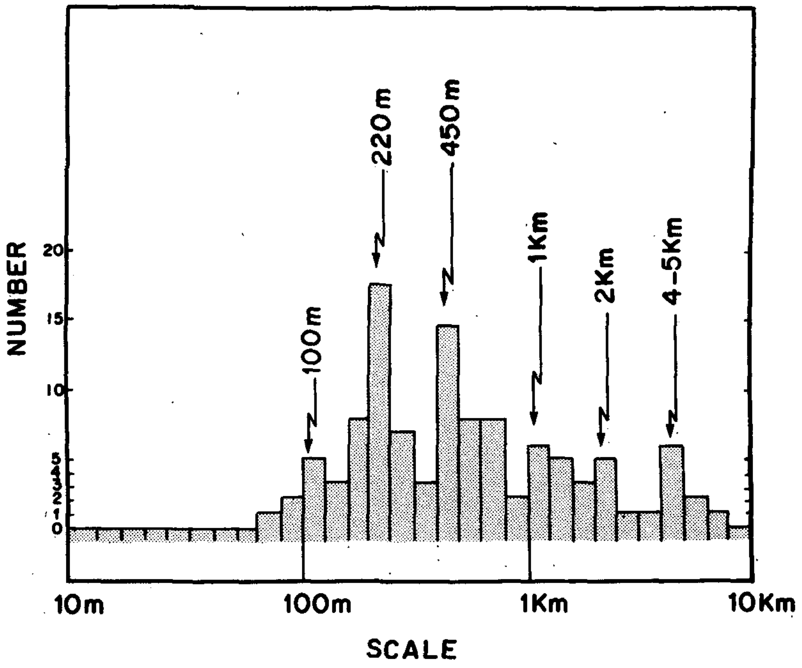

FIG. 1. Distribution of scales of spectral peaks from Table 1. Peaks at the low-end frequency limits (flagged with an asterisk in the table) have been omitted because their actual scale is uncertain. There were six peaks at 21 km and 10 at 7.7 km thus discarded in this presentation.

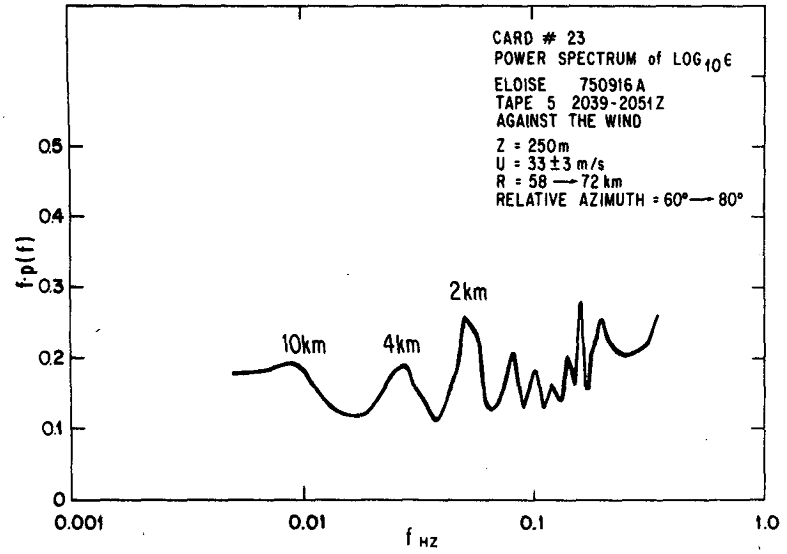

FIG. 2. Frequency-weighted variance spectrum of logε from Hurricane Eloise (1975). Frequency may be converted to wavelength λ using λ = TAS/f, where the aircraft's true air speed (TAS) was 100 m s^{-1}, λ is measured in meters and f in Hz. The spectral estimates have a standard error of 0.41 (DF = 12).

to the logarithm of the dissipation, was routed to a Honeywell model ASI-43 real-time correlator.[2] The resulting autocorrelation was Fourier-transformed to produce the variance spectrum of logε for each record. Since only the dominant scales of variability and not the absolute magnitudes were sought, the variance spectra were not calibrated to MKS units. The variance spectral density $P(f)$ has dimensions of variance of logε per unit frequency. Its scale factor is arbitrary. The spectra used in this study have 12 degrees of freedom per spectral estimate. The corresponding standard error is 41% (Bendat and Piersal, 1966, p. 208). It is emphasized that the data presented hereafter are spectra of logε, *not* velocity spectra.

3. Results

As one expects, the spectra show substantial variation. It is remarkable, however, that they show a consistent set of common features as well. Table 1 presents a listing of the scales of statistically significant spectral peaks for each spectrum. At the largest resolvable scales there is a broad peak in the range 10–25 km which is listed in the table as being at 21 km. At the intermediate range a peak occurs

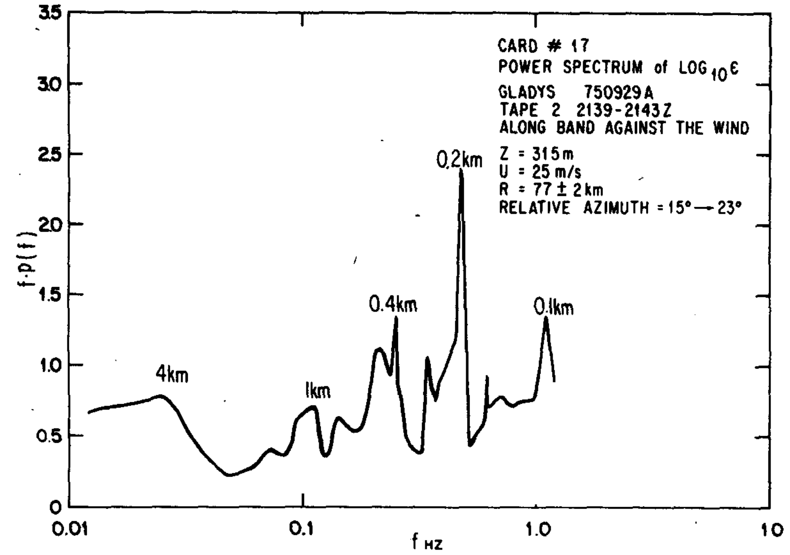

FIG. 3. Frequency-weighted variance spectrum of logε from Hurricane Gladys (1975). λ = 100/f, DF = 12.

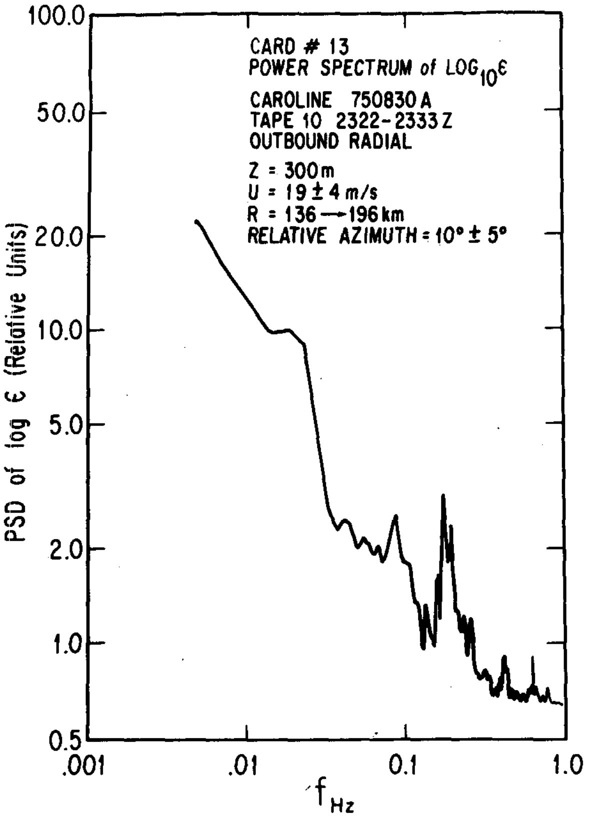

Fig. 4. Variance spectrum of log ε from Hurricane Caroline (1975). $\lambda = 100/f$, DF = 12.

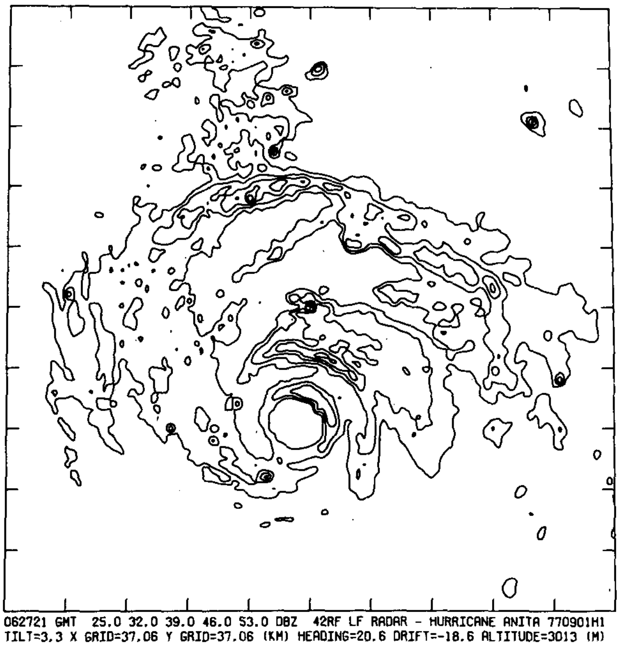

Fig. 5. PPI radar presentation from 5.6 cm airborne weather radar during Hurricane Anita, 1 September 1977. From Jorgensen and Lewis (1978).

in the range 3–5 km. At the smaller scales we see a peak in the 1–2 km range, another at about half that and another at about 200 m. The overall distribution of peaks is shown in Fig. 1. Figs. 2 and 3 show typical spectra. In these, the structure at the low-frequency end is somewhat concealed by the frequency-weighted presentation used. The true relative magnitude of the low-frequency spectral density peak can be seen, for example, in Fig. 4.

These common features appear throughout the records without regard to altitude, wind speed or position, but since the sample size is small at altitudes above 300 m and also small within 50 km of the center it would be premature to conclude that no variation of scales with height or position occurs.

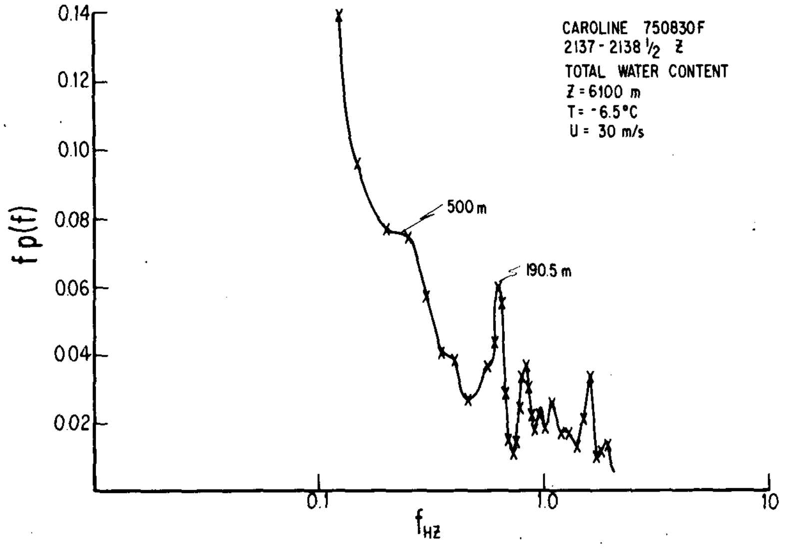

Fig. 6. Frequency-weighted variance spectrum of total water content from Hurricane Caroline (1975). $\lambda = 120/f$. The spectral estimates have a standard error of 0.19 (54 DF).

Nonetheless, the data do suggest that any such variation is not dramatic.

4. Discussion

Examinations of radar presentations of hurricane convection [e.g., Fig. 5 from Jorgensen and Lewis (1978)] shows rainband lengths on the order of 200 km, rainband thicknesses of 10–60 km and mesostructure thicknesses near 4–5 km; hot cores of 1–2 km diameter are frequent. Examination of liquid water and vertical motion power spectra on the cloud scale shows large peaks at scales of the order of 200 and 600 m (Paul T. Willis, private communication, 1978; see Ackerman, 1966). An example is shown in Fig. 6.

Comparison of these data with the results of this study indicates that the same scales which dominate the convective activity dominate the dissipation rate distribution. Since convection produces shear and buoyancy forces which generate turbulence locally and also inputs it from the high-energy surface layer, it is unlikely this similarity is accidental. Then why do the direct correlation studies fail to yield better results? One likely contribution to the smallness of the correlations is the time required for the turbulence to respond to local flow changes. For $\epsilon = 5 \times 10^{-3}$ m^2 s^{-3} and $u_* = 1.5$ m s^{-1}, values reasonable for hurricane turbulence (Merceret, 1976b; Moss, 1978), the decay time of the turbulence is 300 s. This is nearly half the lifetime of many of the smaller convective features seen on radar (Billy Lewis, private communication, 1978). Since true time-lagged correlations at a point fixed with respect to a convective feature (or to the earth) are impossible with present platforms, a direct test of the hypothesis is difficult. An indirect test may be made by computing the correlations for low-pass filtered data with scales large enough that their time constraints are, say, 2000 s or more. This requires longer data records than are presently available. We hope to acquire the necessary data for this purpose during the 1978 hurricane season.

If the tentative suggestion that the scales of variance do not change with position should prove correct and if these scales are associated with convection, then it implies that the scales of convective activity do not change appreciably within the storm. This means that the organization of the convection in the vicinity of the eye involves changes in phase relations and magnitudes rather than changes in convective scales. Additional investigation of this matter may enhance our knowledge of hurricane dynamics substantially.

Acknowledgments. Comments by S. L. Rosenthal, R. I. Sax and H. E. Willoughby on an earlier draft of this manuscript were quite helpful. The contributions of Fig. 5 by David Jorgensen and Fig. 6 by Paul Willis are acknowledged with gratitude.

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