PIV measurements in the atmospheric boundary layer within and above a mature corn canopy. Part A: Statistics and small scale isotropy

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Abstract

Particle Image Velocimetry (PIV) measurements within the atmospheric boundary layer just within and above a mature corn canopy have been performed to clarify the small-scale spatial structure of the turbulence. The smallest resolved scales were about 15 times the Kolmogorov length scale ($\eta \approx 0.4\text{mm}$), the Taylor microscales were about $100\eta$ and the Taylor scale Reynolds numbers ranged between $R_{\lambda} = 2000$ and 3000. The vertical profiles of mean flow and turbulence parameters matched those found in previous studies. Frequency spectra, obtained using time series of data, were combined with instantaneous spatial spectra to resolve more than five orders of magnitudes of length scales. They displayed an inertial range spanning three decades. Local isotropy was reached at $k_{i}\eta$ exceeding $\sim 10^{-3}$ at all measured heights. Terms appearing in the turbulent kinetic energy budget that can be calculated from the PIV data were in agreement with previous results. Evidence of a very strong correlation between dissipation rate and out of plane component of the vorticity was demonstrated by a striking similarity between their time series.

Keywords: Particle Image Velocimetry (PIV), Atmospheric boundary layer, Canopy flow, Corn (Zea mays L.), Local isotropy, Dissipation rate, Vorticity.
Introduction

Turbulent boundary layer flow measurements inside and above canopies have been performed extensively in the last three decades as summarized in Raupach et al. (1981a) and Finnigan (2000a). Several studies have focused on corn canopies (e.g. Shaw et al. 1974a, b, 1983; Wilson et al. 1982). Besides fundamental insights on the structure of turbulent flow over rough boundaries in general, this knowledge is essential for predicting scalar exchange between the atmosphere and the canopy. Furthermore, turbulent entrainment and dispersal of pollen grains (Anemophilous) into the atmosphere is significant for ecological studies on genetic diversity (Wolfenbarger and Phifer 2000) as well as its impact on allergies.

Past measurements of atmospheric turbulence in near-neutral flow within and above different plant canopies have revealed a striking consistency of the mean flow and turbulence characteristics (Raupach et al. 1996). They show that the vertical profiles of normalized mean streamwise velocity exhibit an inflection point at canopy height that generates flow instabilities. The actual profile depends on the canopy density which is characterized by the Leaf Area Index (LAI) and the related Projected Frontal Area Index, \( PFAI \approx \frac{LAI}{2} \) (Poggi et al. 2004). The roughness layer extends up to 3 canopy heights (Raupach et al. 1991) and includes a constant Reynolds stress layer of one to two canopy heights. Beyond the roughness layer, the standard log layer forms. Brunet et al. (1994) observed a similarity between the roughness layer turbulence statistics and those of a plane mixing layer, and consequently Raupach et al. (1996) proposed a canopy-mixing layer analogy. Various subsequent experiments have strengthened this picture.
The existence of local isotropy at small scales in canopy flows is still an unresolved issue (Kaimal and Finnigan 1994). Energy spectra have been obtained both in the field (e.g. Shaw et al. 1974a; Amiro 1990) and in windtunnels (e.g. Brunet et al. 1994) using single point sensors. Based on the ratios between the streamwise and wall-normal components in the inertial (-5/3 slope) range, isotropy was not attained. However, the high Reynolds number field experiments did not resolve the small scales, while the Reynolds numbers in the windtunnel studies were too low for the development of local isotropy. For example, the split hot-film anemometers used by Shaw et al. (1974a) and Wilson et al. (1982) had a physical dimension of 0.9 cm and a sampling frequency $f$ leading to $U/f \sim 0.2$ m, where $U$ is the mean velocity. Sonic anemometers that have typical path lengths of 10-15 cm have been used for studying forest canopies (e.g. Collineau and Brunet 1993). Conversely, local isotropy has been achieved in a well resolved study of high Reynolds number turbulent boundary layer by Saddoughi and Veeravalli (1994).

The summary above indicates that we still lack field data on the small scale turbulence in atmospheric canopy flows. In this study we use a time series of PIV measurements just within and above a mature corn canopy in order resolve both the large and small turbulence scales. 2D PIV measures the instantaneous spatial distribution of two velocity components at a resolution that depends on several system parameters (details follow), ~2.8mm in the present study. The large scale structures are resolved by invoking Taylor’s hypothesis on the time series, whereas the small scales are resolved spatially. The data compare well with other sensors and previously observed trends. We then demonstrate that local isotropy indeed exists in high Reynolds number canopy flows, and we can
therefore use the energy spectra to estimate the dissipation rate and associated small-scale
turbulence parameters. Their variations with height are presented and compared to
previously published trends. Finally, we use a sample time series of velocity fluctuations,
Reynolds stresses, dissipation and vorticity magnitude to demonstrate a weak correlation
between dissipation and stress and a strong correlation between the dissipation rate and
the out-of-plane component of the vorticity.

Description of the field experiments

a. Setup and conditions

The field measurements were performed from 10 July 2003 until 22 July 2003, on the
eastern shore of the Chesapeake Bay, Maryland USA, at a latitude of 38° 35' 31" N and a
longitude of 75° 51' 55" W. The site was a flat, irrigated, 1.2 km² circular field with
diameter of about 800m. Half of this field was planted with corn, and the other half with
potatoes. During the course of the experiments the corn plants were fully matured and
pollinating. The location of the various instruments relative to the center of the field is
shown in Fig. 1. The meteorological station consisted of two 3D Campbell Scientific
sonic Anemometers/Thermometers (CSAT), a Vaisala HMP45C
Hygrometer/Thermometer, an RM Young 03105 propeller windvane (RMY) and a Texas
Electronics Rain Gauge. This station and the PIV system were located about a 100m
south of the center of the field, 6.8m and 5.3m inside the corn field, respectively. As
discussed later, the wind direction during the tests was about parallel to the dirt road,
from south to north.
Particle Image Velocimetry consists of recording two exposures of a section through a flow field seeded with particles that closely follow the flow (Raffel et al. 1998; Adrian 1991). Data analysis provides the instantaneous velocity distribution over the sample area. Thus, one can calculate the spatial energy spectra directly without invoking the Taylor’s hypothesis. It also enables calculation of the spatial distribution of the in-plane strain components and the out of plane vorticity component.

The field PIV system was essentially the same as the one used by Nimmo Smith et al. (2002) with minor modifications. The laser sheet forming optics and the camera were mounted on a retractable, rotating platform that could be raised up to 9.75m above the ground (Fig. 2). A wind vane, mounted on top of the platform, was used for aligning the system with the wind direction.

The light source was a dual flashlamp-pumped dye laser. The laser beam (max. 120mJ/pulse @ 594nm) was guided through a 400µm diameter optical fiber to the experimental platform where the beam was expanded to create a vertical light sheet. The thickness of the light sheet varied between 3 to 4 mm over the sample area. A 12 bit auto-correlation CCD camera (2048x2048 pixels, Silicon Mountain Design), having a hardware-based image shifter between exposures to overcome directional ambiguity (Nimmo Smith et al. 2002), was used. The field of view of the camera was 18.2x18.2 cm² while the distance from the camera to the light sheet was 61.5cm. The camera was mounted inside a temperature controlled enclosure to prevent overheating.

We used oil-based fog as flow tracers, generated by two Rosco 1600 fog generators. The mean fog particle diameter was 2µm (Han et al. 2002; Kähler et al. 2002). The output nozzle of each generator was connected to a 30m long perforated, 10cm diameter
flexible plastic hose, laid out in a half circle of radius 30m around the facility inside the corn field, just below canopy height. During the experiments, fog was slowly released through the perforations, and advected towards the experimental facility. For most of the time this approach created uniform seeding in the camera field of view at all elevations.

Out of the 12 bit data we kept and processed the 8 bits that contained the particle traces. The signal to noise ratio was subsequently increased using a modified histogram equalization method and then processed using in-house developed, direct correlation software (Roth et al., 1999; Roth and Katz, 2001). We subsequently corrected the data for optical image distortion, and for out of plane motion (Nimmo Smith et al. 2002). The interrogation windows were 64x64 pixels (5.6x5.6 mm), that with 50% overlap provided a vector spacing of 2.8mm. Thus each instantaneous velocity distribution contained 64x64 vectors. The uncertainty in the measurements was about 0.2 pixels (0.06 m s\(^{-1}\)) provided there was sufficient seeding. Since the seeding particles were not always uniformly distributed, we discarded vectors that did not satisfy a minimum correlation coefficient, and subsequently utilized only those maps that contained 70% or more vectors. The number of vector maps passing our criteria was 3300 ± 100. A typical instantaneous velocity field superposed on the vorticity distribution is shown in Fig. 3. Note that the instantaneous mean velocity was subtracted from each vector to highlight the spatial structure of the flow. The resulting 2D vector maps were used to calculate the ensemble averaged velocity profiles, turbulence characteristics, vorticity and spatial spectra. Second order finite differencing is used for calculating spatial derivatives. In the results that follow, \(U_i\) is the mean velocity, \(u_i\) is the fluctuating component and \(\sigma_i\) is the
rms value of the fluctuating component, where \( i = 1, 3 \), corresponding to \( x \) and \( z \) respectively (Fig. 2). An overbar is used to indicate ensemble averaging.

The measurements discussed in this paper were carried out during a windy night on the 22 July 2003 between 0030 and 0300 Eastern Daylight Time (EDT). The PIV measurements were performed at 4 different heights, \( z/h = 1.29, 1.20, 1.11 \) and 0.97, where \( z \) is the height of the center of the field of view measured from the ground, and \( h = 2.67 \)m is the average canopy height. At each elevation, 4096 double-exposure images were recorded at an acquisition rate of 4Hz, corresponding to 1024s of sampling time. Before each run the camera was aligned with the wind direction using the wind vane. Based on the meteorological station data (details follow), the 5 min average wind direction did not change by more than 5° during each run, but standard deviations were 20°. The 3D sonic anemometers on the meteorological tower were mounted at \( z/h = 1.0 \) and 1.35, while the Young Propeller wind vane was located at \( z/h = 1.5 \). Data from the meteorological station was continuously acquired at 6.9 Hz, using a Campbell Scientific CR23X data logger, during the entire experiment.

\textit{b. Corn field characteristics}

The planted corn variety was 33B51 Pioneer BT gene plus yield guard Insecticide. The corn was fully matured and as illustrated in Fig. 1, it was planted in double rows in a staggered configuration. The lateral distance between rows in a double row was 0.10m, and the distance between double rows was 0.76m. The centers of the stalks in each row were longitudinally spaced by 0.19m. The resulting surface area per plant was 0.1 m\(^2\). We measured the height of 43 stalks around the PIV system and obtained an average height of 2.67m.
The Leaf Area Index (LAI) is here defined as the ratio between the total one-sided leaf area and the occupied surface area per plant, while the Projected Frontal Area Index (PFAI) is defined as the ratio between the projected frontal area and the occupied surface area of one plant (Finnigan 2000a; Wilson et al. 1982). Both were measured using image processing based on 4 different corn plants located near the measurement site. As illustrated in Fig. 4 for one plant, the PFAI was calculated by thresholding the grayscale images, and calculating the projected area of the silhouette shown in Fig. 4b. The LAI was determined in the same way by pealing the leaves as shown in Figs. 4c and d. The average results were LAI = 6.0 ± 0.6 and PFAI = 3.7 ± 0.5. The ratio PFAI/LAI of 0.6 ± 0.1 is slightly higher than the typically assumed value in canopy flows (PFAI = LAI/2, Finnigan 2000a). The present LAI is about twice as high as that reported by Wilson et al. (1982) because of the double-row configuration, which halves the ground area per plant.

Experimental results

c. Mean flow characteristics

During the tests, the wind was coming from the SSW direction. The mean temperature, as measured by the Vaisala Hygrometer/Thermometer, decreased slightly during the experiments, from 26.5°C to 25.8°C, while the relative humidity increased from 93.5% to 95.9%. The Obukhov length, \( L \), (Kaimal and Finnigan 1994) was calculated using the sonic anemometer data:

\[
L = -\frac{(u_{CSAT}^*)^3 / \kappa}{(g / T_v)(u_1 T_v)_{z=h}}
\]

(1)
where $\bar{T}_v$ is the mean virtual temperature, $(u'_3 T'_v)_{z=h}$ is the covariance between vertical velocity and virtual temperature fluctuations at canopy height, $g$ is the gravitational acceleration, $\kappa = 0.4$ is the Von Karman constant and the friction velocity, $u_{\text{CSAT}}^*$ is determined from the constant stress layer just above the canopy, 

$$u_{\text{CSAT}}^* = \left( (u'_1 u'_3)^2 + (u'_2 u'_3)^2 \right)^{1/4}.$$ 

The Obukhov length was 20 m, indicating weakly to moderately stable conditions at canopy height.

A comparison between 5 min averaged streamwise velocities measured by the PIV system (average of the central 10x10 vectors and 1200 maps), the Sonic Anemometers and the Propeller wind vane is shown in Fig. 5. Note that the measurement heights are different, as specified below the graph. An accompanying comparison between the mean flow and turbulence parameters of the PIV and CSAT measurements is presented in Table 1. The CSAT data is provided only for the cases in which the PIV and CSAT measurements are performed at almost the same height. The PIV data is consistent with the CSAT’s both in absolute values and trends considering that measurements are performed at different locations (see Fig. 1). Differences can be attributed to spatial heterogeneity of the flow field, misalignment (less than 10°) and differences in elevations between the instruments. The mean wind direction (0° being a northern wind) ranges between 190° to 200° with standard deviations of each 5min average of about 20°, i.e. it was about parallel to the dirt road, coming from the south, southwest direction (Fig. 1). This wind direction falls within 20° of the orientation of the PIV system. As is evident, the mean velocities range between 1 to 4 m/s increasing with height.
Normalized mean velocities and turbulent characteristics, nicknamed “family portraits” (Raupach et al. 1996; Finnigan 2000a), as calculated from the PIV data are presented in Fig. 6. The statistics are ensemble averaged over all the datasets at each vector position, and subsequently spatially averaged over the 10 central columns. Thus, each point represents an average of more than 30,000 points. In general, the vertical profiles are consistent with published data for a variety of canopy flows (Shaw et al. 1974b, 1983; Wilson et al. 1982; Finnigan 2000a). In Figs. 7a-c the profiles are normalized by the mean velocity at canopy height, $U_{CSAT}^h$, and the friction velocity $u_{CSAT}^*$, as measured by the CSAT at the same time (Table 2) since they are continuously sampled at $z/h = 1.0$. Other parameters presented in Fig. 6 are the correlation coefficient $-\overline{u_i u_3}/\sigma_i \sigma_3$, the skewness $\overline{u_i^3}/\sigma_i^3$, and the locally normalized rms values of velocity fluctuations, $\sigma_i/U(z)$. The normalized shear stress is not equal to one at canopy height, most likely since the CSAT measurements are performed at a different location, along with effects of spatial inhomogeneity in the field at the scale of the measurement volume. As expected, the streamwise components of the normalized rms value of $u_i$ are larger than their wall normal counterparts. The correlation coefficient is approximately 0.5 at canopy height and decreases to about 0.3 at $z/h = 1.3$. The latter value is already similar to that occurring in the log layer of a typical turbulent boundary layer. Thus, the elevated vertical momentum transfer near canopy height does not extend beyond $z/h = 1.3$. Fig. 6b indicates that the constant shear stress layer is confined to $z/h < 1.25$. The normalized streamwise velocity fluctuations peak at $1.1 < z/h < 1.23$, and then decrease at higher elevation. The wall-normal fluctuations peak at a higher elevation. The wall-normal skewness is consistently negative while $\overline{u_i^3}/\sigma_i^3$ is positive, indicating a preference for
sweeping motions \( (u_1 > 0 \text{ and } u_3 < 0) \) near canopy level, as observed before by Shaw et al. (1983). Both skewness terms decrease with increasing height.

d. Spectral characteristics

In this section we examine the spectral characteristics of the high Reynolds number canopy turbulence. The analysis follows closely the work of Saddoughi and Veeravalli (1994) who measured the spectral characteristics of a turbulent boundary layer in a wind tunnel at slightly lower Taylor scale Reynolds numbers \( (R_\lambda \approx 1800) \) compared to the present values \( (R_\lambda \approx 2000 – 3000, \text{ details follow}) \).

The spectral characteristics are analyzed using the PIV data in a twofold manner. First, the energy at small scales is examined through spatial spectra that can be calculated directly from the instantaneous velocity distributions. Second, invoking Taylor’s “frozen” turbulence hypothesis, the PIV data at each point can be treated as time series \( (f = 4 \text{Hz}) \) to study the energy at large scales. The latter are compared to the spectra calculated from the Sonic Anemometer data \( (f = 6.9 \text{ Hz}) \). In all cases we use Fast Fourier Transforms. In order to reduce the effect of the finite data sets, we remove the mean and apply linear detrending with zero padding. Details are provided in Doron et al. (2001) and Nimmo Smith et al. (2005). The spatial spectra presented in this paper are calculated separately for each horizontal line, ensemble averaged, and then averaged over the 11 central lines of the velocity distributions. The one-dimensional spectra \( E_{11}, E_{33} \) and \(-E_{13}\) are plotted in Fig. 7 as a function of the streamwise wave number \( \kappa_1 \). The spectra calculated treating the PIV data as time series, range between \( 4 \times 10^{-3} < \kappa_1 < 8 \), while the spatial spectra range between \( 34.5 < \kappa_1 < 1.1 \times 10^3 \). The wave numbers in the gap between the two plots corresponding to length scales ranging from 0.2 m to 1 m were not resolved. The spectra obtained from the
PIV and Sonic Anemometer time series are very similar. The minimal discrepancies can be attributed to the slight misalignments and differences in height. The distributions of $E_{11}$ and $E_{33}$ exhibit an inertial range with a $-5/3$ slope (Eq. (2)) over almost three decades of wave numbers. Furthermore, the time series and spatial spectra seem to fit the same $-5/3$ line, i.e. the spatial spectra appear to be an extension of the time series spectra. The same agreement persists in the spectra obtained at all heights (Fig. 8). The ratio between the spatial spectra of the wall-normal and the streamwise component, $E_{33}(\kappa_1)/E_{11}(\kappa_1)$, ranges between 1.41 and 1.48 in the inertial range and is close to 4/3, the isotropic value.

We will discuss and prove the existence of local isotropy at small scales at a later stage in this section. Assuming for now that the turbulence at small scales is isotropic, the 1-D longitudinal spectra in the inertial range follow (Pope 2000):

$$E_{ii}(\kappa_1) = C_i \varepsilon^{2/3} \kappa_1^{-5/3},$$  \hspace{1cm} (2)

where $C_1 \equiv (18/55)l_6$, $C_3 \equiv (24/55)l_6$. Thus by fitting a $-5/3$ slope line to the distribution of $E_{ii}$, one can estimate the dissipation rate, $\varepsilon$. The shear stress spectrum decays at a faster rate, following:

$$E_{13}(\kappa_1) = -C_{13} S\varepsilon^{1/3} \kappa_1^{-7/3}$$  \hspace{1cm} (3)

where $S$ is the mean shear rate magnitude and $C_{13}$ is a constant. The sample shear spectrum, $-E_{13}$ in Fig. 7, is noisier than the normal spectra and seems to decay slightly slower than the $-7/3$ slope line.

The estimated dissipation can subsequently be used to calculate the Kolmogorov length scale $\eta = (\nu^3/\varepsilon)^{0.25}$, the transverse Taylor microscale $\lambda = (15\nu \sigma_i^2/\varepsilon)^{1/2}$, and the
Taylor scale Reynolds number \( R_\lambda = \sigma_\lambda \lambda / \nu \), where \( \nu \) is the kinematic viscosity of air.

The values of \( \varepsilon \), \( \eta \), \( \lambda \) and \( R_\lambda \) are presented in Table 3 for different \( z/h \). When the dissipation rates are normalized by \( u_{\text{CSAT}}^2 / h \) (Table 5), their values range between 2.2-2.5 consistent with the range of magnitudes obtained in a wind tunnel by Brunet et al. (1994) who show that \( \varepsilon \) has a broad peak of \( \approx 2.5 \) at \( z/h \approx 1.4 \). Within our range of elevations, the highest dissipation rate occurs at \( z/h = 1.29 \). The Kolmogorov length scales range between 310-370 \( \mu \text{m} \), with the highest value obtained at canopy height. The Taylor micro scale is almost constant, \( \lambda \approx 40 \text{ mm} \), and the corresponding Reynolds numbers range from \( R_\lambda = 2.08 \times 10^3 \) to \( 3.10 \times 10^3 \). Note that \( \lambda / \eta \) is of the order of 100, consistent with ratios obtained by Saddoughi and Veeravalli (1994) and Saddoughi (1997). The integral scale can be calculated using \( L = k^{3/2} / \varepsilon \) (Pope 2000). Since we have data on two velocity components only, the kinetic energy, \( k \), is estimated assuming, \( \overline{u_z^2} \approx (\overline{u_1^2} + \overline{u_2^2}) / 2 \), i.e. \( k \approx 3(\overline{u_1^2} + \overline{u_2^2}) / 4 \). This assumption is consistent with trends measured by the Sonic anemometers. The values of \( L \) are also tabulated in Table 3, the range between \( 2h \) to \( 3h \).

For \( R_\lambda > 10^3 \), \( L_{11} / L = 0.43 \) (Pope 2000), where \( L_{11} \) is the longitudinal integral length scale, thus \( L_{11} \) is on the order of \( h \), consistent with the literature on canopy flows (e.g. Finnigan 2000a).

As is evident from Fig. 8, the normalized longitudinal, one-dimensional spectra have an inertial range extending over three decades \( \sim 10^{-4} < \kappa_1 \eta < \sim 10^{-1} \). Within the inertial range, all the data collapse onto a single curve, consistent with Saddoughi and Veeravalli
(1994). Also consistent is the increase of the inertial range with Reynolds number, although in the present data, all the values of \( R_\lambda \) are of the same order.

The power law behavior in the inertial subrange is best examined by plotting the compensated Kolmogorov spectrum function, \( \Psi(\kappa \eta) \),

\[
\Psi_{ji}(\kappa_j \eta) = E_{ji}(\kappa_j) e^{-2/3 \kappa_j^{5/3}}.
\]  

(4)

Typical examples of \( \Psi_{11}(\kappa_1 \eta) \) and \( \Psi_{33}(\kappa_3 \eta) \) are plotted in Fig. 9. The inertial range of the wall normal component seems to be about one decade shorter than that of the longitudinal component. The compensated spectra reach plateaus in the inertial region whose values are \( C_1 = (18/55)1.6 \) and \( C_3 = 4C_1/3 \) (Eq. 2), for the longitudinal and wall normal component, respectively, consistent with expected values. At the transition from inertial to dissipation range the wall-normal component seems to exhibit a small hump. All these trends agree with the wind tunnel measurements of Saddoughi and Veerevalli (1994).

In order to investigate the power law behavior of the spatial spectrum in the dissipation region, i.e. for \( \kappa_1 \eta > \sim 10^{-1} \), we plot the compensated spatial spectrum (Eq. 4) on log-linear scales in Fig. 10. The dissipation range of the energy spectrum of isotropic turbulence decays as (Kraichnan 1959):

\[
E(\kappa) = A(\kappa \eta)^{\gamma} \exp\left\{ -\beta(\kappa \eta) \right\}.
\]  

(5)

The present data seems to follow the line plotted for \( \beta = 5.2 \), as obtained previously by Direct Numerical Simulation (e.g. Sanada 1992) and by Saddoughi and Veerevalli (1994). Note that our results become contaminated with noise at \( \kappa_1 \eta > 0.2 \). Existence of
local isotropy in the high Reynolds number canopy flow can be examined using the correlation coefficient:

$$R_{13}(\kappa_1) = \frac{-E_{13}(\kappa_1)}{[E_{11}(\kappa_1)E_{33}(\kappa_1)]^{1/2}}. \quad (6)$$

The value of $R_{13}$ should drop to zero upon reaching local isotropy (e.g. Pope 2000). As is evident from Fig. 11, $R_{13}(\kappa_1)$ decays to zero at $k_1\eta \geq 10^{-3}$ with some slight variations that seem to depend on the local $R_L$. All the spatial data fall within the local isotropy range.

An additional test of isotropy involves the statistics of the velocity gradients (Pope 2000). In isotropic turbulence:

$$G_{ijkl} \equiv \frac{\partial u_i}{\partial x_j} \frac{\partial u_k}{\partial x_l} \left( \frac{\partial u_1}{\partial x_1} \right)^2 = 2\delta_{ik}\delta_{jl} - \frac{1}{2} \left( \delta_{ij}\delta_{kl} + \delta_{il}\delta_{jk} \right), \quad (7)$$

where $\delta_{ij}$ is the Kronecker delta. Thus, $G_{1111} = G_{3333} = 1$, $G_{1313} = G_{3131} = 2$ and $G_{1331} = -0.5$. The spatial derivatives were calculated directly from the instantaneous PIV data using a second order center difference scheme for the central 20x20 points in each map. We obtain that $\left( \partial u_1/\partial x_1 \right) \approx \left( \partial u_3/\partial x_1 \right)$ and $\left( \partial u_1/\partial x_3 \right) \approx \left( \partial u_3/\partial x_3 \right)$ within 5%. However $\left( \partial u_1/\partial x_1 \right)^2/\left( \partial u_1/\partial x_3 \right)^2 \approx 1.5$ instead of two and $\left( \partial u_1/\partial x_3 \right)\left( \partial u_3/\partial x_1 \right)/\left( \partial u_1/\partial x_1 \right)^2 \approx -0.3$ instead of -0.5. This inconsistency cannot be a results of anisotropy since the normal derivatives of both components as well as the cross derivatives of both components are equal to each other. But it could be generated by a contribution of noise. For example, an equal noise contribution to the numerator and denominator of Eq. (7) would alter any ratio except for that equaling 1. Unfortunately, as is evident from the spectra (Fig. 10),
noise adversely affects the data at the smallest scales. As the spectra show, the effect of noise diminishes at larger scale. Thus, isotropy can be re-checked by spatially filtering the data using an 8x8 box filter (denoted by ~), and re-calculate the spatially filtered velocity gradients. We now obtain ratios that approach the isotropic values, i.e. 

\[
\left(\frac{\partial \overline{u_i}}{\partial x_j}\right)^2 \left(\frac{\partial \overline{u_j}}{\partial x_i}\right)^2 \approx 1.8 \quad \text{and} \quad \left(\frac{\partial \overline{u_i}}{\partial x_j}\right)\left(\frac{\partial \overline{u_j}}{\partial x_i}\right) \left(\frac{\partial \overline{u_i}}{\partial x_j}\right)^2 \approx -0.45.
\]

e. Terms appearing in the turbulent kinetic energy budget

Turbulent kinetic energy budgets have been measured in forest canopies by Leclerc et al. (1990) and Meyers and Baldocchi (1991), and in wind tunnel studies by Raupach et al. (1986) and Brunet et al. (1994). One can use the PIV data to examine several terms in the turbulent kinetic energy \((\overline{u_ju_i}/2)\) budget (Pope 2000):

\[
U_j \frac{\partial}{\partial x_j} \left(\frac{1}{2} \overline{u_ju_i}\right) = -\frac{\partial}{\partial x_j} \left(\frac{1}{\rho} \overline{u_j p} + \frac{1}{2} \overline{u_j u_j} - 2\nu \overline{u_j s_j} - \overline{u_j S_j} - 2\nu s_j s_j\right),
\]

where \(S_{ij}\) and \(s_{ij}\) are the mean and fluctuating rates of strain, respectively, and \(p\) is the pressure. Specifically, besides the pressure-velocity correlation, we can calculate the in-plane components of all the above terms in this equation. For example, the four available contributions to the production term \(\overline{u_j u_j S_{ij}}\) are \(\overline{u_iu_i S_{11}}, \overline{u_iu_j S_{13}}, \overline{u_iu_i S_{31}}\), and \(\overline{u_3 u_3 S_{33}}\).

Since the present measurements were performed near the edge of the corn field the spatial derivatives in the streamwise direction are not zero and cannot be neglected.

The normalized convective transport of kinetic energy, along with the dissipation and the production rates are tabulated in Tables 4 to 7. To calculate the \(U_j \partial k/\partial x_j\) terms, the gradients are determined by fitting straight lines through the data within the central 20x20

points of the sample areas. The mean velocities are also averaged over the same area. Since our interrogation area is about 10-15 times the Kolmogorov scale, the estimates of dissipation rate assuming isotropy, i.e. $15\nu\left(\frac{\partial u_i}{\partial x_i}\right)^2$ shown in Table 5, is 2-3 times lower than the estimate based on -5/3 curve fit to the spatial spectra in the inertial range. The production rate terms shown in Table 6, are also calculated locally at each point, and then averaged over the central 20x20 area. Since the light sheet is aligned with the mean flow, the main spatial gradients of the mean flow are within the sample area. Thus, we neglect the contributions of $U_2$ and $\partial / \partial x_2$ terms. In support of this latter assumption, for most of the present data $\partial U_1 / \partial x_1$ is equal in magnitude and opposite in sign to $\partial U_3 / \partial x_3$.

We have tried to calculate the gradients of the triple correlation terms based on the spatial distributions in individual sample areas. Unfortunately, even an average of 3300 measurements still leaves significant spatially non-uniform patches, which cause unreasonable variations in gradients, especially when the magnitudes are very small. Thus, instead a power law was least square fitted through the entire normalized vertical distributions of relevant terms. The results are presented in Table 7. We do not estimate the streamwise gradients due to the scatter discussed above, and have no way of estimating the out of plane gradients. Consequently, the turbulent diffusion is calculated only based on the vertical trends of $u_1u_1u_3$ and $u_3u_3u_3$. Upon examination of the calculated contributors to Eq. (8), there is an increasing imbalance with height between the left and right hand sides. We believe that this imbalance is caused by the missing $\partial / \partial x_1 \left[ (u_1u_1u_1 + u_3u_3u_3) / 2 \right]$ that we cannot calculate at an acceptable level of accuracy for all heights. However, for the $z/h = 0.97$ data set, the horizontal diffusion terms are very
small and the other terms that we do calculate, balance each other (difference of 0.2). For the highest elevation, the estimated horizontal turbulent diffusion is about 4 (based on a linear fit to all the data), greatly reducing the discrepancy between the two sides of Eq. (8). At all heights, the transport by the viscous stresses was negligible, < 10^{-3} and as a result, it is not presented.

The vertical trends of all the calculated terms are also summarized in Fig. 12. Here, the loss terms are negative and the gain terms are positive. The flux by mean flow is small at canopy height and increases with depth, almost linearly. Table 4 shows that the vertical advection by the mean flow is negative and negligible compared to the horizontal advection except for the canopy height. Within the canopy, the horizontal flux weakens, and the vertical term increases, resulting in a weaker contribution of the mean flow.

Of the contributors to the production (Table 6), $-u_i u_i \partial U_j / \partial x_i$ is negligible compared to the other terms. The terms associated with the mean wall-normal gradients, $-u_i u_j \partial U_j / \partial x_i$ and $-u_i u_j \partial U_j / \partial x_i$, act as sources while $-u_i u_i \partial U_j / \partial x_i$ acts as a sink. Although $\partial U_j / \partial x_i$ is relatively small (compared to its vertical gradients), it’s contribution is amplified by the large $-u_i \partial U_j / \partial x_i$. The total production peaks very near to the canopy and decreases at a higher elevation. The production exceeds the dissipation (at $z/h = 0.97$), but these two “source/sink” terms are comparable above the canopy. The vertical turbulent transport is significant only near the canopy, and diminishes at higher elevations. The trends of production, dissipation rates and turbulent transport are consistent with the wind tunnel measurements of Brunet et al. (1994) and field measurements of Leclerc et al. (1990).
f. The relation between the dissipation rate and the out of plane component of the vorticity

Boundary layer flows display an intricate pattern of Sweep (S) –Ejection (E) cycles (e.g. Raupach 1981b; Shaw et al. 1983; Gao et al. 1989; Finnigan and Shaw 2000b) that will be further explored in Part B of this sequence. A sweep is associated with fast moving downward directed fluid, i.e. $u_1 > 0$ and $u_3 < 0$, whereas an ejection is associated with slow moving upward directed fluid, i.e. $u_1 < 0$ and $u_3 > 0$. As an example, Figs. 13a and b present the time series of the fluctuating velocity components and their correlation, respectively, at $z/h = 1.20$. Time series obtained at different heights appear quite similar and are not shown here. In this analysis, we use the central 20x20 vectors of each instantaneous distribution. To highlight trends of large scale flow features, each data point is an average over 20x20 instantaneous vectors, and a 30s running average. The $-u_1u_3$ correlation is calculated for each point and then averaged over the 20x20 area. These plots provide an insight into the sequence of events occurring in the canopy flow boundary layer. A few Sweep - Ejection cycles, characteristic of turbulent boundary layers, can be clearly discerned in Fig. 13a. As is evident, only about 10 major events occur during the measurement period of 1024s, raising questions on the statistical significance of the average trends. The amplitude of the vertical component is much smaller than that of the streamwise component, consistent with the spectral differences at low wave numbers (Fig. 7). The time series of $u_1u_3$ correlation shows conflicting trends, at least from visual observations. In some cases, the sweeps involve high correlation, e.g. at 300s, but in other events the shear stresses during sweeps are low, e.g. at 70s. However, about half of the $-u_1u_3$ peaks are associated with sweeps.
The relation between the dissipation rate and the vorticity is less well documented in the literature (Zhu and Antonia 1997; Nelkin 1999; Zeff et al. 2003), to the best of our knowledge, none in atmospheric flows. For isotropic, homogeneous turbulence, the mean dissipation rate equals the mean enstrophy \( \varepsilon \equiv \nu \omega^2 \) (e.g. Zhu and Antonia 1997) and \( \omega_z^2 \equiv \omega^2 / 3 \). Since the present results indicate that the small scale turbulence near the corn canopy is isotropic, i.e. we have local isotropy, it would be of interest to compare the dissipation rate to the statistics of the enstrophy. Thus, the values of \( 3\nu\omega_z^2 \) are also presented in Table 5. The values of the latter are about 30% lower than those of \( 15\nu(\partial u_i/\partial x_i)^2 \), at all elevations, but similar to \( 7.5\nu(\partial u_i/\partial x_i)^2 \) also shown in Table 5. The discrepancy is caused by deviations of the ratios of cross to normal derivatives from the isotropic values, as discussed at the end of section 3.2. The estimates of dissipation rate based on isotropy are lower than the spectrally estimated dissipation due to resolution limits of the PIV data.

Figs. 13(c) and (d) present the time series of the dissipation rate, and the magnitude of the out of plane component of the vorticity, respectively, both representing running averages over 30s. To calculate the dissipation time series, we average the spectra of central 11 rows over 30s (1320 spectra) and then fit a -5/3 line to them. There is a striking similarity between trends of the enstrophy and dissipation rate, with a correlation coefficient of about 0.9. Furthermore, almost all the major dissipation rate and high enstrophy events occur during sweeps. Conversely, during some of the ejection events, e.g. at 800, 900 and 950s, there are shear stress peaks but the dissipation rate is especially low.
This strong correlation between vorticity and dissipation has been shown to exist in laboratory flows (Zeff et al. 2003; Zhu and Antonia 1997). Zeff et al. (2003) show that local high strain rates cause vortex stretching, which increases the local growth rate of the vorticity. Thus, the peak in vorticity lags behind the dissipation peak. According to Zeff et al. (2003) the delay is about $0.1 - 0.2 \eta \tau$. The present delay between samples is about 25 times the Kolmogorov time scale, $\tau \equiv (\nu/\varepsilon)^{1/2} \approx 10^{-2} \text{s}$, and we can therefore not resolve the lag between the enstrophy and dissipation rate peaks.

**Summary and conclusions**

PIV measurements along with sonic anemometer and other meteorological sensors examine the flow structure within and above a corn canopy. The mean flow and turbulence statistics measured by PIV compare well with the sonic anemometer data. Furthermore, the trends and absolute values of the mean velocity profiles, rms values of velocity fluctuations, Reynolds stresses and third order moments of turbulent velocity fluctuations are consistent with data on canopy flow found in the literature (e.g. Finnigan 2000a). We construct spectra by combining time and spatial series. The small scales at the transition between inertial and dissipation ranges, from $15\eta$ to $450\eta$, are studied using the instantaneous velocity distributions. The low wave number range of the spectra is calculated by invoking Taylor’s hypothesis on the 4Hz time series. The spatial spectra appear as a natural extension of the times series spectra in the inertial range. The energy spectra cover five orders of magnitude of length scales, of them the inertial range spans approximately three decades.
Several methods confirm that the turbulence at small scales (\(k_1 \eta > \sim 10^{-3}\)) is locally isotropic, including ratios of velocity gradient statistics, a comparison between spectra of the vertical and the horizontal velocity component, and the correlation coefficient being zero over the entire range of spatial PIV scales. Thus, the mean dissipation rate can be estimated by curve fits to the spectra, and from them we obtain that the Kolmogorov length is \(\eta \sim 0.4\text{mm}\), and the Taylor micro-scale Reynolds numbers range between \(R_\lambda = 2000 – 3000\) with \(\lambda/\eta \sim 100\).

The terms appearing in the turbulent kinetic energy budget that are directly calculated from the 2D PIV data are of the same order and consistent with published data on canopy flows. The total production peaks and exceeds the dissipation rate at canopy height. With increasing elevation the production rate decreases, while the dissipation rate remains unchanged. At \(z/h = 1.29\) they have comparable magnitudes. The time series of dissipation rate and out of plane component of the vorticity magnitude show a striking similarity, with correlation coefficients of \(-0.9\). Accounting for resolution limits, the data also confirms the isotropic relation that \(\varepsilon = 3\nu \bar{\omega}_z^2\).

Time series of velocity fluctuations show a repeated pattern of sweep-ejection cycles. The Reynolds shear stresses show some but not a definite relation to these cycles, as do the dissipation rate and vorticity. Thus, it is of interest to perform a detailed statistical analysis of these relationships. They are examined in detail in the second part of this paper.

Acknowledgements
We would like to thank Mike Embry of the Wye Research and Education Center of the University of Maryland for his help in finding a proper location to conduct the field experiments. We are also grateful to Mac Farms Inc. in Hurlock, MD, for generously granting us access to their corn field and putting up with our smoke clouds. We are further grateful to Y. Ronzhes and S. King for their technical expertise in developing and maintaining the equipment. Thanks are also due to Prof. G. Brush for support and advice. This research was funded by Bio-Complexity Program of the National Science Foundation under grant 0119903.
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**Figure captions**

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- Meteorological station

Fig. 2. Schematic layout of the platform carrying the PIV system and the relative position of the camera and the light sheet. (not to scale)

Fig. 3. Typical vector map of the instantaneous velocity field superposed on the vorticity distribution. The instantaneous spatial mean velocity, \( U_s \), is subtracted to highlight the flow structure.

Fig. 4. Calculation of the Leaf Area Index and Projected Frontal Area Index of corn plants.

Fig 5 Five minute averaged wind velocities and wind directions on 22 July 2003. Error bars indicate standard deviation.

<table>
<thead>
<tr>
<th>PIV</th>
<th>CSAT</th>
<th>RMY ((z/h = 1.5))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( z/h = 0.97 )</td>
<td>( z/h = 1.0 )</td>
<td>( z/h = 1.0 )</td>
</tr>
<tr>
<td>( z/h = 1.11 )</td>
<td>( z/h = 1.35 )</td>
<td>( \uparrow ) Wind speed</td>
</tr>
<tr>
<td>( z/h = 1.20 )</td>
<td>( \circ ) Wind direction</td>
<td></td>
</tr>
<tr>
<td>( z/h = 1.29 )</td>
<td>( \triangle )</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6. Mean flow and turbulence statistics of the corn canopy flow.

Fig. 7. Comparison of one-dimensional energy spectra obtained from PIV (time series and spatial at \( z/h = 0.97 \)) and CSAT (\( z/h = 1.0 \)).

Fig. 8. Normalized longitudinal spectra of PIV data at different heights.

Fig. 9. Compensated longitudinal and wall-normal PIV spectra at \( z/h = 1.29 \) and \( z/h = 0.97 \).

Fig. 10. Compensated semi-log plot of the spatial PIV spectra. Solid line: Eq. (5) with \( \beta = 5.2 \).
- (a) \( E_{11}(\kappa_1) \)
- (b) \( E_{33}(\kappa_3) \)
Fig. 11. Spectra of the correlation coefficient $R_{13}(\kappa_1)$ for different heights.

Fig. 12. Normalized terms of the turbulent kinetic energy budget.

- $\varepsilon$ (Table 5)
- Convective terms (Table 4)

- Production (Table 6)
- Vertical turbulent transport (Table 7)

Fig. 13. Time series (30s running average) at $z/h = 1.20$ of (a) $u_1$, $u_3$, (b) $-u_1u_3$, (c) $\omega_z^2$

(d) $\varepsilon$
## Tables

### Table 1  Comparison of the mean flow and turbulence parameters between Sonic Anemometers (CSAT) and Particle Image Velocimetry (PIV).

<table>
<thead>
<tr>
<th>Sample time EDT [h:min]</th>
<th>PIV</th>
<th>CSAT</th>
<th>PIV</th>
<th>PIV</th>
<th>CSAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0211 – 0228</td>
<td>0040 – 0057</td>
<td>0111 – 0128</td>
<td>0137 – 0154</td>
<td></td>
<td></td>
</tr>
<tr>
<td>z/h</td>
<td>0.97</td>
<td>1.0</td>
<td>1.11</td>
<td>1.21</td>
<td>1.29</td>
</tr>
<tr>
<td>$U_1$ [ms$^{-1}$]</td>
<td>1.49</td>
<td>1.54</td>
<td>2.50</td>
<td>2.46</td>
<td>2.60</td>
</tr>
<tr>
<td>$U_3$ [ms$^{-1}$]</td>
<td>-0.11</td>
<td>-0.06</td>
<td>-0.08</td>
<td>-0.08</td>
<td>-0.05</td>
</tr>
<tr>
<td>$\sigma_1$ [ms$^{-1}$]</td>
<td>0.78</td>
<td>0.93</td>
<td>1.15</td>
<td>1.07</td>
<td>0.97</td>
</tr>
<tr>
<td>$\sigma_3$ [ms$^{-1}$]</td>
<td>0.47</td>
<td>0.44</td>
<td>0.66</td>
<td>0.66</td>
<td>0.64</td>
</tr>
<tr>
<td>$\overline{u_iu_3}$ [m$^2$s$^{-2}$]</td>
<td>0.18</td>
<td>0.22</td>
<td>0.28</td>
<td>0.26</td>
<td>0.18</td>
</tr>
</tbody>
</table>

### Table 2  Mean friction velocities and mean velocities at canopy height ($h = 2.67$m) used for normalizing the PIV data.

<table>
<thead>
<tr>
<th>Height of PIV system</th>
<th>CSAT @ z/h = 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>z/h</td>
<td>$u_{CSAT}^*$</td>
</tr>
<tr>
<td>0.97</td>
<td>0.47</td>
</tr>
<tr>
<td>1.11</td>
<td>0.60</td>
</tr>
<tr>
<td>1.20</td>
<td>0.57</td>
</tr>
<tr>
<td>1.29</td>
<td>0.54</td>
</tr>
</tbody>
</table>
Table 3  Turbulence parameters calculated from the PIV data.

<table>
<thead>
<tr>
<th>z/h</th>
<th>ε</th>
<th>η [µm]</th>
<th>λ [mm]</th>
<th>$R_λ$</th>
<th>$\mathcal{L}^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.97</td>
<td>0.09</td>
<td>370</td>
<td>40</td>
<td>2.08</td>
<td>5.5</td>
</tr>
<tr>
<td>1.11</td>
<td>0.18</td>
<td>310</td>
<td>40</td>
<td>3.10</td>
<td>8.4</td>
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<tr>
<td>1.20</td>
<td>0.15</td>
<td>310</td>
<td>41</td>
<td>2.92</td>
<td>8.6</td>
</tr>
<tr>
<td>1.29</td>
<td>0.15</td>
<td>320</td>
<td>37</td>
<td>2.38</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Table 4. Convective transport of kinetic energy normalized by $u_{CSAT}^3 / h$.

<table>
<thead>
<tr>
<th>z/h</th>
<th>$U_1 \frac{\partial k}{\partial x_1}$</th>
<th>$U_3 \frac{\partial k}{\partial x_3}$</th>
<th>$U_1 \frac{\partial k}{\partial x_1} + U_3 \frac{\partial k}{\partial x_3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.97</td>
<td>2.8</td>
<td>-1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>1.11</td>
<td>4.5</td>
<td>-0.3</td>
<td>4.2</td>
</tr>
<tr>
<td>1.20</td>
<td>5.6</td>
<td>-0.2</td>
<td>5.4</td>
</tr>
<tr>
<td>1.29</td>
<td>7.5</td>
<td>-0.3</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Table 5. Dissipation rates normalized by $u_{CSAT}^3 / h$.

<table>
<thead>
<tr>
<th>z/h</th>
<th>$15 \nu \left( \frac{\partial u_i}{\partial x_i} \right)^2$</th>
<th>$7.5 \nu \left( \frac{\partial u_i}{\partial x_i} \right)^2$</th>
<th>$3 \nu \omega_z^2$</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.97</td>
<td>1.3</td>
<td>1.0</td>
<td>0.9</td>
<td>2.3</td>
</tr>
<tr>
<td>1.11</td>
<td>0.9</td>
<td>0.7</td>
<td>0.7</td>
<td>2.2</td>
</tr>
<tr>
<td>1.20</td>
<td>1.0</td>
<td>0.8</td>
<td>0.7</td>
<td>2.2</td>
</tr>
<tr>
<td>1.29</td>
<td>1.2</td>
<td>0.9</td>
<td>0.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Table 6  Production terms normalized by $u^*_c / h$.

<table>
<thead>
<tr>
<th>$z/h$</th>
<th>$-u_i u_1 \frac{\partial U_1}{\partial x_1}$</th>
<th>$-u_1 u_3 \frac{\partial U_1}{\partial x_3}$</th>
<th>$-u_3 u_1 \frac{\partial U_3}{\partial x_1}$</th>
<th>$-u_3 u_3 \frac{\partial U_3}{\partial x_3}$</th>
<th>$\sum -\overline{u_i u_j} S_{ij}$</th>
</tr>
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<tbody>
<tr>
<td>0.97</td>
<td>-2.6</td>
<td>7.5</td>
<td>0.2</td>
<td>1.3</td>
<td>6.4</td>
</tr>
<tr>
<td>1.11</td>
<td>-2.8</td>
<td>4.6</td>
<td>-0.5</td>
<td>1.9</td>
<td>3.2</td>
</tr>
<tr>
<td>1.20</td>
<td>-3.8</td>
<td>2.9</td>
<td>-0.3</td>
<td>2.3</td>
<td>1.1</td>
</tr>
<tr>
<td>1.29</td>
<td>-1.9</td>
<td>2.0</td>
<td>-0.3</td>
<td>2.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 7. Gradients of turbulent diffusion terms normalized by $u^*_c / h$.

<table>
<thead>
<tr>
<th>$z/h$</th>
<th>$\frac{\partial}{\partial x_3} \left( \frac{1}{2} \overline{u_1 u_3 u_3} \right)$</th>
<th>$\frac{\partial}{\partial x_3} \left( \frac{1}{2} \overline{u_3 u_3 u_3} \right)$</th>
<th>$\frac{\partial}{\partial x_3} \left[ \frac{1}{2} \left( \overline{u_1 u_3 u_3} + \overline{u_3 u_3 u_3} \right) \right]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.97</td>
<td>1.73</td>
<td>0.94</td>
<td>2.67</td>
</tr>
<tr>
<td>1.11</td>
<td>0.92</td>
<td>0.49</td>
<td>1.40</td>
</tr>
<tr>
<td>1.20</td>
<td>0.66</td>
<td>0.35</td>
<td>1.02</td>
</tr>
<tr>
<td>1.29</td>
<td>0.48</td>
<td>0.25</td>
<td>0.73</td>
</tr>
</tbody>
</table>
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