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FLUID DYNAMIC IMPLICATIONS OF THE INTERMITTENCY OF TURBULENT MOMENTUM TRANSPORT IN THE OCEANIC TURBULENT BOUNDARY LAYER*

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海洋 亂流境界層內 斷續性의 流體力學的 意義

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Abstract: The Intermittent phenomena of the turbulent momentum transports were closely examined in order to know the nature of intermittency and its fluid dynamic implications in the oceanic turbulent boundary layer. Also the connection between the observed intermittency and the bursting phenomenon was studied in detail.

In this investigation, strong intermittency of turbulent momentum transports were found and the peak values of Reynolds stress (i.e., $u'w'$) was about 408 times greater than average Reynolds stress ($\overline{u'w'}$) in the mid-layer and 270 times greater in the upperlayer of the turbulent boundary layer. These values are far greater than presently known maximum value, namely 30 times greater than the average Reynolds stress reported by Gordon (1974) and Heathersaw (1974). The distribution of Reynolds stress were extremely non-normal with the mean peak occurrence period of 5 minutes in the mid-layer and 1.1 minutes in the upper layer of the turbulent boundary layer. Each peak lasted about 2 seconds in the mid-layer and 1.1 seconds in the upper layer of the turbulent boundary layer. Our dimensionless period of peak occurrence are found to be 33.3 in the mid-layer and 7.3 in the upper-layer, which are substantially larger than the often quoted values of 3.2—6.8 for the bursting period (Jackson, 1976).

Some workers have interpreted that the intermittency phenomenon is the reflect of burst and other workers interpreted the intermittency is caused by the passage of the burst across their probe of the currentmeter (Gordon, 1974; Heathersaw, 1974). However, it was known that the burst can be found very near bottom boundary with smoothed bottom (i.e., friction Reynolds number$\leq 3,000$) in the laboratory experiments. Through this investigation, it was found that the intermittent strength of the turbulent momentum transports does not conclusively indicate the presence of burst and the cause of burst. We are inclined to interpret the intermittency is the characteristic feature of the boundary layer turbulence with a rough bottom (i.e., friction Reynolds number$\geq 10^5$).

要約：海洋 亂流境界層內 亂流運動量輸送의 斷續性 現象에 對하여 그 本質을 把握하고 流體力學的

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인 意義를 究明하기 爲한 研究를 企圖했다. 또한 斷續性 現象과 炸裂現象의 相關關係도 아울러 研究했다.

本 研究를 通해 亂流境界層內에서도 中間層에 屬하는 z/h=0.067層에서는 斷續性의 크기가 平均亂流運動量輸送의 408倍에 達하고 上部層 卽 z/h=0.1層에서는 270倍에 達함이 밝혀져, 이제까지 報告되었던 Gordon(1974)이나 Heathersaw(1974)의 30倍보다 越等히 크다는 것이 새로운 事實이다. 一部 學者들은 斷續性現象을 炸裂現象의 反映 또는 炸裂이 流速計에 부딪혀 나타나는 現象이라고 解釋한 바 있으나(Gordon, 1974; Heathersaw, 1974), 本 研究에서 밝혀진 바에 依하면, 이는 摩擦 Reynolds數가 $>10^5$인 實際海洋의 亂流境界層內 亂流運動의 特徵이라는 事實이다.

INTRODUCTION

The laboratory experiments of Kline *et al.* (1967) first showed the intermittency of Reynolds Stress collectively referred to as "Bursting". This phenomenon was observed in the boundary layer by means of flow visualization techniques in laboratory work. The similar physical property was reported by Grass(1971), Seitz(1973), Gordon(1974), Heathersaw(1974), and Jackson(1976) in the field.

We are interested in the extent to which laboratory results on bursting can be directly applied to geophysical flows as, for example, was done by Jackson (1976). Laboratory experiments are commonly carried out in smooth, straight-sided channels at friction Reynolds number, $R^* \simeq 10^3$ to 10^4, using flow visualization techniques and very small hot wires or hot films. In the present study, we have used an electromagnetic flow meter. This has a probe diameter of 0.95cm, which is much smaller than that used in any other geophysical boundary layer study known to us. We estimate that our measurements can resolve "eddy scales" of the order of 5 to 10cm and larger, while the buffer layer in the boundary layer is, with friction velocity, $u_* = 2$cm/s, only 5mm thick.

EXPERIMENTAL DESIGN AND DATA AQUISITION SYSTEM

Through a series of flume test, the basic parameters of the experiments were determined. The digitization time interval was set as 1/8 seconds, the Nyquist frequency, f_N, is 4.0 Hz, and the spectral window of instrument, f_w, is 0.0 to 7.92 Hz.

A series of measurements, which consisted of 7680 sets (i.e., u, v, t., u, w, t., v, w, t) taken over 16 minutes period during the maximum flood and ebb current time, conduced in the Lafayette estuary, Norfolk, Virginia.

The data measuring and aquisition system consisted of the electromagnetic current meter and the data recording system (Chung, 1979). The data recording system consists of a PDP-8/E minicomputer, ARS-33 Teletype, x-y strip chart recorder (Hewlett Packard Model 1750lA), an amplifier box, multimeter (Triplett Model 630), and two isolation transformers (Scientific Products N-58M). The PDP-8/E minicomputer was used as the controller of the digital data gathering system. It also temporarily stores the data and controls the punching of the data on a tape in an 8-bit binary code.

DATA REDUCTION AND ANALYSIS

The recorded data were transfered to the disk of the DEC System-10 Computer through the ARS-33 Teletype by use of the peripheral interchange program (Chung, 1979). The transfered data were plotted as a function of time. It was found that there were many "spikes" of one digitization time interval, which were caused by the variations in the line voltage. Therefore, to remove these high frequency "spikes", a digital low pass filter (Chung, 1979) was designed with 401 smoothed weights by examining smoothed filter function.

After filtering, the runs consisted of 7280 pairs of values. For spectral analysis, the fluctuating velocities, $u'(t)$, $v'(t)$, $w'(t)$, were calculated. After then, means of the squares of the fluctuating components and mean of the cross products of the components were computed. The autocorrelation functions and energy spectra densities, were computed using the method of Blackman and Tukey (1958). Finally, the energy spectra were computed for each component. Besides of the Blackman and Tukey method, Fast Fourier Transformation method was applied for comparison (Grosch and Chung, 1981).

RESULTS AND DISCUSSION

The number of data points, the number of lags used in the calculation of autocorrelation function, the resolution frequency, degree of freedom, and the confidence bounds are given in Table 1 along with the case of FFT method. The measured values of $\bar{U}$, $\bar{u}'^2$, u', etc are listed in Table 2. The turbulent energy production rate ($q^2/2$) and dissipation rate (ε), normalized turbulent intensities (u'/u_*, u'/u_*, w'/u_*), eddy viscosities (ν_T), and eddy sizes (X, Y, Z) are listed in Table 3. The fluid dynamic characteristics (friction velocity, u_*, roughness length scale, Zo, shear stress, τ_o, drag

Table 1. Statistical Characteristics of Experiments

B&T method	Number of data points	Number of lags	Frequency resolution	Degree of freedom	Confidence bounds
	7200	800	0.05Hz	18	1.43&0.61
FFT method	**Number of data points**	**Number of segments**	**Number of data points per segment**	**Frequency resolution**	**Error bounds**
	7200	7	1024	0.0078Hz	23.1%

Table 2. Turbulent Intensities

Z(cm)	z/h	$\bar{U}$(cm/sec)	$\bar{V}$(cm/sec)	$\bar{W}$(cm/sec)	$\bar{u}^2$(cm/sec)^2	$\overline{uw}$(cm/sec)^2
45	0.1	32.67	0	−0.85	230.2	−48.95
30	0.067	25.88	0	−16.40	176.4	−68.70

Table 3. Turbulent Energy and Eddy Sizes of the Nearest Bottom Boundary

	ε (cm^2/sec^3)	ν_T (cm^2/sec)	$q^2/2$ (cm/sec)^2	u'/u_*	v'/u_*	w'/u_*	Averaged Eddy sizes		
							X(cm)	Y(cm)	Z(cm)
z/h=0.100	1.78	57.24	260.5	4.78	3.30	2.56	850	713	35
z/h=0.067	2.57	37.29	270.8	3.91	3.09	4.75	750	225	15

Table 4. Fluid Dynamic Characteristics

u_*(cm/sec)	z_0 (cm)	τ_0 (dynes/cm^2)	C_{100}	U_{100} (cm/sec)	R_*
1.993 ∫ 3.186	0.019 ∫ 0.781	4.020 ∫ 10.272	2.21×10^{-3} ∫ 6.79×10^{-3}	38.71 ∫ 42.37	$\geq 1.43\times10^5$

Table 5. Probability Distribution of Intermittence in the Nearest Bottom Boundary

Normal Distribution		z/h=0.100(7200 data pt.) Observed number		z/h=0.067(7200 data pt.) Observed number	
Interval in σ units	Expected number	N+	N−	N+	N−
0.0—0.2	571	1,326	3,581	5,624	663
0.2—0.4	548	273	704	563	45
0.4—0.6	506	138	268	133	31
0.6—0.8	449	68	111	36	3
0.8—1.0	383	42	87	15	0
1.0—1.2	314	23	71	3	2
1.2—1.4	247	18	51	3	0
1.4—1.6	187	13	45	1	1
1.6—1.8	136	16	28	0	3
1.8—2.0	94	20	25	0	5
2.0—2.2	64	22	20	0	3
2.2—2.4	41	11	21	0	8
2.4—2.6	25	19	19	0	0
2.6—2.8	15	11	6	0	1
2.8—3.0	9	9	1	0	2
>3.0	9	129	24	0	55

Table 6. Probabliity of Peak Occurrences and Nondimensional Periods

z/h	Number of peaks	Probability of peak occurrence	Mean period of peak Occurence ($\bar{T}$) (min)	Mean duration of peak (sec)	Bursting period ($U_0\ \bar{T}/h$)
0.1	14	0.0165	1.1	1.1	7.3
0.067	3	0.0065	5.0	2.0	33.3

coefficient, C_{100}, velocity at 100cm off the bottom, U_{100}, and friction Reynolds number, U_*) are listed in Table 4. The probability distribution of intermittency is shown in Table 5. A detailed nature of the intermittency phenomona are listed in Table 6. The spectral energy densities are shown in Figure 1.

The mean vertical component $\bar{W}$ at depth ratio, z/h=0.067 is not very small compared to the mean stream component $\bar{U}$. This may be due to the existence of cross-streamwise flow (Table 2). The dissipation rate (ε in Table 3) increases towards the boundary, while the turbulent viscosity (ν_T) decreases towards the bottom boundary, and the turbulent energy first increases and then decreases towards the boundary. These trends agree with the data for turbulent boundary layers on smooth walls as given by Hinze (1959). The normalized turbulent intensities decrease towards the bottom boundary and $u'>w'>v'$ (Table 3). This aspects are in general good agreement with the results for the turbulent boundary layer on the smooth walls; however, the turbulent energy, dissipation rate, and intensities are much greater in this case than in the laboratory meaurements discussed by Hinze (1959).

The maximum spectral energy density (Fig. 1) appears at 0.009Hz and spectral energy shows a peak energy at 0.11 Hz. Most of energy lies in the region of 0.32 to 1.61 Hz. The cross-stream spectra show the same trends as the streamwise spectra. The peak energy of the vertical component appears at 0.12 Hz. The

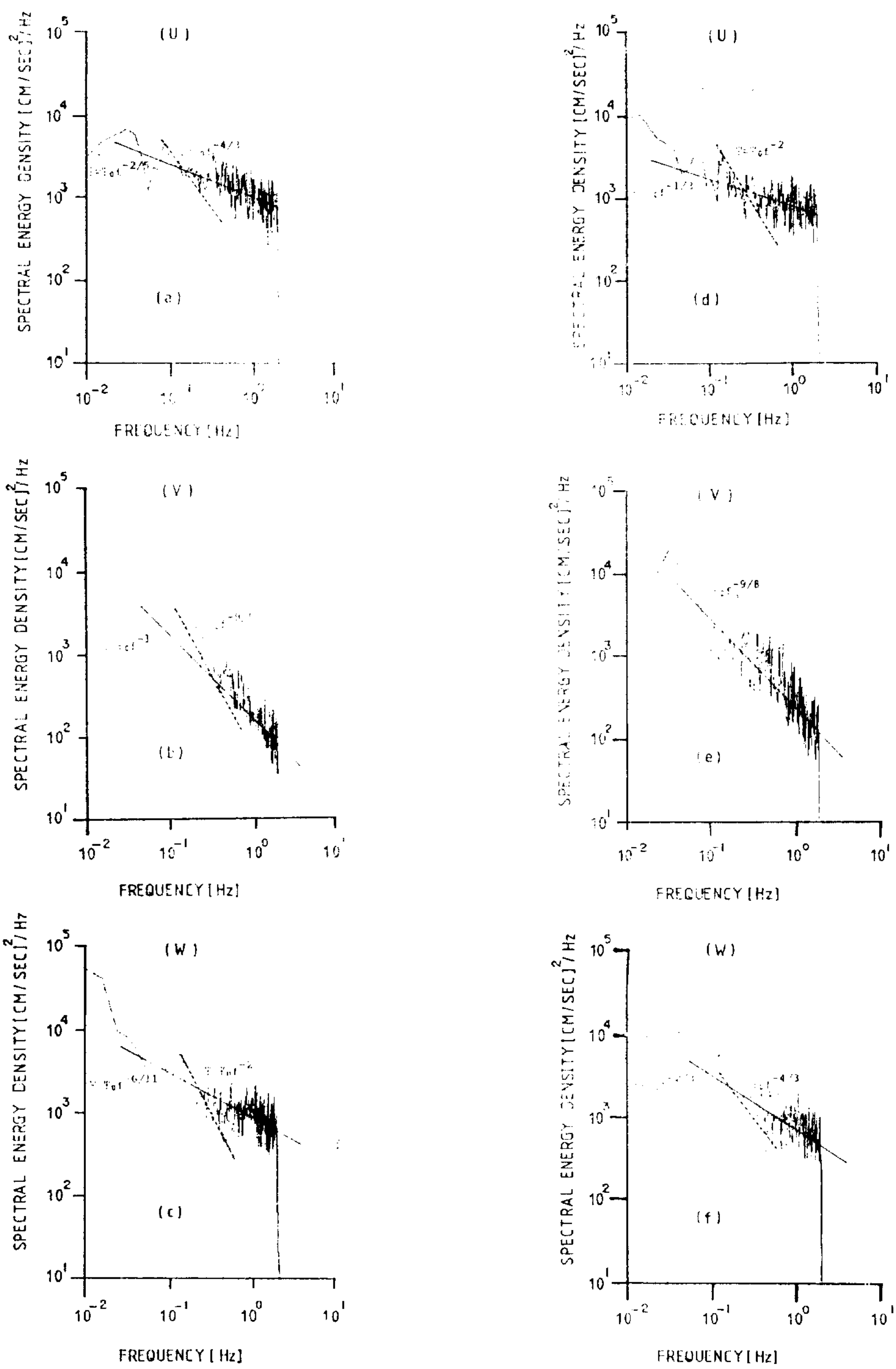

Fig. 1. Log-Log Plots of the Spectral Energy Densities of the Upper layer (a,b,c) and the Mid-layer (d,e,f) in the bottom turbulent boundary layer.

ratio of the averaged energy between streamwise, cross-stream, and vertical components is 1:0. 7: 0. 45.

The resulting analysis shows that a strong intermittency of turbulent momentum transport occurs at a location of $z/h=0.067$ (i.e., 30cm off the bottom) (i.e., at the inner boundary layer). The strength of intermittency is found to be 408 times greater than its average Reynolds stress, which is far greater than the presently known maximum, namely 30 times reported by Gordon (1974) and Heathersaw (1974). At the location of $z/h=0.1$ (i.e., 45cm off the bottom), the strength of intermittency is found to be 270 times greater than the average value. Chung and Grosch (1980) have reported that the intermittency of the Reynolds stress in the intermediate layer (i.e.,at $z/h=0.5$) is 170 times greater than its average value.

The distribution of the Reynolds stress obtained at the midlayer (i.e., $z/h=0.067$) of the boundary layer is highly skewed with the peak occurrence period of 5 minutes, and the half width of the peak profile of the Reynolds stress takes up about 0. 7% of the total measured time with each peak lasting about 2. 0 seconds. Our dimensionless period of peak occurrence is found to be 33. 3, which is substantially larger than the often quoted values of 3. 2—6. 8 for bursting period (Jackson, 1976). Chung and Grosch (1980) have reported that the dimensionless period of peak occurrence in the intermediate layer (i.e., $z/h=0.5$) is 8. 7, peaks in Reynolds stress occur about 1. 2% of the total measured time, and each peak lasting about 0. 5 seconds.

The unusual strong intermittence found in this study could be resulted from the differences in the flow conditions, i.e., rough bottom boundary with the friction Reynolds number, R_*, is 10^5, and differences in frequency response of the employing instruments. For instance, many other workers have used large size probe and poor frequency response meters compared to our sensitive meter, which has a probe diameter of 0. 95cm and response time of 0. 2 seconds. It is, in our opinion, marginally acceptable. In order to resolve the dynamically important structures in the buffer layer, we need a much smaller probe, with a diameter of the order of 1mm and a response time of the order of 0. 01 seconds. Such a probe, rugged enough for field studies, does not seem to exist.

CONCLUSIONS

The normalized turbulent intensities decrease towards the boundary and, in general $u'>w'>v'$. The turbulent energy decreases towards the boundary and the turbulent dissipation rate increases towards the boundary. These trends agree well with the laboratory experiments for the turbulent boundary layer.

The strength of our intermittency of turbulent momentum transport decreases upward from the bottom boundary showing the peak values as 408 times at $z/h=0.067$ and 270 times at $z/h=0.1$, which are far greater than the presently known maximum, namely 30 times reported by Gordon (1974) and Heathersaw (1974). Those other worker's depth ratios coincide with $z/h=0.1$ of our's. In other words, our result of the $z/h=0.067$ is the nearest measurement in the field study.

The peak lasting time is decreasing upward from the bottom by showing 2. 0 seconds at the near bottom (i.e., $z/h=0.067$) and 1. 1 seconds at the upper layer of the turbulent bounday layer (i.e., $z/h=0.1$).

The dimensionless period of the peak occurrence is 33. 3 at the $z/h=0.067$, 7. 3 at the $z/h=0.1$, which are substantially larger than the often quoted values of 3. 2—6. 8 for bursting period (Jackson, 1976).

In general, it was known that the burst can be found very near bottom boundary with R_* is 10^3—10^4 in the laboratory experiments. And also it was reported by the field workers that the intermittence phenomenon is the reflect of burst or caused effect of the burst across the probe of the measuring instrument.

In this investigation, we were not able to find unambiguous evidence that we saw bursting. We believe that bursting occurs in geophysical boundary layers, but the problems of how is effected by the very large value of R_*, the rough and wavy bottom are the open question.

One of our points was that neither our experiments nor any others' in geophysical boundary layers, that are aware of, have provided satisfactory answers.

In order to resolve the dynamically important structures in the buffer layer, which is 5mm thick in our case, we need a much smaller probe, with a diameter of the order of 1mm and a response time of the order of 0.01 seconds. Such a probe, rugged enough for field studies, does not seem to exist.

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