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Effect of coherent structures on structure functions of temperature in the atmospheric boundary layer

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THE BEHAVIOR of structure functions of temperature measured in the atmospheric boundary layer is in basic disagreement with predictions of high Reynolds number local similarity theory. The observed behaviour appears to be due to the presence of relatively large scale coherent temperature structure, whose characteristic signature is evident in temperature records, but not in those of velocity. The organized structures, generally found in thermally stratified boundary layers, have been associated with convective plumes, "microthermals", or roll vortices by previous investigators. A simple idealized ramp model gives predictions for the dependence of higher-order scalar structure functions on separation distance that in some cases are in good agreement with the measured structure functions of both odd and even order. The results suggest that more complex models for the organized structure might be worthwhile.

Zachowanie się funkcji struktury temperatury mierzonej w atmosferycznej warstwie granicznej pozostaje w zasadniczej sprzeczności z przewidywaniami wynikającymi z lokalnej teorii podobieństwa przy wysokich liczbach Reynoldsa. Obserwowane wyniki wydają się wynikać z obecności koherentnej struktury temperatury o stosunkowo dużej skali, przejawiającej się w odczytach temperatury, a nie w pomiarach prędkości.

Поведение функций структуры температуры, измеряемой в атмосферном пограничном слое, остается в принципиальном противоречии с предвидениями, следующими из локальной теории подобия при высоких числах Рейнольдса. Наблюдаемые результаты кажутся вытекать из присутствия когерентной структуры температуры, сравнительно большого масштаба, проявляющейся в отсчетах температуры, но не в измерениях скорости.

1. Introduction

MANY of the most cogent theoretical predictions concerning the statistical description of fluid turbulence apply only for very large values of the Reynolds number. Experimentalists interested in testing such theoretical results are naturally led to measurements in geophysical environments, which furnish the only available flows with large values of the turbulence Reynolds number R_λ, say on the order of 5×10^3. In such studies, one forfeits a great measure of control over basic flow conditions, and encounters a number of new phenomena, some of which are not ordinarily found in the laboratory. These may be not only troublesome, but can produce unacceptable crucial differences between the desired ideal conditions of the theory and the actual flow structure. Such complications may be compensated by interesting surprises that suggest useful extensions of the theoretical ideas. Such is hopefully the case with the present work, which is a study of some of the high Reynolds number statistical properties of a turbulent scalar field, the fluctuating temperature, in the atmospheric boundary layer over the ocean.

The present work is part of a continuing effort to study the process of spectral energy transfer in turbulent flows, which describes the transfer of turbulent kinetic energy or scalar fluctuations from large scales to smaller scales. Direct laboratory measurements of the spectral transfer (e.g., YEH and VAN ATTA (1973)) have been obtained only for rather small values of the turbulence Reynolds number. Experimental data obtained in the locally isotropic range of high Reynolds number atmospheric turbulence could prove to be quite interesting. Useful measurements of velocity spectral transfer in the atmospheric boundary layer would require measurements of three velocity components, whereas corresponding scalar measurements require measurement of only the single scalar variable and one component of velocity. The feasibility of such measurements can be initially tested through measurements of the particular third-order velocity correlations or structure functions that correspond directly (via certain Fourier transform relations) to the spectral transfer terms in the dynamical equations, and by comparing other measured second and third (or higher) order quantities with the predictions of local isotropy theory. The latter test is important because of the necessity of using analytical expressions for the energy transfer which are derived under the assumption of local isotropy in wavenumber or physical space.

The present work was thus begun with the intention of determining structure functions of temperature in the inertial subrange, in order to compare with the theoretical predictions of OBUKHOV (1949) and later modifications by KOLMOGOROV (1962) and VAN ATTA (1971). No previous measurements of higher-order structure functions for scalar fluctuations were previously available for comparison with the results of VAN ATTA and CHEN (1970) and VAN ATTA and PARK (1972) on higher-order structure functions of the fluctuating velocity in atmospheric turbulence. Of particular interest are the third-order correlations, certain of which occur in the dynamical equation for spectral energy transfer derived from the Navier-Stokes and scalar conservation equations. Although some fairly rough results for some of the scalar terms were obtained by PAQUIN and POND (1971), their measurements did not include those structure functions necessary to determine whether the fundamental symmetries required by homogeneity and isotropy were satisfied. Thus one could not assess the validity of comparisons of any of the earlier results for spectra or second order structure functions with available theories. The present measurements and analysis show that the form of measured odd-order structure functions of temperature fluctuations are not consistent with the postulates of homogeneity and isotropy, so that direct comparison with existing theories is not possible, in contrast to the relatively straightforward comparison for the velocity. A simple statistical model based on the properties of observed large scale coherent structures in the atmospheric boundary layer predicts the variation of the odd-order structure functions with separation distance quite well.

2. Theoretical relations for structure functions

2.1. Local isotropy theory

Following the ideas of the original KOLMOGOROV theory (1941) for the velocity field, the inertial subrange behavior of spectra and second-order structure functions for passive scalars was first discussed by OBUKHOV (1949) and CORRSIN (1951). Corresponding relations for structure functions of higher order may be found in MONIN and YAGLOM (1975). Modified expressions for these quantities were derived by VAN ATTA (1970) using the later ideas of KOLMOGOROV (1962) and OBUKHOV (1962) in an attempt to account for the influence of fluctuations in the local rates of dissipation of kinetic energy and scalar fluctuations. The result for the n-th order structure function, i.e., the mean value of the n-th power of the difference $\Delta\theta$ of the scalar fluctuations at two points separated by a distance r is

$$\text{(2.1)} \quad \langle(\Delta\theta)^n\rangle / c_n \langle\chi\rangle^{n/2}\langle\varepsilon\rangle^{-n/6} = r^{n/3}\exp(\beta)\,(L/r)^{n[(n-2)\mu_s/8+(n+6)\mu/72]}\exp[-n^2\varrho(r)\sigma_{\ln\chi_r}\sigma_{\ln\varepsilon_r}/12],$$

where $\beta = n[(n-2)A_s/8+(n+6)A/72]$, A, A_s, μ, and μ_s are constants, and $\varrho(r)$ is the normalized correlation between $\ln\chi_r$ and $\ln\varepsilon_r$, where χ_r and ε_r are respectively the mean rates of dissipation of scalar fluctuations and turbulent kinetic energy averaged over a volume with linear dimension r, i.e.

$$\text{(2.2)} \qquad \varrho(r) = \frac{\langle(\ln\chi_r - \langle\ln\chi_r\rangle)\,(\ln\varepsilon_r - \langle\ln\varepsilon_r\rangle)\rangle}{\sigma_{\ln\chi_r}\sigma_{\ln\varepsilon_r}}.$$

The original Kolmogorov-Obukhov theory is recovered by setting A, A_s, μ, μ_s, and ϱ equal to zero in Eq. (2.1). For an isotropic field, or in a range of r for which the flow is locally isotropic, the c_n must be zero for odd n, i.e.

$$\text{(2.3)} \qquad \langle(\Delta\theta)^n\rangle \equiv 0 \quad \text{for} \quad n \quad \text{odd}.$$

Using the same hypothesis, it is possible to derive analogous expressions for mixed structure functions of arbitrary order involving both velocity and temperature. The most physically relevant of these is the third order correlation $\langle\Delta u(\Delta\theta)^2\rangle$, which, according to YAGLOM'S (1949) inertial subrange analysis of the scalar conservation equation, must have the form

$$\text{(2.4)} \qquad \langle\Delta u(\Delta\theta)^2\rangle = -\frac{4}{3}\langle\chi\rangle r.$$

2.2. Anisotropic coherent structure theory

It is immediately clear from the experimental data (see Figs. 2 and 3) that the behavior predicted by Eq. (2.3) is definitely not observed in the atmosphere, and that the isotropic theory obviously cannot begin to describe the measured regular variation of the odd-order temperature structure functions with r. In searching for an explanation for this behavior, one notes that for some time large scale organized structures have been observed in the temperature field, and that such structures are not observed in the velocity field, for which the structure functions do exhibit roughly the behavior expected from isotropic theory (see VAN ATTA and CHEN (1970) or VAN ATTA and PARK (1972)). The question thus arises as to whether a model incorporating the observed large scale coherent features can be constructed which can adequately describe the behavior of the temperature data shown in Figs. 2 and 3. Here we describe the first attempt at such a model.

Very regular repetitive coherent features in fluctuating temperature (or humidity) signals in the atmospheric boundary layer, indicative of gross anisotropy, have been reported by many investigators. The characteristic signature of the organized temperature structure is usually observed as a slow, nearly linear increase of temperature with time, followed by an abrupt sharp decrease in temperature to the ambient level before the rela-

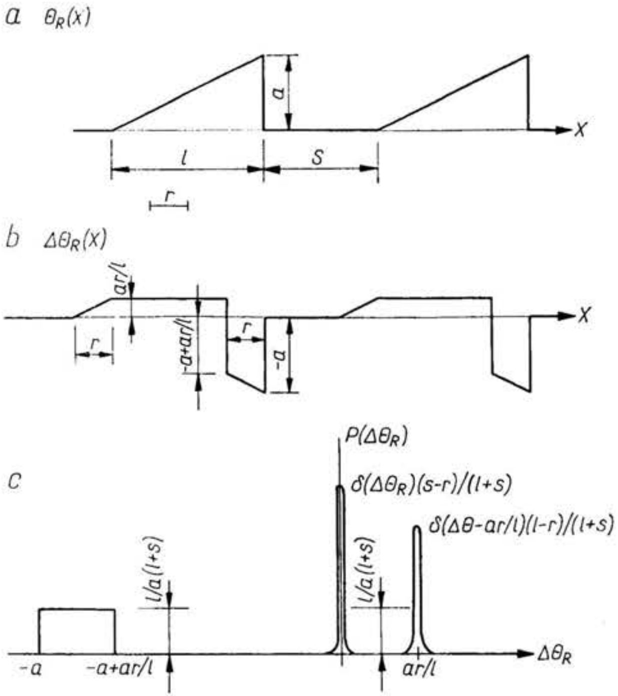

FIG. 1. Properties of ramp model for $r < l$ and $r < s$.
(a) $\theta_R(x)$, (b) $\Delta\theta_R(x)$, (c) $p(\Delta\theta_R)$.

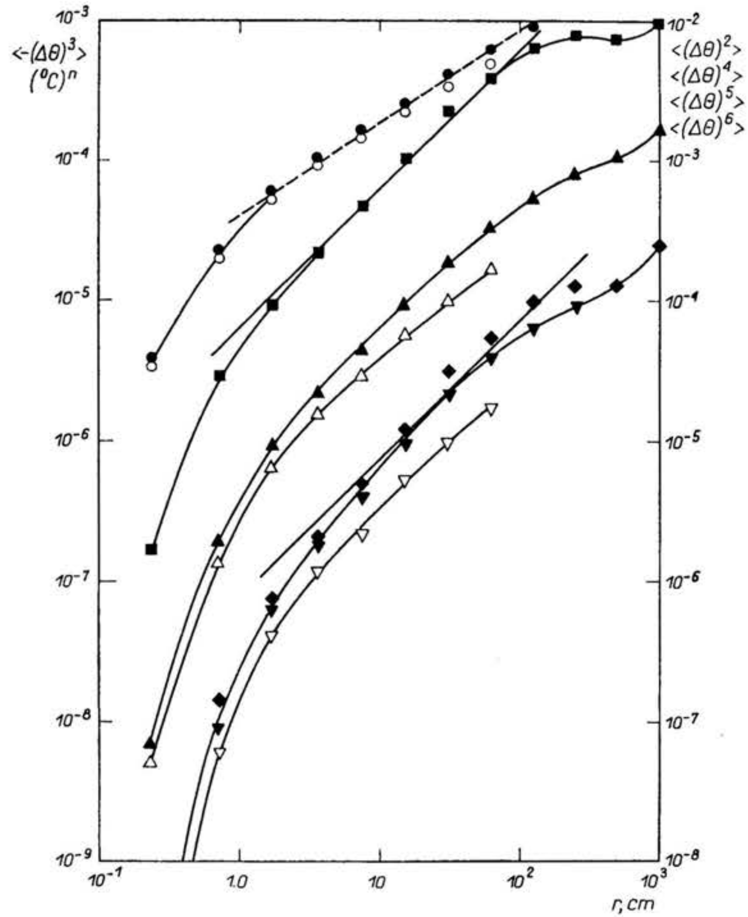

FIG. 2. Structure functions of temperature; second through sixth order. Closed symbols are measured $\langle(\Delta\theta)^n\rangle$. Open symbols are computed $\langle(\Delta\theta_T)^n\rangle$.
●, ○; $n = 2$. ■; $n = 3$. ▲, △; $n = 4$. ♦; $n = 5$. ▼, ▽; $n = 6$. The dashed line has a slope of 2/3. The solid straight lines have a slope of 1.0.

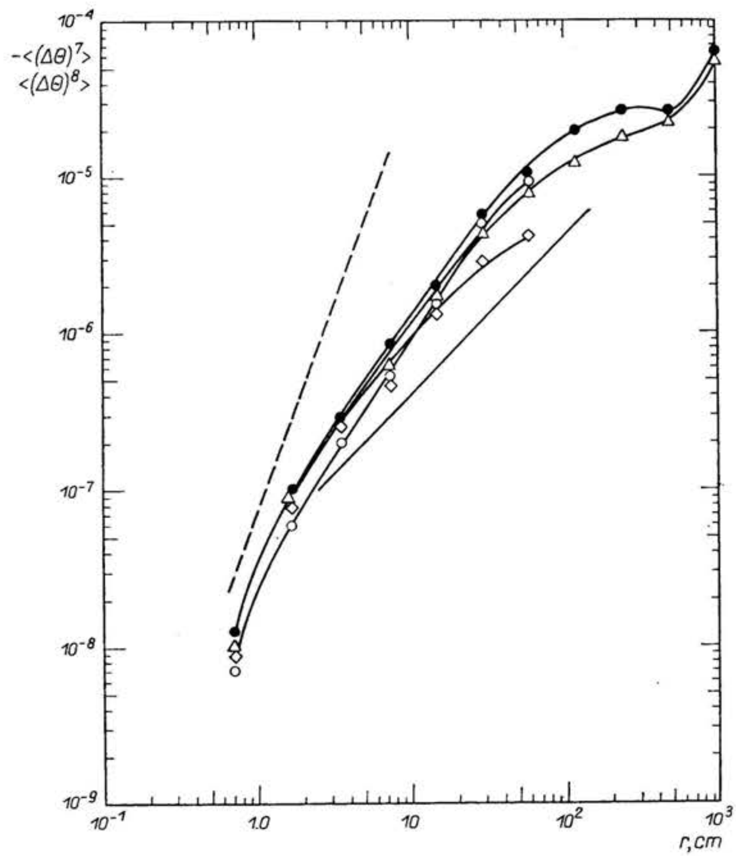

FIG. 3. Structure functions of temperature; seventh and eighth order.
●: $\langle(\Delta\theta)^7\rangle$. ○; $\langle(\Delta\theta)^7\rangle$ calculated from Eq. (2.9). △; $\langle(\Delta\theta)^8\rangle$. ◇; $\langle(\Delta\theta_T)^8\rangle$. The dashed line has a slope of 8/3. The solid line has a slope of 1.0.

tively slow increase began. Superimposed on this regular feature, which reappears randomly, is a smaller amplitude turbulent fluctuation having a much smaller characteristic scale than that of the regular ramplike, or sawtooth structure. The earliest observations of this phenomenon (discussed in PRIESTLEY (1957)) appear to have been by TAYLOR (1958). Taylor recognized that "this and other evidence points to the existence of organized thermal structures of considerable vertical extent which are superimposed on a background of random turbulent disturbances". KAIMAL and BUSINGER (1970) first conclusively demonstrated that over land the ramps can be due to sheared convective plumes. Other proposals for the form of the underlying large scale structure have been referenced by BEAN et al. (1972), who found that comparison with their measurements over the tropical ocean did not resolve the question of whether the ramps in that case were caused by a horizontal roll vortex system, sheared convective plumes, or puffs under shear.

The organized ramp structure causes a basic anisotropy in the temperature signals, i.e. for one fixed direction of the time (or space) axis they always rise slowly and fall abruptly, whereas if time were reversed in the other direction they would rise abruptly and fall slowly.

This produces a skewed distribution for $\Delta\theta$, with corresponding non-zero odd-order moments that cannot be described by theory based on isotropy. The question thus naturally arises as to how structure functions determined from a signal containing such regular features would vary with the separation distance r.

We assume that the total measured scalar signal consists of a random turbulent part θ_T plus a coherent organized part θ_R. Then

$$\begin{aligned}\theta &= \theta_T+\theta_R,\\ \Delta\theta &= \Delta\theta_T+\Delta\theta_R.\end{aligned} \tag{2.5}$$

For the first two non-zero moments, we have

$$\begin{aligned}\langle(\Delta\theta)^2\rangle &= \langle(\Delta\theta_T)^2\rangle+2\langle\Delta\theta_T\Delta\theta_R\rangle+\langle(\Delta\theta_R)^2\rangle,\\ \langle(\Delta\theta)^3\rangle &= \langle(\Delta\theta_T)^3\rangle+3\langle(\Delta\theta_T)^2\Delta\theta_R\rangle+3\langle\Delta\theta_T(\Delta\theta_R)^2\rangle+\langle(\Delta\theta_R)^3\rangle.\end{aligned} \tag{2.6}$$

If $\Delta\theta_R$ and $\Delta\theta_T$ are statistically independent, we have

$$\begin{aligned}\langle(\Delta\theta)^2\rangle &= \langle(\Delta\theta_T)^2\rangle+\langle(\Delta\theta_R)^2\rangle,\\ \langle(\Delta\theta)^3\rangle &= \langle(\Delta\theta_T)^3\rangle+\langle(\Delta\theta_R)^3\rangle,\end{aligned} \tag{2.7}$$

and the contributions from the organized structures and the random turbulence are simply additive. Similar expressions may be derived for other higher-order moments. For example,

$$\begin{aligned}\langle(\Delta\theta)^4\rangle &= \langle(\Delta\theta_T)^4\rangle+6\langle(\Delta\theta_T)^2\rangle\langle(\Delta\theta_R)^2\rangle+\langle(\Delta\theta_R)^4\rangle,\\ \langle(\Delta\theta)^5\rangle &= \langle(\Delta\theta_T)^5\rangle+10\langle(\Delta\theta_T)^2\rangle\langle(\Delta\theta_R)^3\rangle+\langle(\Delta\theta_R)^5\rangle.\end{aligned} \tag{2.8}$$

If the turbulent component of the signal has the properties appropriate for a locally isotropic scalar field, then terms like $\langle(\Delta\theta_T)^n\rangle = 0$ for odd n, and the structure functions through eighth order become

$$\begin{aligned}\langle(\Delta\theta)^2\rangle &= \langle(\Delta\theta_T)^2\rangle+\langle(\Delta\theta_R)^2\rangle,\\ \langle(\Delta\theta)^3\rangle &= \langle(\Delta\theta_R)^3\rangle,\\ \langle(\Delta\theta)^4\rangle &= \langle(\Delta\theta_T)^4\rangle+6\langle(\Delta\theta_T)^2\rangle\langle(\Delta\theta_R)^2\rangle+\langle(\Delta\theta_R)^4\rangle,\\ \langle(\Delta\theta)^5\rangle &= 10\langle(\Delta\theta_T)^2\rangle\langle(\Delta\theta_R)^3\rangle+\langle(\Delta\theta_R)^5\rangle,\\ \langle(\Delta\theta)^6\rangle &= \langle(\Delta\theta_T)^6\rangle+15\langle(\Delta\theta_T)^4\rangle\langle\Delta\theta_R)^2\rangle+15\langle(\Delta\theta_T)^2\rangle\langle(\Delta\theta_R)^4\rangle+\langle(\Delta\theta_R)^6\rangle,\\ \langle(\Delta\theta)^7\rangle &= 35\langle(\Delta\theta_T)^4\rangle\langle(\Delta\theta_R)^3\rangle+21\langle(\Delta\theta_T)^2\rangle\langle(\Delta\theta_R)^5\rangle+\langle(\Delta\theta_R)^7\rangle,\\ \langle(\Delta\theta)^8\rangle &= \langle(\Delta\theta_T)^8\rangle+28\langle(\Delta\theta_T)^6\rangle\langle(\Delta\theta_R)^2\rangle+70\langle(\Delta\theta_T)^4\rangle\langle(\Delta\theta_R)^4\rangle\\ &\quad+28\langle(\Delta\theta_T)^2\rangle\langle\Delta\theta_R)^6\rangle+\langle(\Delta\theta_R)^8\rangle.\end{aligned} \tag{2.9}$$

Similar expressions can be derived for mixed moments of velocity and temperature differences. For example, consider the third-order moment of Eq. (2.4). Assuming, in accordance with experimental observations, that there are no ramps in the velocity signal, then $\Delta u = \Delta u_T$, and

$$\langle\Delta u(\Delta\theta)^2\rangle = \langle\Delta u_T(\Delta\theta_T)^2\rangle+2\langle\Delta u\Delta\theta_T\Delta\theta_R\rangle+\langle\Delta u(\Delta\theta_R)^2\rangle.$$

If Δu is statistically independent of $\Delta\theta_R$ and $\Delta\theta_T$, then we have the important result that coherent structures do not affect measurements of this triple moment, i.e.

$$\langle\Delta u(\Delta\theta)^2\rangle = \langle\Delta u_T(\Delta\theta_T)^2\rangle. \tag{2.10}$$

To estimate the individual ramp and turbulence contributions to the measured structure functions, most generally one must assume a model for the joint distribution of ramp amplitude a, length l, and the repetition rate. Here we consider only the simplest possible uniform ramp model.

Consider a signal $\theta_R(x)$ consisting of a sequence of ramps of amplitude a and length l, separated from one another by quiet periods of length s, as shown in Fig. 1a. For separations r that are less than l or s, the corresponding function $\Delta\theta_R(x) = \theta_R(x+r)-\theta_R(x)$ is given in Fig. 1b, and the probability density $p(\Delta\theta_R)$ of $\Delta\theta_R(x)$ is given in Fig. 1c. The moments of this distribution are

$$\langle(\Delta\theta_R)^n\rangle = \int_{-\infty}^{\infty} (\Delta\theta_R)^n p(\Delta\theta_R)\,d(\Delta\theta_R)$$

which, up to fifth order, are

$$\begin{aligned}
\langle(\Delta\theta_R)^2\rangle &= a^2r[1-(r/l)^2/3]/(l+s),\\
\langle(\Delta\theta_R)^3\rangle &= a^3r[-1+5(r/l)/2-2(r/l)^2+(r/l)^3/2]/(l+s),\\
\langle(\Delta\theta_R)^4\rangle &= a^4r[1-2(r/l)+2(r/l)^2-4(r/l)^4/5]/(l+s),\\
\langle(\Delta\theta_R)^5\rangle &= a^5r[-1+5(r/l)/2-10(r/l)^2/3+5(r/l)^3/2-5(r/l)^5/6]/(l+s).
\end{aligned} \tag{2.11}$$

Experimental observations indicate that in the range of interest we have $r \ll l$, so that the linear term in r dominates the behavior of all the ramp structure functions, and as a good approximation

$$\langle(\Delta\theta_R)^n\rangle = (-1)^n a^n r/(l+s). \tag{2.12}$$

Thus if a ramp structure function of one order is known, the $\langle(\Delta\theta_R)^n\rangle$ are known for all n. The dominant linear term in $\langle(\Delta\theta_R)^n\rangle$ is a direct consequence of the abrupt drop of amplitude a in θ_R at the end of each ramp. Any other nonsymmetrical waveform which has a sharp decrease (or increase) on one side will produce the same functional dependence of the leading term on r and a, i.e. $\langle(\Delta\theta_R)^n\rangle \sim \pm(-a)^n r$. This behavior, which as we shall see fits the data quite well, is due to the simple physical property that the temperature gradients in the large scale coherent structure are relatively diffuse on one side of the structure and relatively sharp on the other.

Because of the second equation in (2.9) it is convenient to let

$$\langle(\Delta\theta_R)^n\rangle = (-1)^{n-1}a^{n-3}\langle(\Delta\theta)^3\rangle$$

and then the first, second, and fourth equations of (2.9) may be combined in an equation for the ramp amplitude a

$$a^3+(10\langle(\Delta\theta)^2\rangle-\langle(\Delta\theta)^5\rangle/\langle(\Delta\theta)^3\rangle)a+10\langle(\Delta\theta)^3\rangle = 0 \tag{2.13}$$

in terms of the known measured values of $\langle(\Delta\theta)^2\rangle$, $\langle(\Delta\theta)^3\rangle$, and $\langle(\Delta\theta)^5\rangle$.

With the value of a determined from (2.13), the even-order structure functions of the turbulent part of the signal may be determined from (2.9), e.g.

$$\begin{aligned}
\langle(\Delta\theta_T)^2\rangle &= \langle(\Delta\theta)^2\rangle+\langle(\Delta\theta)^3\rangle/a,\\
\langle(\Delta\theta_T)^4\rangle &= \langle(\Delta\theta)^4\rangle+6\langle(\Delta\theta)^3\rangle\big(\langle(\Delta\theta)^2\rangle+\langle(\Delta\theta)^3\rangle/a\big)/a+a\langle(\Delta\theta)^3\rangle,\\
\langle(\Delta\theta_T)^6\rangle &= \langle(\Delta\theta)^6\rangle+\big(15\langle(\Delta\theta_T)^4\rangle/a+15a\langle(\Delta\theta_T)^2\rangle+a^3\big)\langle(\Delta\theta)^3\rangle,\\
\langle(\Delta\theta_T)^8\rangle &= \langle(\Delta\theta)^8\rangle+\big(28\langle(\Delta\theta_T)^6\rangle/a+70a\langle(\Delta\theta_T)^4\rangle+28a^3\langle(\Delta\theta_T)^2\rangle\big)\langle(\Delta\theta)^3\rangle.
\end{aligned} \tag{2.14}$$

The internal consistency of the model may be further checked by comparing measured odd-order structure functions with those calculated from (2.9) for $n = 7$ and larger.

The total length of the ramp plus quiet period is determined from the second of Eqs. (2.9) and Eq. (2.12) as

$$(l+s) = -a^3 r/\langle(\Delta\theta)^3\rangle. \tag{2.15}$$

3. Comparison of theory with experimental results

3.1. Experimental conditions

The primary data to be discussed here are part of that obtained by PARK (1975). Park measured temperature and velocity fluctuations in the atmospheric boundary layer over the ocean using cold-wire and hot-wire probes mounted on booms extending from the Naval Undersea Center Oceanographic Research Tower near San Diego. The NUC tower is located off Mission Beach about one mile from the coastline, where the depth of the water is about 17 meters. The sensors were mounted on a platform at the end of a 3-meter traversing boom located on the seaward (and generally windward) side of the tower. The data described here were obtained at a height of 3.81 m above the mean water surface, where the mean wind velocity was 4.95 m/s. At the air-sea interface, the water was warmer than the air by 1–2°C. Using a CDC 3600 computer, the structure functions of temperature and velocity were computed from time series of the digitized fluctuating signals, recorded at a single point, by using G. I. Taylor's hypothesis in the form $r = -U\tau$, where τ is the time separation.

3.2. Comparison of data with model

The measured structure functions of temperature for $n = 2$ through $n = 8$ are shown in Figs. 2 and 3. The odd-order structure functions do not behave like the null or zero function expected for a locally isotropic temperature field, but are of the same order as the measured even-order structure functions and behave in a similar way, increasing smoothly with increasing separation distance r. For an intermediate range of r, the third and fifth-order structure functions increase in a nearly linear fashion with r, as in Eq. (2.12). This behavior of the odd-order moments encouraged further detailed comparison with the simple ramp model. Values of a were computed from equation (2.13) for each lag r using the measured values of $\langle(\Delta\theta)^n\rangle$. Each calculation yielded only one positive real root for a, so that no ambiguity was encountered. As shown in Fig. 4 the values of a are remarkably constant, varying between about 0.27 and 0.32°C over the range of r in which the second and third order structure functions are very nearly simple power law functions of r. These values are quite reasonable, as they are of the same order of magnitude as the amplitudes of some of the more pronounced ramp-like features found in strip chart recordings of the data, and of the same order of magnitude as the root mean square temperature fluctuation, which was about 0.18°C. The computed values of $(l+s)$, also shown in Fig. 4, are also quite reasonable, varying between 35 and 45 meters over the same range of r.

These scales are of the same order as many of the ramp features seen in the present data and by previous investigators. The individual values of a and l observed in the data of course vary appreciably, and the values determined from the present simple deterministic ramp model should only be considered as representative mean values derived from the measured structure functions. For $(l+s) = 45$ m, the average ramp repetition rate is $U/(l+s) = 7$ per minute. This number is of the same order of magnitude as the recurrence of ramps at intervals of one or two per minute reported in PRIESTLY (1957). An attempt has not yet been made to visually count the ramp-like events in Park's data for comparison with the results obtained from the structure functions via the ramp model.

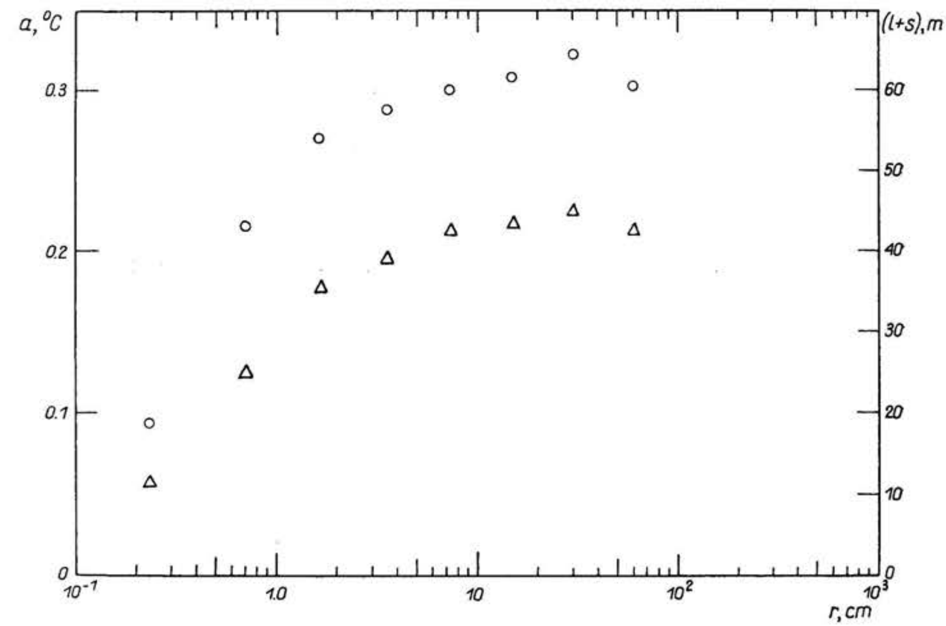

FIG. 4. Values of ramp height a and period $(l+s)$ computed from $\langle(\Delta\theta)^n\rangle$ data using ramp model. ○; a. △; $(l+s)$.

The values of $\langle(\Delta\theta_T)^2\rangle$, $\langle(\Delta\theta_T)^4\rangle$, and $\langle(\Delta\theta_T)^8\rangle$ determined from Eq. (2.14) for each value of r are also plotted in Figs. 2 and 3, allowing one to assess the relative size of the $\langle(\Delta\theta)^n\rangle$ and $\langle(\Delta\theta_T)^n\rangle$. $\langle(\Delta\theta_T)^2\rangle$ and $\langle(\Delta\theta)^2\rangle$ are almost equal over the range of applicability of the ramp model, i.e. most of the contribution to the measured second order structure function comes from the random turbulence, and very little from the coherent structures. $\langle(\Delta\theta_T)^4\rangle$ ranges from two-thirds to one-half the size of $\langle(\Delta\theta)^4\rangle$ as r increases over its middle range, so the contributions of the turbulence and coherent structure to $\langle(\Delta\theta)^4\rangle$ are roughly equal. Similarly, $\langle(\Delta\theta_T)^6\rangle$ varies from about 58% to 43% of $\langle(\Delta\theta)^6\rangle$ over the same range, so that the turbulent and coherent contributions are again roughly equal. However, for eighth order, $\langle(\Delta\theta_T)^8\rangle$ and $\langle(\Delta\theta)^8\rangle$ are more closely equal, especially for the smaller values of r, so the coherent structure makes relatively little contribution to $\langle(\Delta\theta)^8\rangle$ compared with the turbulence. The computed values of $\langle(\Delta\theta)^7\rangle$ using Eq. (2.9) are reasonably close to the measured values, suggesting consistency in comparison of model and experimental data, but the rate of increase of $\langle(\Delta\theta)^7\rangle$ with r is considerably faster than linear.

Since the $\langle(\Delta\theta_T)^n\rangle$ were derived under the assumption of local isotropy for the turbulent part of the temperature field, it would seem reasonable to compare their computed behavior with that of the local isotropy theory of Sect. 2.

The measured second order structure function closely follows the $r^{2/3}$ law, in agreement with the original Kolmogorov inertial subrange theory. However, the higher-order even-order structure functions increase much more slowly with r than the $r^{n/3}$ dependence of the original Kolmogorov theory. Perhaps the modified theory of Eq. (2.1) can be used to furnish a possible explanation for this behavior. Calculations are presently in progress to estimate the value of $\varrho(r)$ for the data in order to allow comparison with Eq. (2.1).

PARK (1975) has found that the mixed moment data satisfy Eq. (2.4) fairly well. In view of Eq. (2.10), this observation and the small measured value of $\langle(\Delta\theta)(\Delta u)\rangle = -0.01$ lends further support to the assumption of statistical independence of $\Delta\theta_R$ and $\Delta\theta_T$ and the consistency of the model as compared with experiment.

The analysis indicates that the presence of coherent structures can produce large effects on higher-order structure functions, even when the effect on the second-order structure function, and therefore on the measured power spectrum, may be too small to be noticeable. The influence of the coherent structure on the second-order structure function might eventually help to explain the absence of inertial subrange type behavior (spectrum, $E \neq Ck^{-5/3}$) for scalar spectra sometimes observed in other data of PARK or FRIEHE et al. (1975). This matter will be pursued in the future. The present fairly good agreement between a simple coherent structure model and the data suggests that it might be useful to pursue more sophisticated models that take into account more of the statistical properties of the signatures of the organized structures, such as the probability density and moments of the ramp amplitude a, the ramp length l, etc.

4. Conclusions

The present rather simple anisotropic coherent structure analysis, based on decomposition of the temperature field into organized and turbulent contributions and a deterministic ramp structure model, fairly successfully predicts the rather unexpected behavior of odd-order temperature structure functions measured in the atmospheric boundary layer. The results of the analysis can be used to determine the individual contributions from the organized and turbulent parts of the signal. The amplitudes and lengths of the "average ramps" derived from the analysis are in reasonable agreement with the observations.

Acknowledgments

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