Spectra and Cospectra of Turbulence in an Internal Boundary Layer over a Heterogeneously Irrigated Cotton Field

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ABSTRACT

During the Energy Balance Experiment, patch-to-patch irrigation generated gradients in soil moisture in a north-south oriented cotton field. An internal boundary layer (IBL) developed as a result of strong horizontal advection from relatively dry upstream patches to relatively wet downstream patches associated with the prevailing northerly winds. This generated large eddies of multiple sizes, which had significant influences on the structure of turbulence in the IBL. The power spectra and cospectra of wind speed, temperature, humidity, and energy fluxes measured at two heights within the IBL are presented and used to investigate the influence of the IBL on surface layer turbulence. The spectra and cospectra were greatly enhanced by external disturbances at low frequencies. The peak frequencies of these disturbances did not change with height. The spectra and cospectra typically converged and were parallel to the Kansas spectrum at high frequencies (in the inertial subrange). A clear gap in the spectra of horizontal wind velocity existed at intermediate frequencies when the surface layer was stable. The results indicate that large eddies that originated in the upstream convective boundary layer had considerable impacts on the spectra and cospectra of surface layer turbulence. The influence of these large eddies was greater (1) when the IBL was well-developed in the near surface layer than when the IBL did not exist, (2) at higher levels than at lower levels, and (3) when the atmospheric surface layer (ASL) was unstable than when the ASL was stable. The length scales of these large eddies were consistent with the dominant scales of surface heterogeneity at the experiment site.

Key words: internal boundary layer, spectra, cospectra, patch-to-patch irrigation

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1. Introduction

Large eddies greatly disturb the atmospheric surface layer (ASL) and play an important role in the transport of energy and scalar fluxes between the ground and the atmosphere. Large eddies have many sources, such as surface inhomogeneities, topography, and synoptic weather systems. The contribution to eddy flux by low frequency eddies has drawn considerable scientific attention. Some studies have suggested that low frequency eddies contribute approximately 10%–20% of the total flux (Sakai et al., 2001; Kang and Davis, 2007, 2008, 2009; Zhang et al., 2010), while others have found no significant fluxes of scalars or momentum at horizontal scales greater than 10 km (Lenschow and Sun, 2007). Previous work reveals that large eddies occurring over different underlying surfaces make different contributions to surface-atmosphere exchange of momentum, heat, and scalars. Sakai et al. (2001), Vickers and Mahrt (2003), Foken (2008a), and others analyzed the importance of low frequency contributions to turbulent fluxes and energy

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balance closure; however, both the mechanism underlying large eddies and the influence of these eddies on fluxes remain unclear. The existence of large eddies is generally thought to be one of the main uncertainties in energy balance closure.

In addition to local turbulent mixing, large eddies influence the spectra of wind velocity and scalar components in the ASL. Considerable work has been done to study locally-generated turbulence using ideal turbulent structures in a quasi-stationary atmosphere over homogeneous surface conditions, resulting in the generation of empirical relationships between normalized spectra/cospectra and frequency (Kaimal et al., 1972; Wyngaard and Coté, 1972; Moraes and Epstein, 1987). However, the surface conditions at most experimental sites are not ideal, meaning that the surface layers at these sites are disturbed by large eddies. These large-eddy disturbances are included in observations of turbulence and contribute to flux estimates (Sakai et al., 2001). A number of recent experiments have investigated how boundary layer disturbances respond to a variety of surface roughness and atmospheric stability conditions (e.g., Andreas, 1987; Smeets et al., 1998; McNaughton and Laubach, 2000; Hong et al., 2004; Li et al., 2007). Most research indicates that low frequency eddies induced by topography generally enhance the observed spectra, producing complicated cospectra with unpredictable sign at low frequencies and nearly-isotropic spectra/cospectra that obey the $-5/3$ power law at high frequencies. The behaviors of the v spectrum and uw cospectrum are quite complicated. However, Hong et al. (2004) found that the v spectrum contains a spectral gap at moderate frequencies; moreover, this spectra does not obey the -1 power law as suggested earlier by Hunt and Morrison (2000), and inactive eddies at low frequencies do not affect momentum fluxes (Hong et al., 2004). Li et al. (2007) compared the inner peak frequency of the v spectrum over valley and flat terrains. Their results indicated that topography affects the inner structure of the ASL. The peak frequency of the normalized v spectrum is the same as the peak frequency of the normalized u spectrum over valley terrain, and corresponds to the height of the boundary layer (Li et al., 2007). These studies have shown that the ASL can be influenced by large eddies generated by topography, but the mechanism behind this influence is still unknown.

McNaughton and Laubach (2000), McNaughton and Brunet (2002), and McNaughton (2004) developed a theoretical framework for understanding the results described above. They noted that the spectra and cospectra in the ASL contain three separate scaling regions: inner layer scaling (ILS), outer layer scaling (OLS), and combined scaling (CS). ILS describes the parts of the spectra and cospectra that are dominated by mechanical friction at the ground surface; the spectral characteristics in this region have been defined by an experiment in Kansas, USA (Kaimal et al., 1972). The amplitude and shape of the ILS frequency range do not change with height, but the peak frequency does. The turbulence frequency scale in the OLS frequency range depends on the length scales of the large eddies in the outer layer, defined by Deardorff as the convective boundary layer (CBL). The OLS length scale is related to the height of the CBL (Z_i). The amplitude and position of the peak frequency in the OLS part of the spectra are not dependent of height, but the shape is. In the CS frequency range, both spectra and cospectra should obey the requirements of both OLS and ILS. The intensity of turbulence in the CS frequency range is independent of both height and frequency (McNaughton and Laubach, 2000).

Typical landscapes comprise surfaces with heterogeneous characteristics. Wind and temperature profiles over each surface depend on the surface roughness and surface temperature, respectively. Profiles are shifted downwind by the horizontal wind field, forming a discontinuous layer called the internal boundary layer (IBL) (Foken, 2008b). In the experiments mentioned above, the disturbances are mostly induced by topography or differences in the roughness of the surface layer. Little attention has been paid to effects of the IBL on turbulent fluxes and the spectra and cospectra of turbulence. The summer 2000 international Energy Balance EXperiment (EBEX-2000) location was flood irrigated using a patch-to-patch approach from north to south, forming an inhomogeneous surface. An IBL was detected during this experiment, probably due to contrasts in soil moisture induced by patch-to-patch irrigation. This work investigates interactions between large eddies and local turbulence by analyzing the characteristics of the spectra and cospectra of turbulence in the IBL. The results are then inspected to identify whether McNaughton's (2004) theoretical framework holds under these conditions. The influences of large eddies on turbulent fluxes are interpreted according to characteristics of the turbulence spectra and cospectra.

This research focuses on three aspects of turbulent mixing in the ABL: 1) the influences of the IBL on turbulence spectra and cospectra; 2) the relationship between surface layer stability and these influences; and 3) the height dependence of these influences.

2. Experiment

2.1 Site description

The EBEX-2000 was carried out over a flat and flood-irrigated cotton field in the San Joaquin Valley of California (36°06′N, 19°56′W). The experimental site was located in a 1600 m×800 m field about 20 km southwest of the town of Lemoore and approximately 67 m above sea level with a slight slope of 0.1 degree.

The weather during the project was clear with no recorded precipitation. The prevailing upper-level winds were steady from the north-northwest, due in part to the topography of the valley. Winds in the near-surface layer were more variable than those at upper levels.

Patch-to-patch flood irrigation from north to south was performed on the field twice during the experiment, leading to inhomogeneous distributions of soil moisture. The irrigation schedule during EBEX-2000 is given in Fig. 4 of Oncley et al. (2007). An IBL, which may have been induced by the spatial variations of surface temperature that accompanied the irrigation schedule, was observed. The mechanism underlying the formation of the IBL will be discussed later in this paper.

This experiment used an array of ten towers with 200-m spacing in the along-wind direction and a typical fetch of more than 400 m. Profiles of temperature, specific humidity, and wind were measured at nearby towers at 12 near-surface levels (up to 11 m) to provide information about horizontal advection. The EBEX-2000 proceeded in two operational periods: 18–29 July 2000 focusing on instrument inter-comparisons, and 1–24 August 2000 for formal experiment. Oncley et al. (2007) described the layout of the experimental sites and other details of the EBEX-2000.

The data used in this paper were observed at Site 7 by the City University of Hong Kong. The canopy coverage at Site 7 during the operational period was about 90%–95%, with the average canopy height assumed to be 0.9 m. The zero-displacement was taken to be 0.6 m, two-thirds of the canopy height.

2.2 Instrumentation

Site 7 contained 5 towers with 8 eddy-covariance systems at 5 levels each, and 2 profile towers with anemometers and dry/wet-bulb psychrometers at 12 levels. This study uses turbulence data at 2.7 and 8.7 m, observations of wind/temperature profiles, and soil conditions (soil temperature, soil volumetric water content, and soil heat flux). Signals from the eddy-covariance systems were sampled at a rate of 10 Hz, while signals from the cup anemometers and dry/wet-bulb psychrometers were sampled at a rate of 0.2 Hz at all levels. Table 1 lists all of the devices and the heights/depths of measurements used in this study.

Table 1. Instruments at Site 7, operated by the City University of Hong Kong

Parameter	Device (height/depth)
Wind velocity and sonic temperature	CSAT3 (2.7 m), CSAT3 (8.7 m)
Humidity	KH20 (2.7 m), KH20 (8.7 m)
Fine-wire temperature	FW05 (8.7 m)
Wind speed	Climatronics F460 (1.2, 3.7, 5.7, 7.7, and 9.7 m)
Temperature and relative humidity	Frankenberger (0.7, 1.2, 3.7, 7.7, and 9.7 m)
Soil temperature	107B (8 cm)
Soil water content	CS615 (8 cm)
Soil heat flux	HFT3.1 (8 cm)
Net radiation	REBS Q7.1 (2 m)

3. Data selection and processing

3.1 Data selection

The experiment location was flood-irrigated from north to south. The land surface of Site 7 became very wet on 2 August; however, some turbulence data was not recorded at Site 7 during the first few days of the formal experiment period. Measurements for the irrigated case were taken during 5–7 August, and measurements for the non-irrigated case were taken during 11–13 August. These two cases are compared to investigate the effects of heterogeneous irrigation on turbulence spectra and cospectra, especially in the low-frequency domain.

3.2 Data processing

3.2.1 *Calculation of spectra and cospectra*

Turbulence data were recorded at 10 Hz during 30-min runs, yielding records of 16000 data points at two vertical levels for each time segment. The Fast Fourier Transform (FFT) is used to calculate power spectra and cospectra. There were 214 (16384) data points used for every 30-min segment.

The data series are conditioned prior to the application of the FFT algorithm following several procedures commonly used in micrometeorological data analysis. First, bad data points are eliminated using a 9-point smoothing. Second, three-dimensional rotations are applied. The block averages of each individual segment are then removed, leaving turbulent fluctuations of wind velocity, temperature, and specific humidity. The series are then multiplied by a Hanning window. The effects of these procedures have been described by Kaimal and Finnigan (1994).

3.2.2 *Averaging of spectra and cospectra*

The spectra and cospectra analyzed here have been averaged over six runs. For example, the average of spectra at 1000 LT (Local Time) for the irrigated case is calculated from the six segments at 1000 and 1030 LT 5–7 August. The individual spectra and cospectra are normalized by the scaling parameters before averaging. The averaged spectra are then smoothed as follows. An overlapping block average with a width of 3 points is used for the first 20 points to reduce the erratic variability at the statistically unreliable low-frequency end (McNaughton and Laubach, 2000). The other points are averaged into nonoverlapping blocks with logarithmically increasing width (Kaimal and Finnigan, 1994). All of the spectra and cospectra series are then smoothed using 3-point averages, with the three points assigned weights of 3/11, 5/11, and 3/11, respectively.

3.2.3 *Profile data processing and flux calculations*

Profile data (such as wind speed, dry temperature and wet temperature) were collected every 5 minutes. A non-overlapping block average of six data points is therefore used to calculate the mean value for each half hour.

The net fluxes are calibrated by the observed wind. If the FW05 fine-wire temperature measurements are of good quality, data from the fast-response thermocouple are used to calculate the sensible heat flux. Otherwise, crosswind-corrected sonic temperatures are used instead (Schotanus et al., 1983). The latent heat flux is calculated using data from the KH20 (calibrated at both levels using level-specific calibration constants), and then the Webb correction is applied (Webb et al., 1980). Soil moisture is represented by the measured volumetric water content. All of these calibration methods have been described in the user manual for the Hong Kong tower data collected during the EBEX-2000.

4. Results

The general characteristics of the energy balance, statistical quantities, turbulence spectra and structure during the EBEX-2000 have been reported previously (e.g., Li et al., 2003; Liu et al., 2005, 2006a, b). Here, data collected on 5 August are taken to represent an irrigated case with an IBL, while data collected on 11 August are taken to represent a non-irrigated case without an IBL. The irrigation schedule and the durations of the wet, moist, and dry periods of the field during the experiment are summarized in Fig. 4 of Oncley et al. (2007). The patch-to-patch irrigation proceeded from north to south (roughly one patch per day with a patch size of 200–300 m), so the two patches upstream (north) of the patch where Site 7 was located were drier than Site 7 on 5 August. Moreover, the land upstream of the experiment was dry bare soil on 5 August, when Site 7 was still freshly irrigated (Oncley et al., 2007). These multiple transitions from warm/dry to cool/wet surface conditions (i.e., dry bare soil to wet cotton field; relatively drier upstream patches to relatively wet Site 7 patch) led to horizontal advection of relatively warm and dry air over the wetter patches downwind. By 11 August, Site 7 was relatively dry after several days without irrigation; accordingly, the downstream transitions from warm/dry to cool/wet were weak relative to those on 5 August.

4.1 Evidence of the IBL and its influence on heat fluxes

The dominant circulation on 5 August was anticyclonic. The prevailing winds at low levels were northeasterly and weak (∼1–3 m s^{-1}). The sky was sunny and cloudless, with a maximum net radiative flux of about 700 W m^{-2} at 1300 LT (Fig. 1). These conditions led to the existence of a well-developed convective boundary layer (CBL). The CBL was accompanied by an unstable atmospheric surface layer (ASL) in the morning, which was replaced by a stable ASL in the afternoon (after 1200 LT; Fig. 2). This transition indicates the development of a stable IBL, presumably related to the horizontal advection of relatively warm and dry air over a relatively cool and wet surface. The existence of this stable IBL hastened the appearance of the stable ASL beneath the CBL in the afternoon. On 11 August, the warm/dry to cool/wet transition was relatively weak; accordingly, a stable IBL did not develop and the stable ASL did not appear until 1700 LT (Fig. 2).

The diurnal variations of sensible heat flux (H) and latent heat flux (LE) were quite different between the irrigated and non-irrigated days, even though the net radiation changed very little (Fig. 1). LE fluctuated significantly in the daytime, with a number of local minima and maxima. The amplitudes of these LE fluctuations were larger on the irrigated day (5 August) than that on the non-irrigated day (11 August). Furthermore, these amplitudes were larger at 8.7 m than at 2.7 m. H changed sign from positive to negative at noon on the irrigated day, but this transition did not occur until 1700 LT on the non-irrigated day. H and LE were correlated with fluctuations in w, T, and q, so the differences in H and LE between the two days may be related to differences in the structure of turbulence.

4.2 Turbulence spectra and cospectra

The spectra and cospectra of turbulence associate

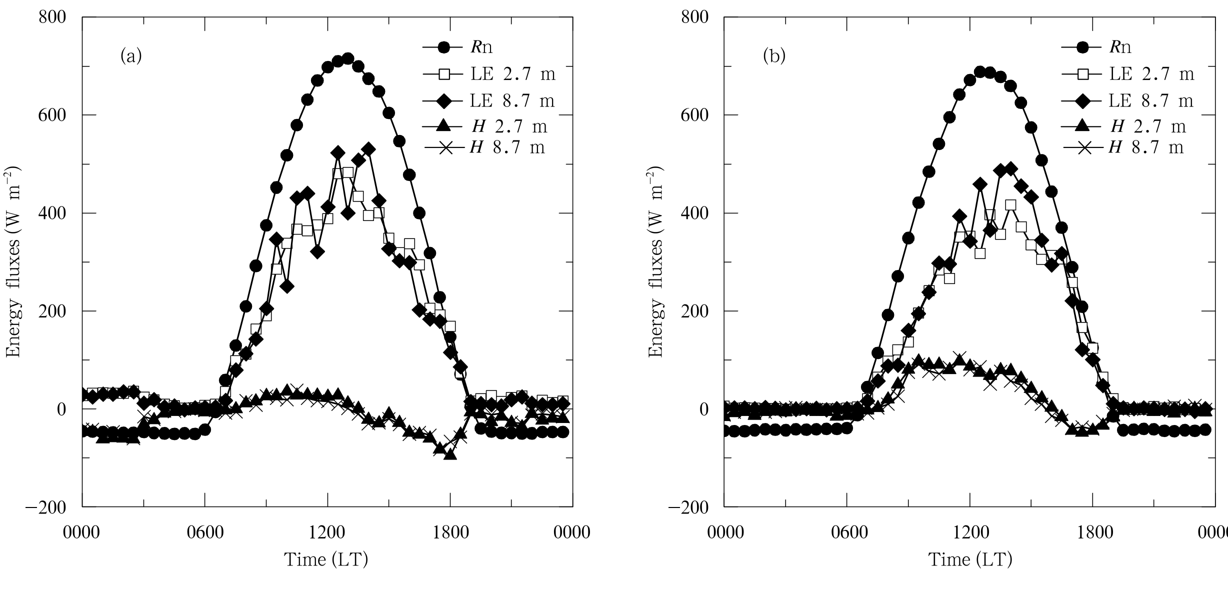

Fig. 1. Diurnal variations of energy fluxes (R_n: net radiative, H: sensible heat flux, and LE: latent heat flux) on (a) August 5 (an irrigated day) and (b) August 11 (a non-irrigated day).

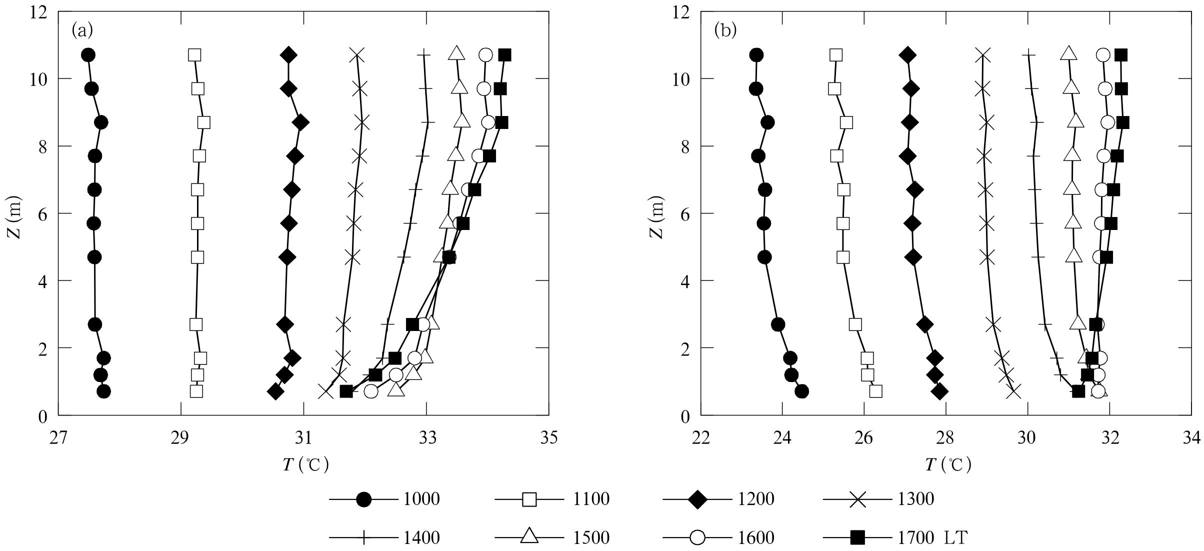

Fig. 2. Air temperature profiles at different times (LT) on (a) August 5 (the irrigated day) and (b) August 11 (the non-irrigated day).

each scale of motion with the amount of kinetic energy, variance, or eddy flux it contributes to the whole. The characteristics of the turbulence spectra and cospectra can be used to analyze the structure of turbulence and explain the behavior of H and LE. The spectra of u, v, w, T, and q and the cospectra of uw, wT and wq will be analyzed in the following paragraphs. The behavior of these spectra and cospectra at low frequencies will be studied carefully to determine the strength and scale of large eddies, and to identify interactions between large eddies and local turbulence.

Figures 3–10 show the spectra of u, v, w, T, and q, and the cospectra of uw, wT, and wq at the two levels (2.7 and 8.7 m) on irrigated and non-irrigated days. Data at 1000, 1200, 1400, and 1700 LT are used to represent four different stability regimes (unstable, weakly unstable, near-neutral, and weakly stable). Each group contains six data series (each representing a 30-min segment) for irrigated days (5–7 August) and six data series for non-irrigated days (11–13 August). The horizontal coordinate in Figs. 3–10 is natural frequency; the vertical coordinate is the normalized spectrum/cospectrum. The spectra and cospectra under stationary conditions (Kaimal et al., 1972; Andreas, 1987) are presented for comparison to evaluate the applicability of the −2/3 power law and local isotropy in the inertial subrange. The empirical functions for the normalized spectra and cospectra are given as follows.

$$\frac{nS_u(n)}{u_*^2}=\frac{102n}{(1+33n)^{5/3}}, \tag{1}$$

$$\frac{nS_v(n)}{u_*^2}=\frac{17n}{(1+9.5n)^{5/3}}, \tag{2}$$

$$\frac{nS_T(n)}{u_*^2}=\frac{2.1n}{(1+5.3n^{5/3})}, \tag{3}$$

$$\frac{nS_T(n)}{T_*^2}=\frac{34.8n}{(1+24n)^{5/3}},\ n\leqslant 0.15; \tag{4}$$

$$\frac{nS_T(n)}{T_*^2}=\frac{15.9n}{(1+12.5n)^{5/3}},\ n>0.15, \tag{5}$$

$$\frac{-nC_{uw}}{u_*^2}=\frac{12n}{(1+9.6n)^{7/3}}, \tag{6}$$

$$\frac{-nC_{wT}}{u_*T_*}=\frac{11n}{(1+13.3)^{7/4}},\ n\leqslant 1.0; \tag{7}$$

$$\frac{-nC_{wT}}{u_*T_*}=\frac{4n}{(1+3.8n)^{7/3}},\ n>1.0. \tag{8}$$

Equations (4) and (5) apply to the spectra of both T and q. Equations (7) and (8) apply to the cospectra of both wT and wq.

4.2.1 *Horizontal wind velocity spectra*

Figure 3 presents the power spectra of the zonal component of wind speed at 2.7 and 8.7 m on irrigated and non-irrigated days. Figure 4 presents the corresponding power spectra of the meridional component of wind speed.

4.2.1.1 *Zonal wind spectra*

Figure 3 provides the general characteristics of the u spectrum. The power spectra of u are much larger than the Kansas spectra at low frequencies. The substantial variance in this region reflects disturbance of the surface layer by large eddies. The peak frequencies at both vertical levels occur at the same true frequency (see also Table 2), indicating that the large eddies passing through these two levels have the same length scales. This result is consistent with the OLS theory: frequency scale depends on the turbulent length scale and the velocity scales that characterize motion in the outer layer, and does not change with height. The u spectra converge and are approximately parallel to the Kansas spectra at high frequencies, in the inertial subrange. This result suggests that the u spectra obey ILS at high frequencies. The separation between OLS and ILS is not notable at moderate frequencies except in the stable case. This result reveals that the differences between OLS and ILS in the scales of turbulence affecting the zonal wind speed are relatively indistinct. The two scalings combine well during daytime when

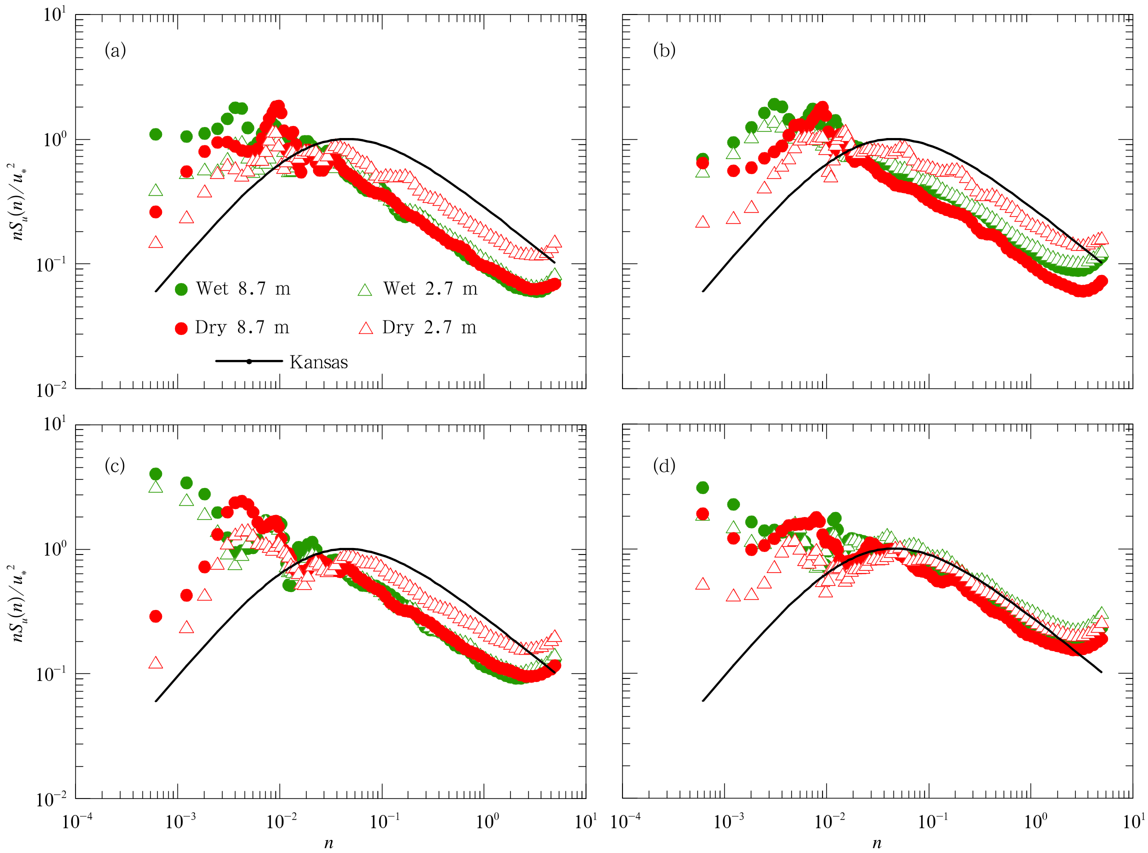

Fig. 3. The u spectra versus natural frequency for the irrigated case (5–7 August) and the non-irrigated case (11–13 August) on two levels (2.7 and 8.7 m) at (a) 1000, (b) 1200, (c) 1400, and (d) 1700 LT.

Table 2. Dominant peak frequency of the u spectra at low frequencies

Case	Height	Unstable		Weak unstable		Neutral		Weak stable	
		$f1$	$f2$	$f1$	$f2$	$f1$	$f2$	$f1$	$f2$
Wet	8.7 m	0.0037	0.0085	0.0031	0.0073	—	0.0073	0.0049	0.0122
	2.7 m	0.0043	0.0092	0.0031	0.0061	—	0.0073	0.0049	0.0116
Dry	8.7 m	0.0031	0.0098	0.0055	0.0092	0.0043	0.0091	—	0.0079
	2.7 m	0.0031	0.0085	0.0061	0.0085	0.0049	0.0098	0.0049	0.0079

"—" indicates that a peak does not appear or is not evident.

the surface layer is unstable, so no gaps appear in the spectrum at moderate frequencies.

The main characteristics of the u spectra in this experiment are similar to the results reported by McNaughton and Laubach (2000) and Hong et al. (2004), but differ from those reported by Li et al. (2007). Here, no clear spectral gaps appear in the u spectra in unstable cases, whereas spectral gaps are apparent in the spectra calculated by Li et al. (2007). The length scales of the topographically induced outer layer eddies are much larger in their experiment than in this one. The frequency differences between OLS and ILS are therefore greater in their experiment, resulting in less merging of OLS and ILS eddies and the appearance of a spectral gap at moderate frequencies.

Comparison of the spectra for the irrigated case (marked as "Wet" in Fig. 3) and the non-irrigated case (marked as "Dry" in Fig. 3) shows that the development of the IBL is associated with greater power at low frequencies. This result indicates that the existence of the IBL corresponds to a greater number of large eddies in the surface layer. The power spectra of u do not change significantly in the OLS region as the stability of the surface layer increases, but the energy contained in the inertial subrange increases substantially. The u spectra show substantial variance at low frequencies in all cases, reflecting the disturbances caused by large eddies. This effect is greater at 8.7 m than at 2.7 m.

4.2.1.2 *Meridional wind spectra*

Figure 4 shows that the v spectra can also be decomposed into three frequency ranges. Just like the u spectra, the v spectra are convergent and parallel to the Kansas spectra at high frequencies. This result demonstrates that the v spectra also obey ILS at high frequencies. The v power spectra are also enhanced at low frequencies due to disturbances from the outer layer. Under unstable or near-neutral conditions, the power spectra generally peak twice at low frequencies then decrease as the frequency increases. Under stable

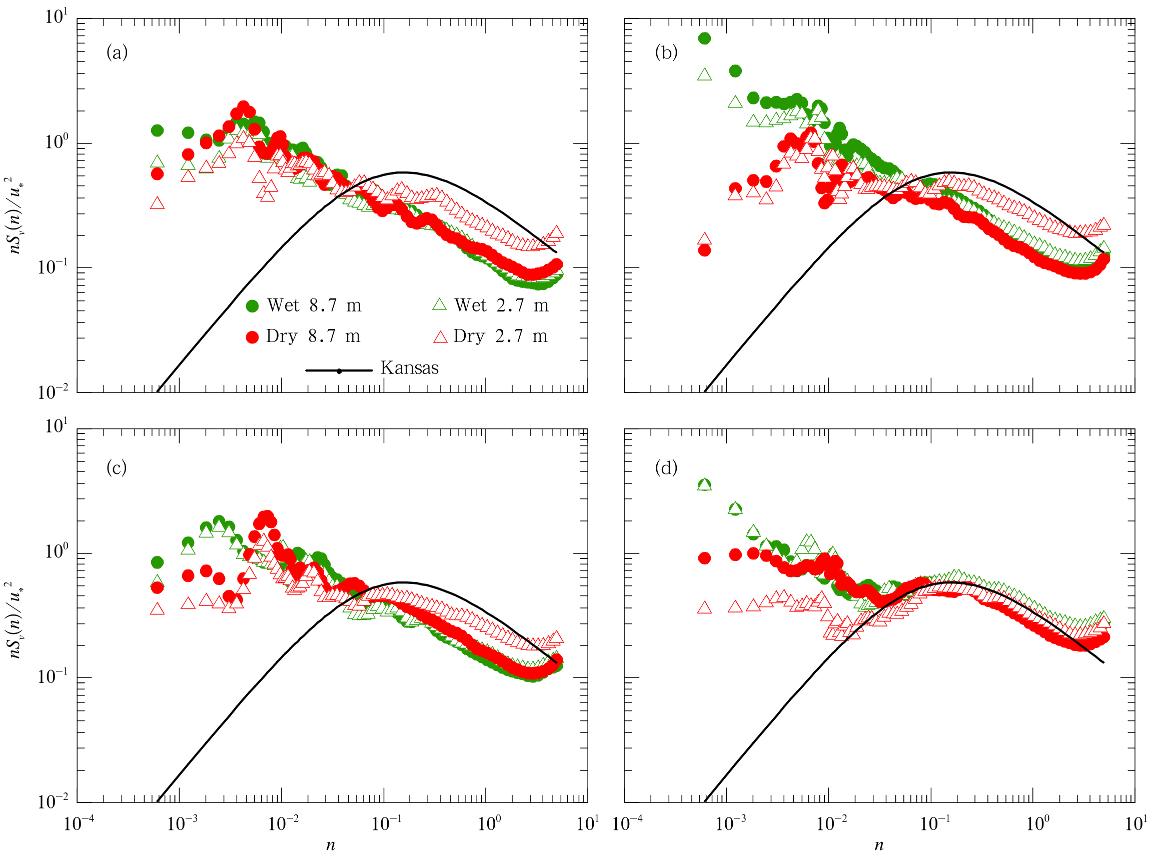

Fig. 4. As in Fig. 3, but for the v spectra.

conditions, the v power spectrum contains double peaks at both high and low frequencies, with a distinct minimum at intermediate frequencies. This feature has been described as a spectral gap, and is characteristic of spectra in a disturbed surface layer (McNaughton and Laubach, 2000). This phenomenon is inconsistent with Monin-Obukhov similarity theory. McNaughton and Laubach (2000) obtained similar results over a paddy field when the surface was stable. These spectral gaps may demonstrate a distinguishable scale separation between the active local turbulence in the inner layer and the inactive turbulence in the outer layer. This would occur if the large-eddy length scales were much larger than the local turbulence length scales. The two would then merge less at moderate frequencies, producing clear spectral gaps.

The v spectra contain broader spectral gaps than the u spectra, especially under stable conditions. OLS motions travel faster than ILS structures in the zonal direction due to the influence of horizontal advection (McNaughton and Brunet, 2002). Similar results have been obtained by Hong et al. (2004) and Li et al. (2007).

The spectra of v are greatly enhanced at low frequencies for irrigated days with a well-developed IBL. Moreover, the IBL-related enhancement of the v spectra is greater at 8.7 m than at 2.7 m and decreases with the increase of surface layer stability. These features are similar to those of the u spectra.

4.2.2 *Vertical velocity spectra*

The w spectra (Fig. 5) are similar to those obtained during the Kansas experiment, but with greater power at low frequencies. The w spectra are also broader throughout the frequency range, especially under unstable conditions, with spectral peaks in the range n = 0.1–0.5. The low frequency variability of vertical wind is enhanced in these spectra relative to those obtained during the Kansas experiment. This enhancement has previously been observed during other experiments conducted under disturbed conditions (Smeets et al., 1998; Andreas, 1987; McNaughton and Laubach, 2000). Högstrom (1990) also

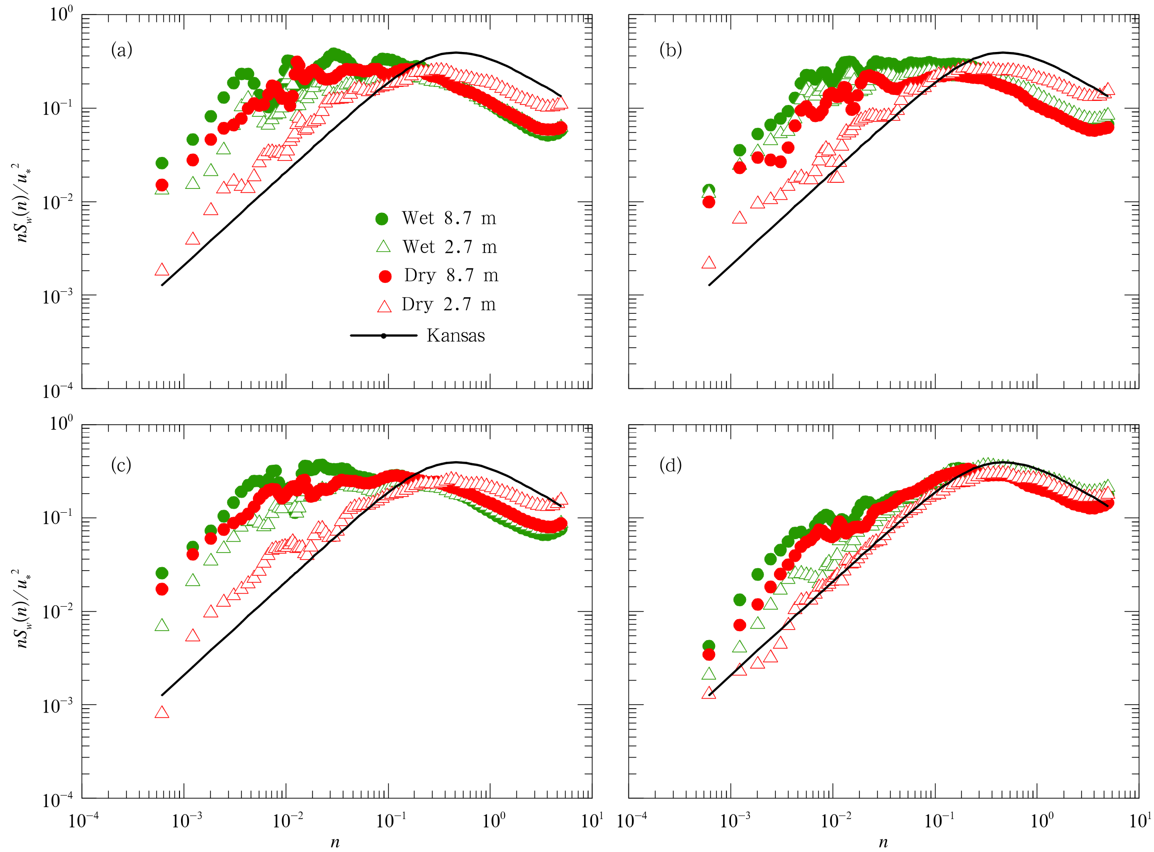

Fig. 5. As in Fig. 3, but for the w spectra.

noted a similar effect in a study conducted over less-disturbed agricultural land. He concluded that the additional variance was attributable to inactive turbulence, and he also provided a number of interesting lines of evidence to support this conclusion. Here, the additional turbulence is treated using OLS with height dependence as the distinguishing feature (McNaughton and Laubach, 2000).

Peltier et al. (1996) also reported an enhancement in the w spectrum at low frequencies. They proposed that the variations in vertical velocity could be produced by the convergence and divergence of the dominant horizontal motions near the ground. Continuity demands spectral energy transfer from horizontal to vertical motion. The total energy involved in this transfer is small, so it can be identified in w spectra but is imperceptible in u and v spectra. This indicates that vertical motion is related to the coherence of updrafts and downdrafts. The w spectra contain greater height dependence at low frequencies than the u and v spectra. This feature is consistent with the OLS theory as proposed by McNaughton and Laubach (2000). The skewness of w decreases significantly and even turns negative with the development of the IBL (Table 3). This change implies a weakening in the prevailing narrow updrafts, and is more apparent at

Table 3. Skewness of w in the irrigated and non-irrigated cases

Height	Date	Time (LT)							
		1000	1030	1200	1230	1400	1430	1700	1730
8.7 m	August 7	0.50	0.48	0.25	–0.05	0.35	0.14	0.05	0.25
	August 11	0.36	0.32	0.49	0.54	0.31	0.34	0.07	0.09
2.7 m	August 7	0.30	0.46	0.31	0.24	0.31	0.35	0.07	0.01
	August 11	0.19	0.15	0.33	0.26	0.15	0.24	0.03	0.15

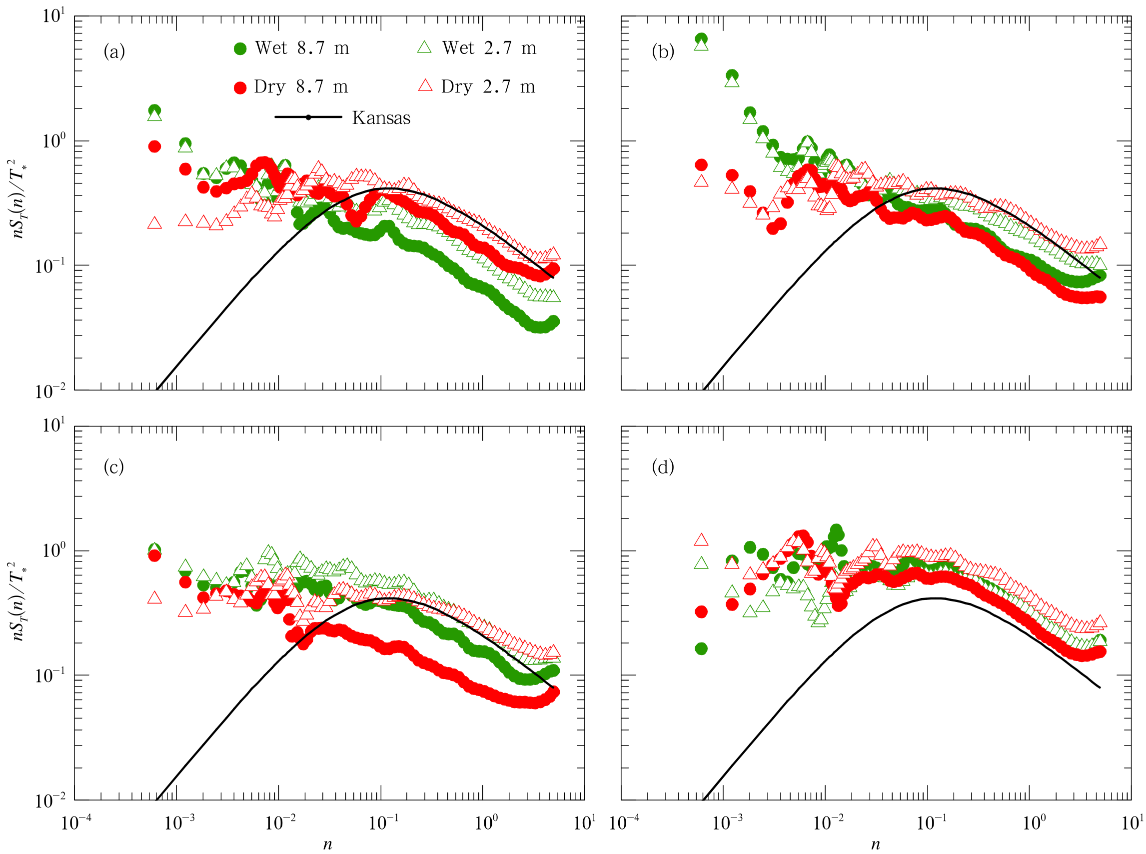

Fig. 6. As in Fig. 3, but for the T spectra.

8.7 m than at 2.7 m. This is consistent with the hypothesis that OLS motions enter the IBL from above, thereby affecting the structure of turbulence at 8.7 m more than at 2.7 m.

The power spectra of w in the OLS frequency range decrease as the stability of the ASL increases from unstable to weakly stable, revealing that the power of the large eddies induced by the IBL decreases with increasing stability. The ILS part of the w spectra corresponds more closely to the Kansas spectrum under the more stable nighttime conditions, when large eddies are suppressed and locally generated turbulence is dominant (e.g., the non-irrigated case at 2.7 m as shown in Fig. 3d).

4.2.3 *Temperature spectra*

Figure 6 shows the spectra of surface air temperature. The T power spectra decrease gradually with increasing frequency when the surface layer is unstable, with no obvious peaks in power. Under unstable and near neutral conditions, the power of the T spectrum in the inertial subrange is larger at 2.7 m than at 8.7 m. This result indicates that the small-length-scale turbulent eddies are induced by the ground surface. Spectral gaps appear at intermediate frequencies under unstable conditions, but these gaps are not as pronounced as the gaps in the v spectra.

4.2.4 *Humidity spectra*

The q spectra (Fig. 7) contain some interesting features. The humidity spectra contain more energy at low frequencies than predicted by the Kansas experiment, even under stable conditions. This excess energy is presumably induced by the effect of large-scale velocity fluctuations on the scalar field. The q spectra are smaller than the Kansas experiment spectrum in the inertial subrange under unstable and near-neutral conditions, but are larger than and parallel to the Kansas spectrum under stable conditions. The shapes of the spectra of the two scalars (T and q) are dissimilar, especially at intermediate frequencies. The q spectra at 2.7 m are larger than those at 8.7 m,

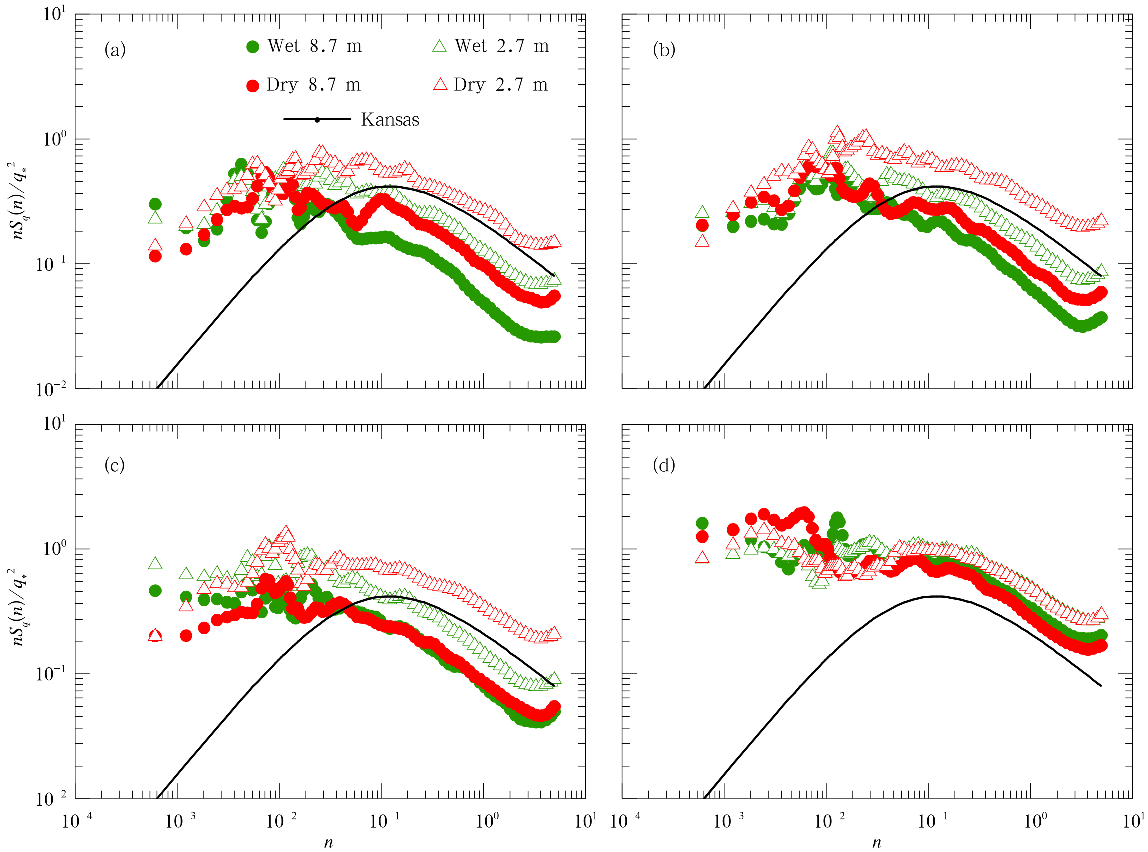

Fig. 7. As in Fig. 3, but for the q spectra.

indicating that humidity fluctuations are generated by the ground surface.

4.2.5 *Momentum cospectra*

The power of the *uw* cospectra at low frequencies is much larger than that obtained during the Kansas experiment (Fig. 8). This enhancement of energy at low frequencies is due to large eddies induced by the coherence of the zonal and vertical wind components. The normalized momentum cospectra converge and parallel the Kansas experiment spectrum in the inertial subrange. This behavior demonstrates that the *uw* cospectra obey ILS at high frequencies.

4.2.6 *Heat flux cospectra*

The *wT* and *wq* cospectra vary in similar ways (Figs. 9 and 10). When the stratification of the surface layer is unstable or near-neutral, the *wT* and *wq* cospectra contain much more energy at low frequencies than predicted by the Kansas experiment, but much less energy at high frequencies than predicted by the Kansas experiment. The results coincide well with those of the Kansas experiment when the surface layer is stable, but with significant fluctuations at low frequencies. These fluctuations can be attributed to the effects of large eddies, as mentioned above. The power of the *wT* and *wq* cospectra at 1700 LT decreases substantially at frequencies greater than $n \approx 0.01$ Hz at both levels on irrigated days and at the 2.7-m level on non-irrigated days. The *wT* and *wq* cospectra at 2.7 m are flatter than those at 8.7 m under unstable and near-neutral conditions because local turbulence (which operates on small scales) is much more active at 2.7 m. The differences in scale between local turbulence and large scale motions are therefore much more significant at 2.7 m, resulting in a much wider intermediate frequency regime. The top-down eddies from the outer layer cannot penetrate downward to the surface as well when the surface layer is stable, so the structure of turbulence at 2.7 m is affected less substantially by large eddies. The interaction between large eddies and local turbulence is consequently weaker at 2.7 m

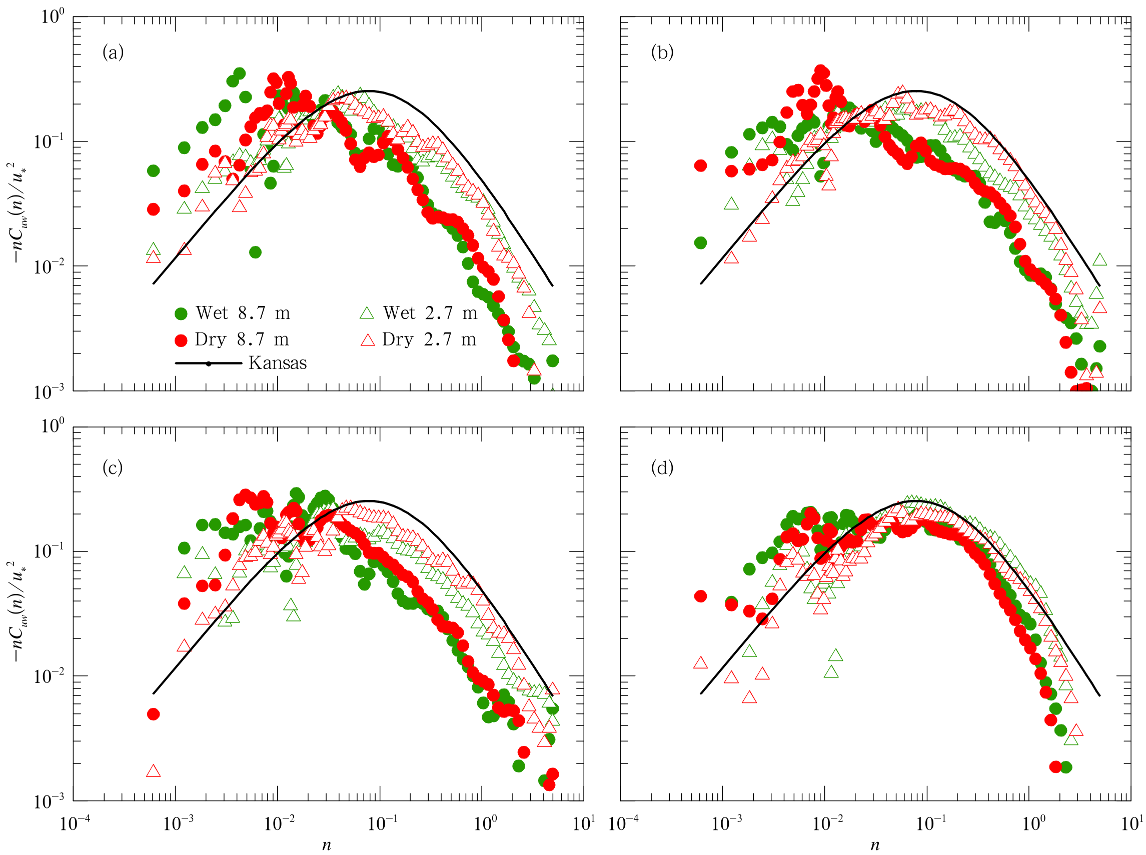

Fig. 8. As in Fig. 3, but for the *uw* cospectra.

than at 8.7 m. The characteristics of the wT and wq cospectra at 2.7 m are accordingly dominated by local turbulence; thus, the spectral gaps at intermediate frequencies are much more pronounced than those in the cospectra at 8.7 m (Figs. 9d and 10d).

The relationship between the dominant scale of large eddies and the dominant scale of heterogeneity is explored by identifying the minima and maxima of the spectra and cospectra. Large-scale motions at 1000 LT occur at three dominant frequencies: 0.005, 0.01, and 0.015 Hz. The mean wind speed during this time is approximately 3 m s^{-1}, so the corresponding large eddy length scales are approximately 600, 300, and 200 m. The 600-m eddies are induced by horizontal advection from the bare soil upstream of the experiment site. The eddies at the other two length scales are induced by the development of the IBL caused by patch-to-patch irrigation. The length scales of these eddies are consistent with the dominant scales of surface heterogeneity at the experiment site.

The differences in the behavior of the spectra and cospectra at different levels and above different surface conditions also provide interesting results. For example, the q spectra at 8.7 m have maxima at 0.01 Hz on irrigated days but minima at this frequency on non-irrigated days. This result demonstrates the substantial enhancement of the spectra and cospectra at this frequency due to the existence of large eddies with an approximate 300-m length scale on irrigated days. Turbulence is affected by large eddies at other scales on non-irrigated days, eliminating the peak at this frequency. The maxima in the spectra and cospectra are much sharper at 8.7 m than at 2.7 m, indicating greater interaction between inactive OLS motions and active ILS turbulence at 8.7 m than at 2.7 m. Comparison of the dominant peak frequencies at the two levels indicates that the peak frequencies at 2.7 m are slightly larger than the peak frequencies at 8.7 m. Analysis of the strengths and length scales of eddies at the two vertical levels therefore suggests that outer

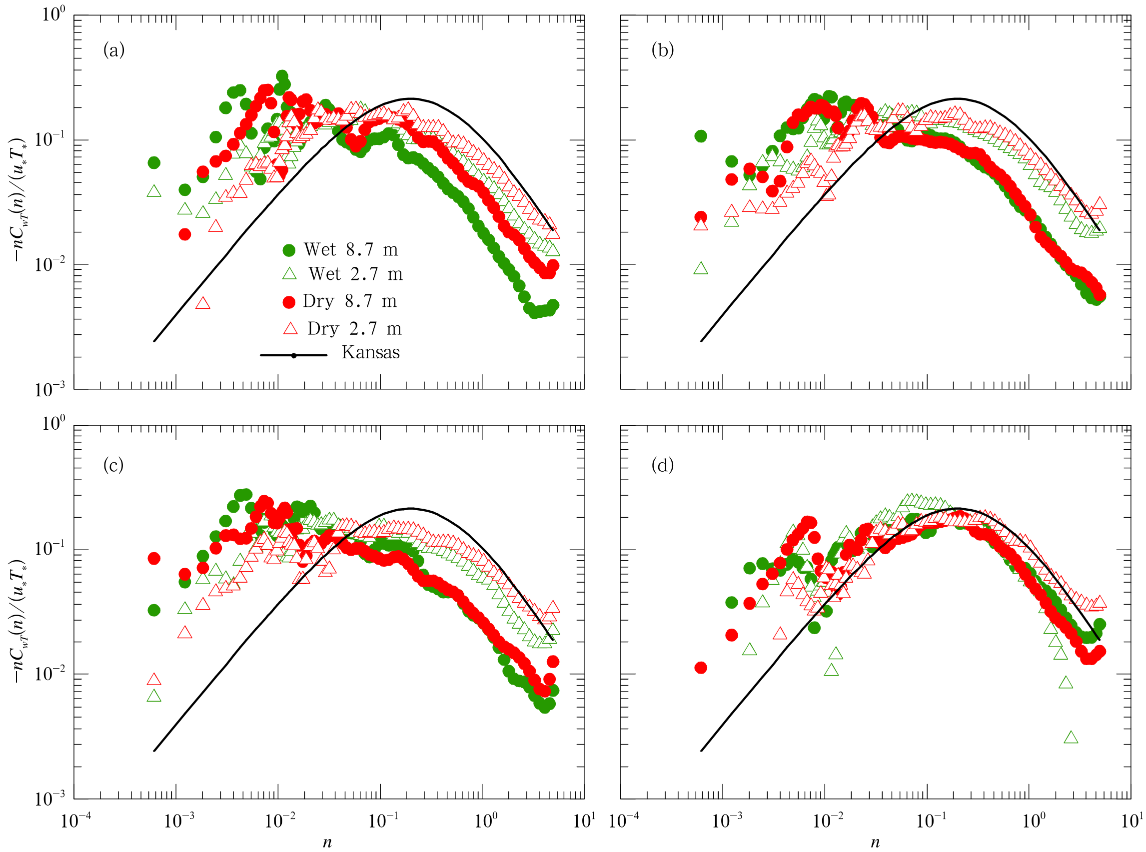

Fig. 9. As in Fig. 3, but for the wT cospectra.

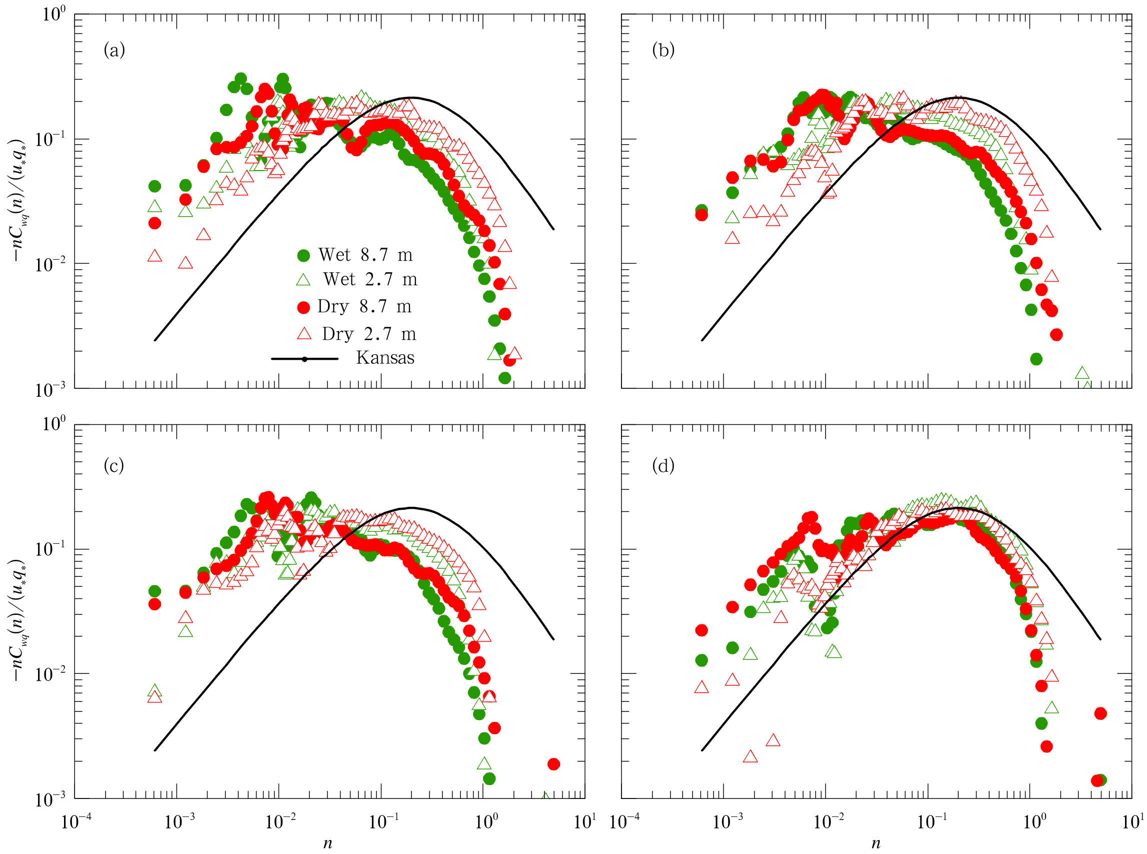

Fig. 10. As in Fig. 3, but for the wq cospectra.

layer eddies propagate downward through the IBL and interact with local turbulence. These large eddies from the outer layer gradually break up into smaller eddies during this interaction process.

5. Summary

The power spectra of wind velocity, temperature, and humidity, and the cospectra of momentum flux and heat flux at EBEX-2000 Site 7 during daytime have been analyzed. The influence of the development of an IBL on the structure of turbulence in the ASL has been examined by comparing an irrigated case (with a well-developed IBL) and a non-irrigated case (with no IBL). This work identifies several features of the structure of turbulence in the presence of an IBL that deserve further discussion.

Spectra and cospectra can be decomposed into three components according to their dependence on frequency and height. Spectral power at low frequencies is associated with external disturbances. The frequencies of peak power in this spectral regime are independent of height, but their amplitudes vary with height. These features are consistent with OLS. The power spectra of wind velocity for the irrigated case with a well-developed IBL are greatly enhanced by OLS motions, reflecting the importance of external disturbances under these conditions. The spectra and cospectra for the irrigated and non-irrigated cases tend to converge and run parallel to the Kansas spectrum in the high frequency inertial subrange, indicating the importance of ILS turbulence in this spectral regime. The spectra and cospectra are not independent in either the frequency or height domain in the intermediate frequency regime. They typically fluctuate in the frequency domain under most unstable and near-neutral conditions, and often contain a "spectral gap" in this frequency range under stable conditions. These results do not provide enough evidence to determine whether these spectra obey CS. The interactions between large-scale motions and local turbulence in the ASL require further investigation.

The behavior of the w spectra indicates that the power of OLS motions decreases as the stability of the surface layer increases from unstable to weakly stable, suggesting that the net influence of large eddies induced by the IBL also decreases. The ILS turbulence also matches the Kansas spectrum better when conditions are more stable, i.e., large eddies are suppressed and locally generated turbulence is dominant.

The different behaviors of the spectra and cospectra in the low and intermediate frequency regimes reveal that the power of turbulent fluctuations in wind velocity, scalars, and energy fluxes is affected by OLS motions more strongly at 8.7 m than at 2.7 m. This result suggests that OLS motions descend from above the surface layer to interact with local turbulence, and should be investigated further.

Three dominant frequencies of OLS motions are detected in the power spectra at 0.005, 0.01, and 0.015 Hz. The length scales of these motions are consistent with the dominant scales of surface heterogeneity at the experiment site.

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