United States
Environmental Protection
Agency

Environmental Sciences Research
Laboratory
Research Triangle Park NC 27711

Research and Development

EPA-600/S3-82-062 August 1982

EPA

Project Summary

An Experimental Study of Turbulence in an Urban Environment

John F. Clarke, J. K. S. Ching, and J. M. Godowitch

The structure of turbulence in the urban surface boundary layer is discussed. Wind and temperature fluctuations were measured with fast-response sensors at a height of 31 m in four land-use areas in the St. Louis environs (a rural and three urban sites). The second moments of the fluctuations were computed for one-hour time series and analyzed within the framework of the Monin-Obukhov similarity theory (i.e., normalized by appropriate velocity and temperature scales). The results are discussed relative to observed land-use features and calculated surface roughness lengths for each of the sites.

Average surface roughness lengths ranged from 0.7 to 1.7 m for the urban sites, varying by several meters as a function of wind direction at individual sites. The normalized velocity and temperature variances for the rural site were consistent with the Monin-Obukhov similarity theory. For the urban sites, plots of the normalized velocity variances showed an orderly departure from similarity theory for both neutral and unstable stratifications; they were smaller than the corresponding normalized variance for the rural site.

The urban anomalies to similarity theory are discussed relative to the terms in the turbulent kinetic energy budget equation. For neutral stratification, the anomaly is suggested to be due to the wake region of the roughness elements extending to near the height of the measurements. For unstable stratification, it is suggested to be due to increased importance of vertical transport processes within the urban area.

Ancillary analyses suggest that the spectral peak wavelength may be a more appropriate scaling length for free convection similarity than the height of the mixed layer, z_i. During the afternoon transition period the two scales may differ significantly.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The research reported here is concerned with the structure of turbulence in the surface boundary layer over a city. It is based on extensive observations of the turbulent wind and temperature above four land-use areas in the St. Louis, Missouri, environs. The purpose of the study is to suggest a framework for parameterizing urban turbulence statistics.

The research was designed to seek relations between turbulence parameters based on the interpretation of empirical data. The form of select nondimensionalized urban turbulence statistics as a function of atmospheric stratification is tested against the form predicted by the Monin-Obukhov similarity theory. In this respect, the empirical specifications of similarity relationships resulting from the Kansas and Minnesota boundary layer experiments are used as standards for comparing the urban results.

Within the constant stress layer, the Monin-Obukhov similarity theory is a useful tool for making predictions about certain statistics of atmospheric turbulence. According to similarity theory, the mean velocity gradients and turbulence characteristics are completely determined by the height z, the surface momentum flux τ_0/ϱ, the kinematic heat flux $H/\varrho C_p$, and the buoyancy parameter g/T. From these parameters velocity, temperature, and length scales can be defined as:

$$u^* = \overline{-u'w'}^{1/2} = \tau_0/\varrho$$
$$T^* = \overline{-wT'}/u^* = H/\varrho c_p u^*$$
$$L = -Tu^{*3}/gk\overline{wT'},$$

where the prime quantities are the fluctuating components of the wind and temperature. It follows that any other parameter describing the structure of ideal flow in the surface boundary layer, nondimensionalized by the above scaling parameters, should be a universal function of the only other dimensionless quantity that can be formed, i.e., the Monin-Obukhov stability ratio z/L. Some parameters which scale with z/L include the velocity and temperature gradients, the second moments of the fluctuations of the velocity components and temperature, spectra and cospectra, and other higher-order quantities.

The Monin-Obukhov similarity relationships cannot be expected to hold *a priori* for urban areas due to the large and nonhomogeneous surface features. Thus the specific objectives of this study are:

(1) to determine how extensively the similarity relationships, as verified empirically for ideal rural sites, apply to urban data; and
(2) to discuss significant and orderly differences between the urban results and the similarity predictions in terms of site land-use, i.e., surface scaling features.

Procedure

The analyses in this study are based on high resolution fast response measurements of the three components of the wind and temperature at 31 m above four land-use areas in the St. Louis environs during the summer and fall of 1976. Profile data were not obtained and thus the study is limited to turbulent quantities. In other respects the data are extensive, covering a total of nine weeks during two seasonal periods; approximately 3800 hours of data were obtained. With few exceptions, all the data were used in the analyses; that is, the data were not screened to eliminate nonstationary periods or nonhomogeneous flow situations.

The turbulence measurements were obtained at RAPS Regional Air Monitoring Systems (RAMS) sites 105, 107, 109, and 111. Site 105 was located in a high density urban commercial area 3 km south of the urban center and 1 km west of the Mississippi River. Land in the vicinity of the station was used for trucking, warehousing, and commercial operations. Buildings, predominately two-story and of large aerial extent, contributed ~ 25 percent of the land-use features. Approximately 60 percent of the area was paved; the remainder was primarily lawn with a few small trees along the streets.

Site 107 was located in the northwest section of St. Louis about 6 km from the center of the city. Land use for several kilometers surrounding the site consisted mostly of older single family and duplex two-story dwellings. Population density is high and the area is considered urban in nature. However, in contrast to site 105, ~60 percent of the land area is covered by trees or grass. Twenty-five percent of the land is used for buildings; streets and other paved surfaces make up the remaining 15 percent.

Site 109 was located in a rural agricultural area ~ 10 km east of the city. Farm land generally surrounded the station; however, a group of farm buildings was located in the immediate northeast quadrant, and small trees and underbrush occupied the immediate southeast quadrant. Small fields separated by hedgerows and scattered homes characterized the land use at greater distances in the easterly quadrants.

Site 111 was located in an older residential community approximately 9 km southwest of the urban center. The area immediately surrounding the site was composed of high-density single family residences. Buildings at an average height of 7.5 m covered ~ 15 percent of the area and trees averaging ~ 13.5 m made up ~ 25 percent of the land use.

Turbulence instrumentation at all sites consisted of a Gill UVW anemometer and a fast response temperature system of inhouse design. Net radiation was measured with a Swissteco net radiometer at sites 105 and 109. Humidity fluctuations were obtained for a short period of time (several days) at sites 105 and 109. All instruments were located 31 m above the surface. The 3-compc nent wind, temperature, and humidit data were recorded at a frequency c 2/s. Land-use characteristics, displace ment lengths, and roughness lengths fc the four sites are presented in Table 1.

Results

Land use features varied significanth among the four sites. Thus, at the outse each site was characterized numericall by an estimated displacement lengtl and a site-averaged roughness lengtl calculated through the similarity winc profile formulation. Estimated displace ment lengths, d, ranged from 2 to 6 m a the urban sites and site-averaged rough ness lengths, Z_o, ranged from 0.7 to 1.7 m (Table 1). Surface roughness lengtl varied significantly with wind directior at both urban and rural sites as demonstrated in Figure 1 for site 107, suggesting the surface features were not homogeneous in space. The surface wind stress, u*, was proportional to Z_o (as expected from the method of calculation of Z_o). Relatively large values of u* occurred at the urban sites throughout the diurnal cycle. The value of u* for the convective period of the day was 0.2 m/s or larger at all sites.

The surface energy budget also varied with the composition of land use features. Afternoon values of heat flux at the urban commercial site 105, which has a high percentage of paved areas and few trees, were about twice those at the rural site 109. During the nocturnal hours, the heat flux was generally negative at site 109, but was seldom negative at site 105. Latent heat flux was significantly greater at site 109 than at site 105; afternoon Bowen ratios of 0.5 and 2.0 were characteristic of sites 109 and 105, respectively. The heat flux at urban site 107, which had numerous tall trees, was similar to that at site 109 during daylight hours. At night, site 107 had a zero or very small negative heat flux characteristic of an urban site.

The boundary layer stratification reflected the land-use features responding to the ambient air flow and solar radiation. Based on computations of z'/L (z' = z − d), which includes the effects of both heat flux and surface stress, site 109 was strongly stable at night and strongly unstable during the afternoon. Site 105 was neutral and strongly unstable for the two periods, respectively. Site 107 was essentially neutral at night but only slightly to moderately unstable during the convective period of the day (due to

Table 1. *Site Land-Use Characteristics and Estimated Displacement (d) and Roughness (Z_o) Lengths Based on the Work of Kutzback (K) and Counihan (C) and Average Calculated Values*

Site	*105*		*107*		*111*		*109*	
Land Use	*Ar/A*	*h (m)*	*Ar/A*	*h (m)*	*Ar/A*	*h (m)*	*Ar/A*	*h (m)*
Buildings	*.25*	*5.5*	*.25*	*7.5*	*.16*	*7.5*	*.05*	*4.5*
Trees	*.01*	*5.5*	*.25*	*12*	*.25*	*13.5*	*.05*	*3.0*
Paved	*.59*	*0*	*.16*	*0*	*.14*	*0*	*.01*	*0.0*
Grass	*.15*	*0*	*.34*	*0*	*.45*	*0*	*.89*	*0.0*
d(K)	*4.0*		*8.4*		*9.2*		*.84*	
d(C)	*1.65*		*6.3*		*5.8*		*.19*	
Z_o(K)	*1.2*		*		*		*.04*	
Z_o(C)	*1.65*		*1.17*		*1.89*		*.06*	
Calculated Values								
d(1)	*2*		*6*		*6*		*0*	
Z_o(2)	*0.67*		*1.39*		*1.71*		*0.33*	
Z_o(3)	*0.67*		*1.20*		*1.37*		*0.46*	

**Method of calculation not valid for this category of Ar/A.*
(1) Estimated for use in wind profile equation.
(2) Calculated from profile equation.
(3) Z_o = h/8.15.

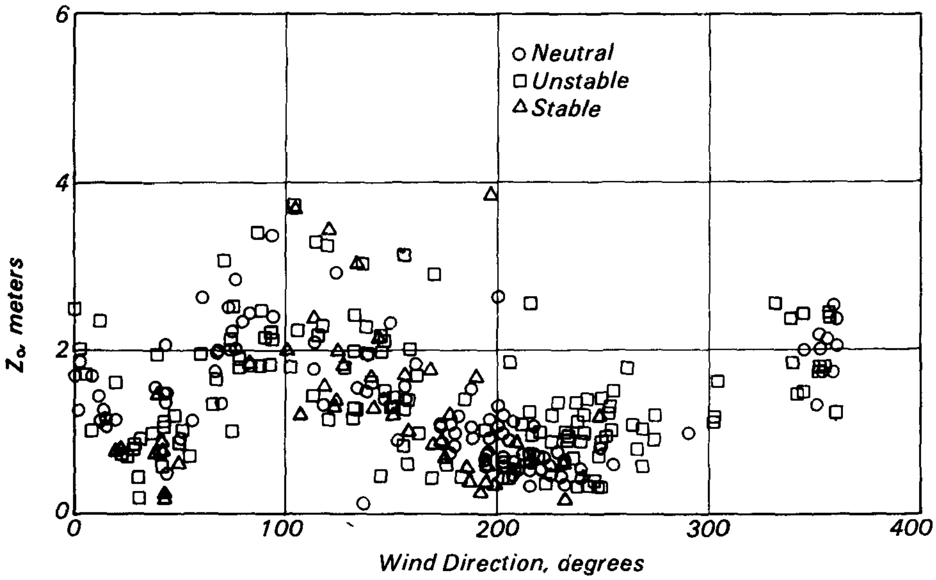

Figure 1. *Surface roughness length vs. wind direction for site 107.*

the large surface stress and relatively small heat flux).

Partly in response to the temporal and spatial variation of stratification, the diurnal variation of most turbulence parameters differed significantly between the urban and rural environs. The turbulent wind standard deviations, turbulence intensities, and the spectral peak wavelengths were higher at the urban sites during nocturnal hours due to the urban heat island and associated deeper momentum boundary layer. The turbulence parameters tended to converge during the morning transition period (i.e., the normalized turbulence structure was similar in both the urban and rural environs between 8 a.m. and 10 a.m.) and diverged during the afternoon transition of the boundary layer to stable stratification.

The afternoon transition of the boundary layer from unstable to stable stratification in both urban and rural environs occurred over a relatively long period of time. Both horizontal and vertical turbulence intensity components reached a maximum about noon and declined steadily to near their nocturnal equilibrium value by 6 p.m. The velocity variances and peak wavelengths, while peaking about 12 m. (noon), declined only slightly to 2 p.m., and then decreased steadily to 7 p.m. Figure 2 demonstrates this feature for the peak wavelength of the longitudinal component of the wind for sites 105, 107 and 109. Note that the decline after 2 p.m. is well in advance of the decline in the mixing height. These observations suggest that free convective turbulence may be scaled to the peak wavelength of the horizontal velocity components rather than the height of the mixed layer. During the late afternoon period these two scale lengths may differ significantly. Turbulent mixing to the top of the "mixed layer," as specified by lidar or temperature-dewpoint profiles, probably does not cease abruptly after the heat flux peaks. It is suggested, however, that the probability of any thermal reaching the top of the "mixed layer" decreases significantly after 1 p.m. to 2 p.m. and continues to decrease to near zero prior to sunset, such that the peak in the energy spectrum is continually shifting to higher frequencies. The probability of a thermal reaching z_i or any height within the mixed layer after 2 p.m. likely depends on the height and strength of the mixed layer capping inversion, meso and synoptic scale advective processes, and on the surface energy budget which may have significant spatial variability in urban environs.

Results of the validation tests of current similarity parameterizations using this data set were mixed. The nondimensionalized turbulence parameters (i.e., the velocity and temperature variances, turbulence intensities, and spectra) for site 109 generally behaved as expected from similarity theory; the average magnitude of the data as a function of z'/L was consistent with corresponding values at ideal sites. However, the large scatter of data points (for example, see plots for σ_w/u^* in Figure 3) probably resulted from the nonhomogeneous distribution of land-use features and the abrupt change in roughness features near the tower in the eastern quadrants. A fully developed turbulent boundary layer may not have existed with easterly winds. The observational scatter for site 109 probably reflects the uncertainty inherent in the application of the similarity approach to practical diffusion problems.

The nondimensionalized turbulence parameters for the urban sites were generally an orderly function of z'/L; the data exhibited less scatter than the corresponding ratio for site 109. The plots of some urban parameterizations (e.g., σ_T/T*) were in very good agreement with the empirical expressions derived by others for flat homogeneous sites (such as Kansas). Other nondimensionalized ratios for the urban sites (for example, σ_w/u^* for site 105 in Figure 3), depart noticeably from the Monin-Obukhov similarity theory as empirically verified for homogeneous sites of small roughness. For small z'/L the slope of σ_w/u^* is smaller than expected. For large $-z'/L$ (approaching free convection), the ratio was lower than expected, however, the slope is approximately proportional to $(-z'/L)^{1/3}$ as predicted by similarity theory. Even under neutral stratification the data suggest site specific differences; the normalized vertical velocity variance decreases with increasing Z_0. Similar anomalies occurred with σ_v/u^* and σ_u/u^*.

The lateral and vertical turbulence intensities were essentially as expected from the similarity wind profile equation for neutral stratification, but much lower in magnitude than expected for $z'/L = -0.5$. The nondimensionalized dissipation rate of turbulent kinetic energy ϕ_ε behaved much like the ratio σ_w/u^*. At urban site 107, ϕ_ε was significantly less than the expected value of unity for neutral stratification, and at site 105 it was lower than expected throughout the range of unstable stratification. The results for ϕ_ε for site 109 were in general agreement with similarity theory; however, the scatter was large.

The differences between the derived empirical similarity forms for the urban sites and those for the rural sites are ~ 10 percent to 15 percent for neutral and stable stratifications and about a factor of ~ two for unstable stratification. For many applications (e.g., atmospheric diffusion estimates) these differences are within the reliability of the application form such that the Monin-Obukhov similarity theory, or a simple modification, derived out of the analysis, can be applied to urban areas.

Conclusions

The purpose of this study was to describe the structure of turbulence in the surface boundary layer of an urban area. From the extensive analyses of the turbulence data obtained in the St. Louis environs, it is concluded that parametric formulations for many nondimensionalized turbulence parameterizations (e.g., σ_w/u^*, σ_u/u^*, σ_v/u^*) for the urban sites differ significantly from existing theory, although the parameterizations for the rural site were in general agreement with similarity theory. The following more specific findings amplify this gener conclusion:

- The standard deviation of the vert cal velocity at both urban and rur sites can be described as a functio of u*, $\overline{w'T'}$, g/T and z. The horizor tal velocity standard deviations scal with u*, $\overline{w'T'}$, g/T and z_i (height o the mixed layer). In this respect th urban data can be described withi the framework of similarity theory.
- For neutral stratification, the nor malized velocity standard deviation were inversely proportional to sur face roughness. The nondimension alized dissipation rate had a simila tendency—it was considerably les than unity at site 107. These ano malies from similarity theory are be lieved due to the roughness wak region extending to the height of th instrumentation at site 107.

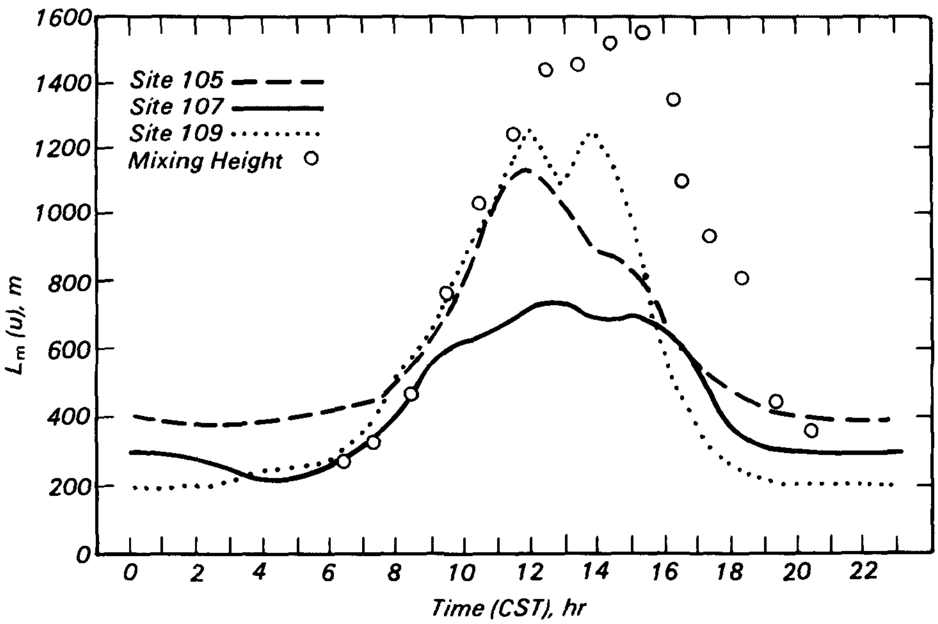

Figure 2. *Estimated fit to plots of peak wavelength of longitudinal velocity component.*

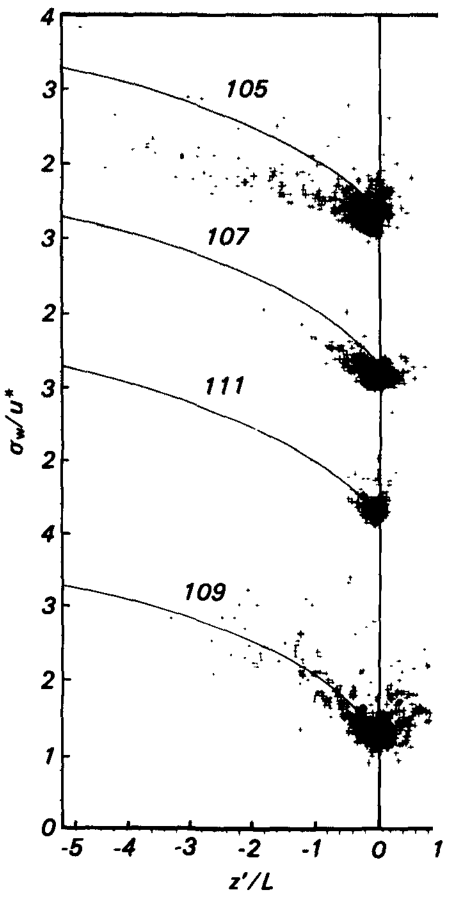

Figure 3. *Plots of σ_w/u^* vs. z'/L for indicated sites. The solid lines represent $\sigma_w/u^* = 1.3(1-z'/L)^{1/3}$.*

- For unstable stratification, the urban velocity standard deviations, turbulence intensities, and ϕ_ε were smaller than expected from similarity theory. Flux divergence of turbulent energy due to organized and possibly stationary vertical motions over portions of the city is the likely cause of the anomalies.
- For stable stratification, the velocity variances were a linear function of u* (i.e., σ_w/u^* = constant) at each of the sites. The individual slopes (for each site) appear to be a function of Z_o.
- Temperature spectra at all sites compared well with the Kansas empirical form of the Monin-Obukhov similarity theory.
- For neutral stratification, turbulence length scales were largest for the urban sites suggesting that ϕ_m may be correspondingly smaller above the rougher urban surface.
- The peak wavelength of the longitudinal velocity spectrum appears more appropriate than Z_i for free convection scaling. During the afternoon transition of the boundary layer to stable stratification, the two length scales may differ significantly.

*The EPA authors **John F. Clarke** (also the EPA Project Officer, see below), **J. K. S. Ching**, and **J. M. Godowitch** are on assignment to the Environmental Sciences Research Laboratory, Research Triangle Park, NC 27711 from the National Oceanic and Atmospheric Administration.*

The complete report, entitled "An Experimental Study of Turbulence in an Urban Environment," (Order No. PB 82-226 085; Cost: $15.00, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Environmental Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

☆U. S. GOVERNMENT PRINTING OFFICE: 1982/559-092/0492

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Postage and
Fees Paid
Environmental
Protection
Agency
EPA 335

Official Business
Penalty for Private Use $300

PS 0000329
U S ENVIR PROTECTION AGENCY
REGION 5 LIBRARY
230 S DEARBORN STREET
CHICAGO IL 60604