GEOFIZIKA VOL. 29 2012

Preliminary communication
UDC 551.551.6

Determining a turbulence averaging time scale by Fourier analysis for the nocturnal boundary layer

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Received 23 January 2012, in final form 22 June 2012

Atmospheric boundary layer motions are statistically non-stationary, and therefore, it is necessary to transform them into statistically stationary (statistical properties do not change in time) time series. This transformation is performed by the mean removal process, which defines an integral time scale for turbulent fluctuations. The present study compares two methods for estimating physically relevant time scale in a stable, wintertime nocturnal boundary layer. This time scale is used to remove the unsteady mean component of the instantaneous time signal for any meteorological variable. In this way, turbulent fluxes that appear statistically stationary can be yield. The first method employs the Fourier analysis in order to remove the contamination by mesoscale motions in calculation of eddy correlation flux. The second method used for determining a relevant turbulence avenging time scale represents a cumulative integral of the kinematic heat flux or momentum flux cospectrum: the ogive method. The time scale is evaluated using three-dimensional sonic anemometry data acquired at five levels of a meteorological mast (20, 32, 40, 55 and 62 m a.g.l.) located in the industrial part of Kutina, a town in Croatia. The results indicate the existence of the spectral gap scale in the spectrum of streamwise velocity component at all levels except at 32 m. This gap scale can be found for periods between 30 and 7 min for 20 m level and between 22 and 7 min at other levels. The time scale estimated by the second method is based on the location of the local maximum value of the ogive function of the kinematic heat flux and momentum flux cospectra. The ogive method gives time scales that define the high-frequency end of the spectral gap.

Keywords: stable boundary layer, integral time scale, spectral gap, ogive function

1. Introduction

The application of the eddy covariance method requires the separation of the instantaneous signal into the mean and fluctuating parts (e.g., Metzger and Holmes, 2007; Večenaj et al., 2011; 2012). The concept of this decomposition has existed for over a century and was illustrated by Osborne Reynolds in, what is now considered, his classic paper (Reynolds, 1895). One of the key features of this approach is the averaging, which defines the mean, variance and covariance and consequently simplifies the governing equations of turbulent flow (Stull, 1988). The implicit assumption that allows us to separate the flow field into mean and fluctuating parts is that of the mesoscale spectral gap (e.g., Večenaj et al., 2012). Van der Hoven (1957) was the first to observe the evidence of this gap in the horizontal wind speed spectrum. In his study, a separation of scales was evident due to the appearance of a large spectral gap that contained very low energy between microscale and synoptic scale peaks. Many numerical atmospheric models use grid spacing that falls within the spectral gap, which means that large-scale motions can be resolved, while the small-scale features, such as covariances of momentum, sensible heat, moisture and concentration, are parameterized in order to close the Reynolds averaged equations (Stull, 1988). The application of the Reynolds decomposition requires that non-stationary atmospheric motions be transformed into statistically stationary time series. Turbulent motions are unsteady by definition (Agrawal, 1997). However, a turbulent flow can be statistically stationary. According to Pope (2000), random field $U(x, t)$ is statistically stationary if all statistics are invariant under a shift in time; in other words, the statistical properties do not change in time. The transformation into statistically stationary time series can be performed using a mean removal process or filter. A mean removal process determines the integral time scale for turbulent time series, τ. It is important, however, to make a distinction between the averaging time T, which is required for the convergence of statistical moments (Lumley and Panofsky, 1964; Sreenivasan et al., 1978; Lenschow et al. 1994), and the time scale τ. We require that the averaging time is much longer than the period of fluctuations in the original time series, $\tau / T << 1$ (Kristensen, 1998). In statistically stationary processes, $T \equiv \tau$ (e.g., turbulence generated in laboratory experiment); however, for non-stationary processes, τ represents the time scale of the slowest energetic motions with T representing the averaging time that governs the convergence of variance (Metzger and Holmes, 2008). In experiments performed during the past several decades, time periods between 10 and 60 min were usually used as the averaging interval τ over which to calculate means and products regardless of stability, turbulence levels or other factors (Oncley et al., 1996). Based on the results from 1968 Kansas data, Wyngaard (1973) showed that the averaging time increases with the order of the moment of the statistic and with increasing instability. For example, for Reynolds stress components $\overline{u'w'}$ and $\overline{v'w'}$, τ was predicted to be on the order of hours for unstable conditions and to be larger than times for scalar covariances and other lower order statistics. A multitude of papers on methods describing techniques for the mean removal operation, such as temporal filtering (Moore, 1986; McMillen, 1988), linear detrending (Stull, 1988; Kaimal and Finigan, 1994) or sliding windows (Rannik and Vesala, 1999; Sakai et al., 2001; Večenaj et al., 2010) can be found. Each of these methods, however, requires a specification of the integral time scale to define the “mean” quantity. Vickers and Mahrt (2003) propose a multiresolution flux decomposition method for selecting an appropriate time scale for the mean removal process during stable and near-neutral conditions. It has been shown that different integral time scales should be used for different conditions of atmospheric stability. For example, Sozzi and Favaron (1997) found that good averaging time under convective conditions is 30–60 min, while Metzger and Holmes (2008) found that for the same conditions over Utah’s western desert, an appropriate mean removal time scale is between 20 and 27 min. Vickers and Mahrt (2003) show that the average time scale increases with instability because of large convective eddies and decreases with increasing stability due to the suppression of large eddies by stratification. They found an average time scale of 9 min for neutral conditions, which decreases sharply with increasing stability to 100 s for strong stability. Many studies indicate that an appropriate integral time scale is highly site specific and therefore should be calculated locally.

The present study describes the application of two methods based on a Fourier analysis to estimate characteristic time scales in stable, wintertime, nighttime ground-based layer. In Section 2 of this paper, we describe the measuring site and data, while Section 3 provides an overview of the methods used. In Section 4, the results of applied methods are described, and Section 5 summarizes our conclusions.

2. Measuring site, instrumentation and measurement time interval

Kutina is a small city in a continental part of Croatia, located at the southern slopes of the afforested Moslavačka Mountain whose highest peak Humka stands at 489 m a.g.l. Lonja Field is located South of Kutina, which is the largest protected wetland in both Croatia and the entire Danube basin. The measurement site is located above a grassy surface, surrounded by approximately 20 m high trees. The closest trees are approximately 20–30 m far from the measurement mast and encompass an area of approximately 100 × 400 m^2 (Fig. 1). From Fig. 1, it is obvious that the mast is situated in a rather heterogeneous surrounding. To the east, low crop fields can be found, while a large petrochemical industry plant is situated south-southeast of the mast. The city center and main residential area are located westward of the mast. In a sector that encounters NNW to NE wind directions, low, forested hills are located. This is a dense forest of beech, sessile oak, hornbeam, chestnut, black alder and birch, and in the lower regions, there are cultivated orchards and vineyards.

Turbulence measurements were performed using five ultrasonic anemometers (WindMaster Pro, Gill Instruments) placed on a 62 m high tower. Instruments were mounted 2 m away from the triangular lattice tower to minimize any flow distortion effect by the tower. Three-dimensional wind and sonic temperature data were measured at five levels above the canopy layer, namely at

Figure 1. Satellite view of Kutina. The size of the shown area is 12.7 km in horizontal and 6.8 km in vertical. The red balloon indicates the position of our measurement mast (source: Google Earth).

20, 32, 40, 55 and 62 m above the ground, with a sampling frequency of 20 Hz (Fig. 2). All raw data were stored via serial ports on a PC. The accuracy of the data is given by the manufacturer with < 1.5% RMS at 12 m s^{-1} for wind speed.

Figure 2. Closer (*left*) and distant (*right*) view of the mast. Ultrasonic anemometers are mounted at 12, 20, 32, 40, 55 and 62 m a.g.l.

In this study, the data collected during the 4-h period of the wintertime, nocturnal boundary layer (22 December 2008 from 00 to 04 LST) are analyzed. Fig. 3 shows synoptic conditions represented by surface air pressure distribution on 22 December 2008 at 00 UTC. The pressure chart indicates the existence of high-pressure fields over Croatia with very weak pressure gradients. These conditions were favorable for the establishment of a stable boundary layer with light winds in the city of Kutina.

In order to better understand the nature of turbulence during the investigated period, we calculated simple index of the flux intermittency as in Mahrt et al. (1998) for all five heights. In all cases we obtained values greater than 1, which implies that the turbulence during investigated time interval was substantially intermittent.

Figure 4 shows a coordinate system fixed to the sonics used in this study. For the whole time interval and for each height, the data are rotated into a right-handed Cartesian coordinate system with the x-axis aligned with the mean wind ($\overline{u_x}$), while the mean lateral and vertical wind components ($\overline{u_y}$, $\overline{u_z}$) are zero. The coordinate system is rotated into the along-wind direction because the longitudinal direction should necessarily be defined along the mean (streamwise) flow in the case of in-situ ground measurements, where Taylor's hypothesis has to be applied to make the transformations from time to space domain (e.g., Stull, 1988;

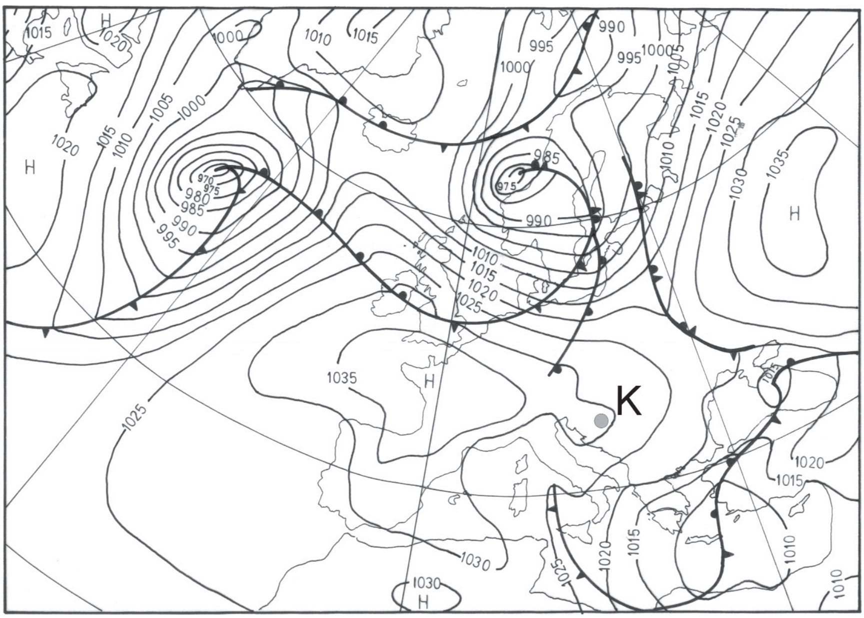

Figure 3. Synoptic conditions on 22 December 2008 at 00 UTC represented by surface pressure distribution (Deutscher Wetterdienst). Position of Kutina (K) is indicated by a gray circle.

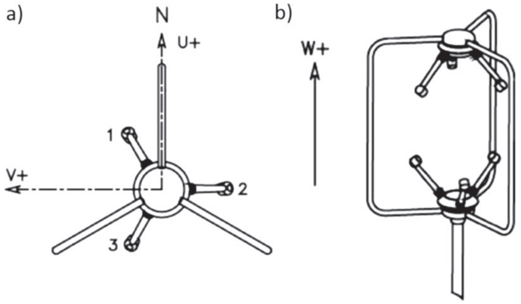

Figure 4. (a) Illustration of the WindMaster Pro sonic anemometer showing the coordinate system used in this study (top view) where the *x*-axis was aligned parallel to true north-south. Velocity components u_y and u_z were aligned with the true east-west and vertical, respectively. Numbers 1, 2 and 3 indicate the positions of anemometer sensors. (b) Position of ultrasonic anemometer on a boom, with the direction of vertical wind component is indicated.

Oncley et al., 1996; Piper and Lundquist, 2004; Večenaj et al., 2010; 2011). In the analysis, raw sonic data are utilized, and pre-processing involved quality checks. Quality control criteria based on objective and subjective methods indicated the need for reducing the sampling rate due to the instrument's resolution. Therefore, four consecutive data points were block averaged and a 5-Hz database was constructed. A portion of sonic temperature data at 62 m was also removed due to unrealistic spikes that occurred after 03 LST.

3. Methods

To analyze the surface-layer turbulence, the concept of Reynolds averaging is used. Reynolds averages are ensemble averages that can be applied only to statistically stationary processes. Because atmospheric observations are inherently non-stationary (in a statistical sense), they must be transformed into time series that are statistically stationary so that one may apply Reynolds decomposition. Single point measurements in space are functions of time; hence, we must assume an ergodic hypothesis and replace ensemble averages with time averages. This action guarantees that the mean of fluctuating components remains zero, while it does not change the mean value for any given variable. The assumption of stationarity is never fulfilled because all meteorological variables show a diurnal cycle. Quasi-stationary conditions can be achieved, however, by choosing an appropriate averaging interval. For a given time series for any variable $x(t)$ we write:

$$x(t) = \bar{x}(t) + x'(t). \tag{1}$$

In this way, we separate the slow varying, "passive" large scale fluctuations in $x(t)$, which we write as $\bar{x}(t)$, from the rapid, "active" turbulent variations, $x'(t)$, about $\bar{x}(t)$. The time average is defined as follows:

$$\overline{x(t)} = \bar{x} = \frac{1}{\tau}\int_0^{\tau} x(t)dt \ . \tag{2}$$

We than remove this mean in the period τ, which represents the sliding average size, to define the turbulent perturbation.

This averaging interval can be derived from the spectrum of atmospheric motions, which often show a gap between periods of 20 min to 1 hour (e.g., Van Gorsel, 2003). According to Kaimal and Finnigan (1994), 1-h period is as long as we can extend the averaging period without accounting for the nonstationarity in the form of diurnal, i.e., large scale, variations. One of the ways to perform a spectral analysis is by Fourier analysis. Here, we estimate turbulence averaging intervals by applying two methods, both based on Fourier analysis. Assuming Taylor's frozen turbulence hypothesis we can make conversion from space scales (wave number) to the frequency domain. In this context, spectral analysis is a very useful tool for deriving information on large-scale to small-scale eddy energy transport. The value of the spectrum at a specific frequency is equal to the mean energy in that eddy size.

The Fourier theorem states that function $g(t)$, which is a time series of a meteorological parameter with turbulent fluctuations (i.e., wind components or sonic temperature), can be represented by a system of orthogonal sine and cosine functions with appropriate amplitude and phase:

$$g(t) = \sum_{k=-\infty}^{\infty} c_k e^{ikt} \tag{3}$$

$$c_k = \frac{1}{2\pi}\int_{-\infty}^{\infty} g(t)e^{-ikt}dt \ , \ e^{ikt} = coskt + isinkt. \tag{4}$$

The Fourier transform uses this concept to transform between time and frequency domains. For the same continuous function $g(t)$, the Fourier transform is defined as

$$\hat{G}(f) = \int_{-\infty}^{\infty} g(t)e^{i2\pi ft}dt \tag{5}$$

with frequency f. The inverse Fourier transform is

$$g(t) = \int_{-\infty}^{+\infty} \hat{G}(f)e^{-2\pi ft}df. \tag{6}$$

The time integral over the frequency spectrum corresponds to the variance.

The second method for estimating appropriate turbulence averaging time was introduced by Desjardins et al. (1989) and Oncley et al. (1990) for the investigation of turbulent fluxes. This method uses the cumulative or running integral of the cospectrum to determine the frequency at which there is no more contribution to the covariance (e.g., Desjardins et al., 1989). This cumulative integral is an ogive function defined by

$$Og_{xy}(f_0) = \int_{\infty}^{f_0} Co_{xy}(f)df \tag{7}$$

where Co_{xy} represents the cospectrum of any two variables x and y (e.g., Oncley et al., 1996; Metzger and Holmes, 2008). The integral ranges from a higher frequency (highest frequency recorded) toward a lower frequency (frequency of interest). The ogive plots show the cumulative contribution of eddies of increasing period to the covariance. If the ogive reaches an asymptote at some frequency f_c, than this indicates that there is no more flux beyond this frequency (Moncrieff et al., 2004). Averaging time scale is equal to the reciprocal of this frequency f_c, $\tau = f_c^{-1}$. τ denotes the minimum averaging time necessary to include all flux contributions, that is, to separate local turbulent fluxes that produce surface-layer turbulence from mesoscale / diurnal fluxes that are associated with the diurnal fluctuations. The ogive and cospectrum provide the same information because a point on the ogive curve is equal to the integral under the cospectral density curve. Another advantage of the ogive plots is that we can determine whether we have sampled the data for a long enough period without needing to compare our measurement to some chosen standard that can be inappropriate for our conditions (Moncrieff et al., 2004).

4. Results

Fig. 5 shows the time series of 1-min block averages of horizontal wind speed and direction at five levels for the period of interest. As shown, horizontal wind speed is generally very low, approximately 1 ms^{-1} or lower, at three lower levels and does not exceed 2 m s^{-1} at 55 and 62 m, except for the first 40 min of the period. The wind direction shows much more variation at the three lower levels than at the two highest levels. A Fourier analysis is applied here to estimate characteristic turbulence time scales in the stable, wintertime boundary layer. The use of the gap time scale to calculate eddy correlation flux removes contamination by mesoscale motions (Vickers and Mahrt, 2003). The evidence of such a gap, however, does not always appear. The spectra of horizontal wind speed observed by Van der Hoven (1957) showed low-frequency peak, which corresponded to the time scale on the order of 4 days and was attributed to the synoptic scale. The high-frequency peak occurred near the time scale of 1 min, which represents a local turbulence scale. In the present data, a definitive gap can be observed in the spectra of horizontal velocity and temperature (except at the 32 m level) but not in the spectra of vertical velocity (not shown). Fig. 6 shows a log-linear representation of multiplied (by frequency) streamwise u spectra as a function of frequency for the 4-h period of interest at all five levels. A longer period was not investigated because of the daily cycle of fluxes and the desire to

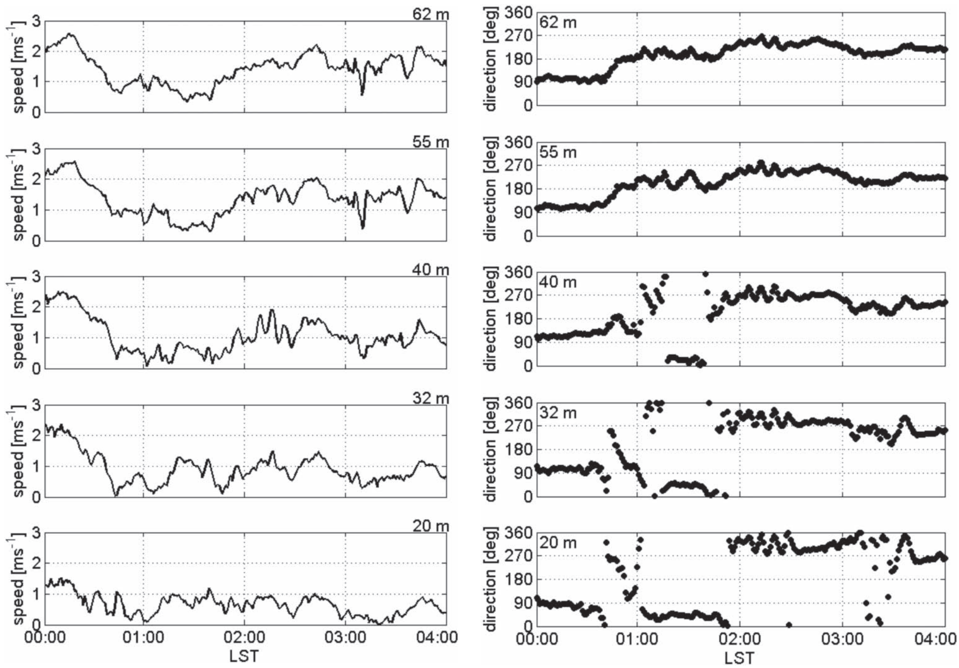

Figure 5. Time series of 1 minute block averages of wind speed (*left*) and wind direction (*right*) at 5 levels from 00 to 04 LST on 22 December 2008.

exclude non-steady conditions. The spectra were calculated by multiplying the u time series with a hamming window with 2^{16} data points (approximately 3.6 hours); a fast Fourier transform (FFT) algorithm was used to perform the Fourier transform.

The FFT was then multiplied by its complex conjugate, and the real part of this product was maintained. The vertical dotted lines in Fig. 6 indicate a period of 30 min, which is usually taken as an averaging interval for turbulent fluxes, and a period of 1 min, which represents the time scale of local turbulence. The peaks in the spectrum indicate the eddy sizes that contribute the most to turbulent kinetic energy (Stull, 1988). As shown in Fig. 6, several peaks exist at high-frequency part of the spectrum. At all levels, except at 32 m, two distinct high-frequency peaks exist near $f \approx 1.7 \times 10^{-3}$ Hz and $f \approx 2.4 \times 10^{-3}$ Hz. The later peak is undeniable in this 4-h record, possessing much more energy than any other peak, except for 32 m level, and is the strongest at the 40 m. This peak corresponds to the period of approximately 7 min, which is the period of oscillations that appear in the wind direction at the lowest three levels approximately between 0150 and 0230 LST (Fig. 5). Moreover, the peak at this frequency is present in the vertical wind component spectrum at all levels except at 20 m (not shown). This frequency corresponds to the wavelength of $\lambda \approx 467$ m, where $\lambda = U/f$ with U denotes the mean horizontal wind speed for 4 levels (20, 40, 55 and 62 m) averaged over the same time period of interest. At a height of 32 m, no evident spectral gap exists. Tab. 1 shows the periods between which spectral gaps occur.

Due to the much different behavior of results for the height of 32 m compared to other heights (Fig. 6), we calculated 3-min moving averages for all three wind

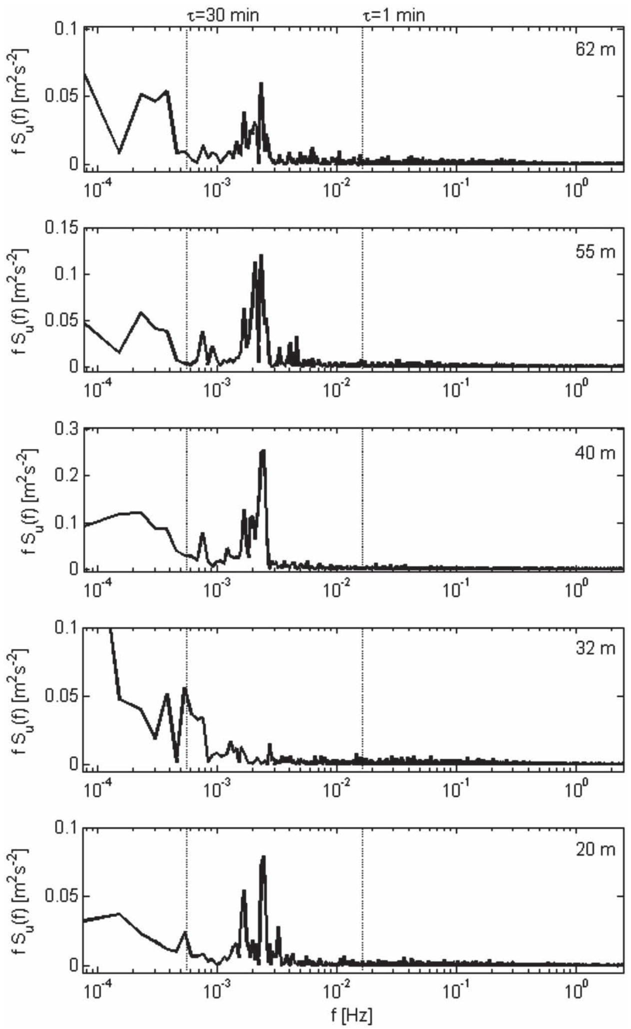

Figure 6. Spectra of the streamwise velocity u (multiplied by frequency) as a function of frequency at five levels for the 4-h period of interest (between 00 and 04 LST). Vertical dotted lines indicate periods of 30 and 1 min. The heights of the levels are indicated on the right y-axis.

components at all five heights (not shown here). At all heights (including the height of 32 m), and in all smoothed time series oscillations with periods of about 7 minutes can easily be seen. Additionally, correlation coefficient between smoothed streamwise component at 32 m and streamwise component at adjacent height was rather high, that is 0.938 (for 20 m) and 0.981 (for 40 m). Above two quality controls do not suggest any questionability of the data collected at 32 m. Therefore, we do not have any logical explanation for the different behavior of the spectrum calculated at the height of 32 m compared to spectra at other heights.

Table 1. Positions of peak frequencies (given in minutes) that indicate the existence of spectral gaps in the data according to Fig. 5.

Level	20 m	32 m	40 m	55 m	62 m
Period [min]	30–7	–	22–7	22–7	22–7

A relevant integral time scale can be determined from the cospectrum of kinematic heat flux (Fig. 7) or momentum flux (Fig. 8) (calculated from the raw u, w and θ time series). The cospectra were calculated using the same technique as described for the u spectra. We consider corresponding ogives so that we can estimate the appropriate averaging time scale. In an unstable atmosphere, where convection dominates the dynamics, one would expect the vertical heat flux cospectrum to be a good indicator of the actual scales of motion that drive surface-layer turbulence. On the other hand, in the stable boundary layer, where turbulence is primarily produced by mechanical factors, the momentum flux cospectrum can be used to estimate the averaging time scale. In this study, we are using ogive functions of both flux cospectra because both have very low flux values as shown in Figs. 7 and 8. In an ideal case, the ogive function increases during integration from high frequencies to low frequencies until a certain value is reached and remains more or less constant. From Figs. 7 and 8, we observe that we do not have an ideal case. Instead, the ogive functions usually decrease to a certain frequency, after which they suddenly start to increase until they reach the first local maximum value. After this local maximum, they decrease again for longer integration times. This erratic behavior of ogive functions corresponds to the behavior of the kinematic heat and momentum flux cospectra. It can be easily seen that the fluxes have a uniform behavior from high frequencies until a frequency of approximately $f_c \approx 2.2 \times 10^{-3}$ Hz at which they show minimum or maximum values. As shown in Tab. 2, ogive functions typically show an extreme value for time periods lower than 30 min. At levels of 20, 32 and 55 m, both ogive functions show an extreme value approximately at frequencies $f_c \approx 1.6 \times 10^{-3}$ Hz, $f_c \approx 2.1 \times 10^{-3}$ Hz and $f_c \approx 2.2 \times 10^{-3}$ Hz, respectively. Kinematic heat flux and momentum flux ogives at heights of 40 and 62 m have maximum values at slightly different frequencies that correspond time periods between 7 and

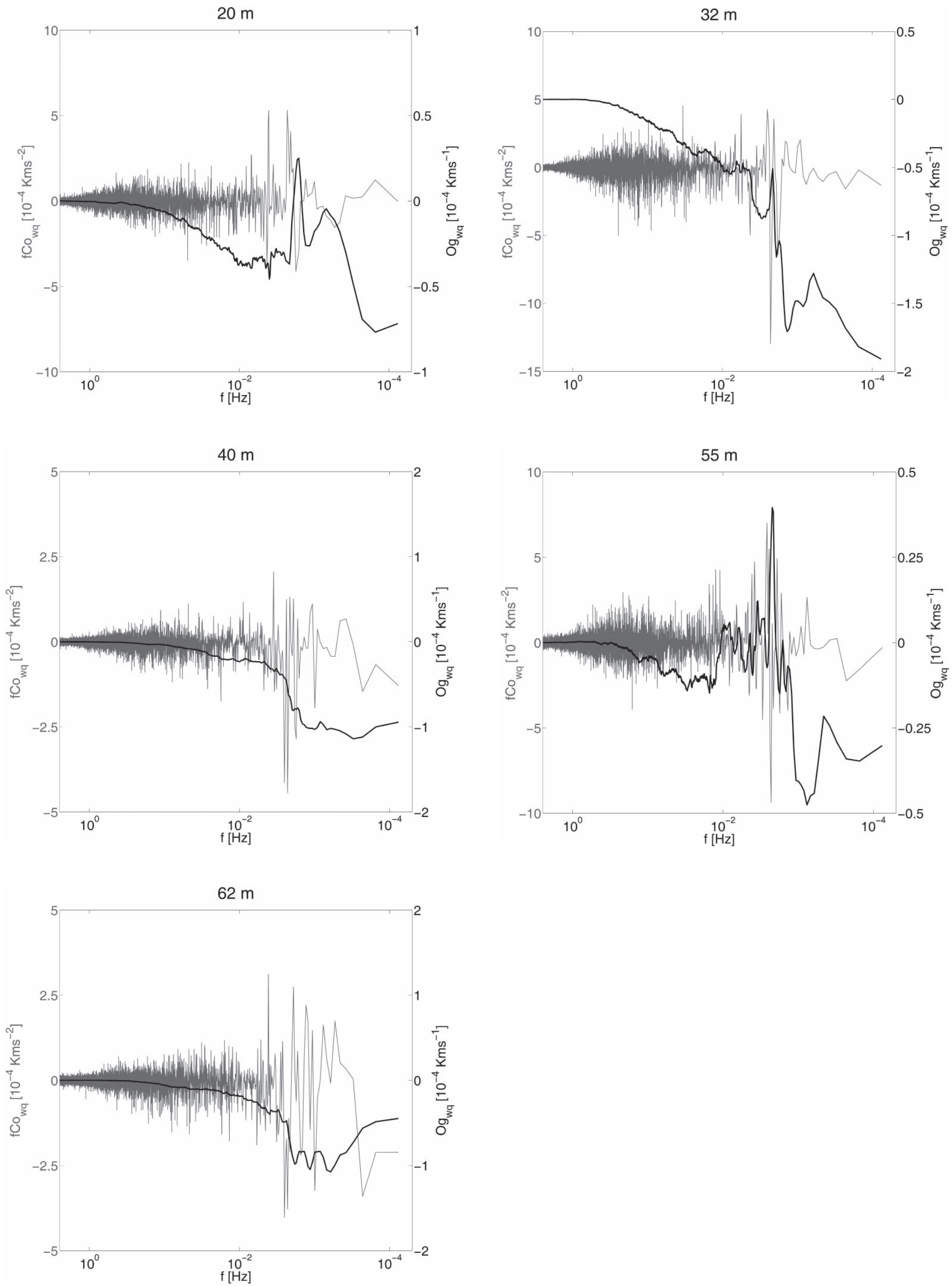

Figure 7. Absolute ogives of the kinematic heat flux (black, right y-axis) and corresponding cospectra (grey, left y-axis) as a function of frequency at the five measured heights (indicated on the top x-axis).

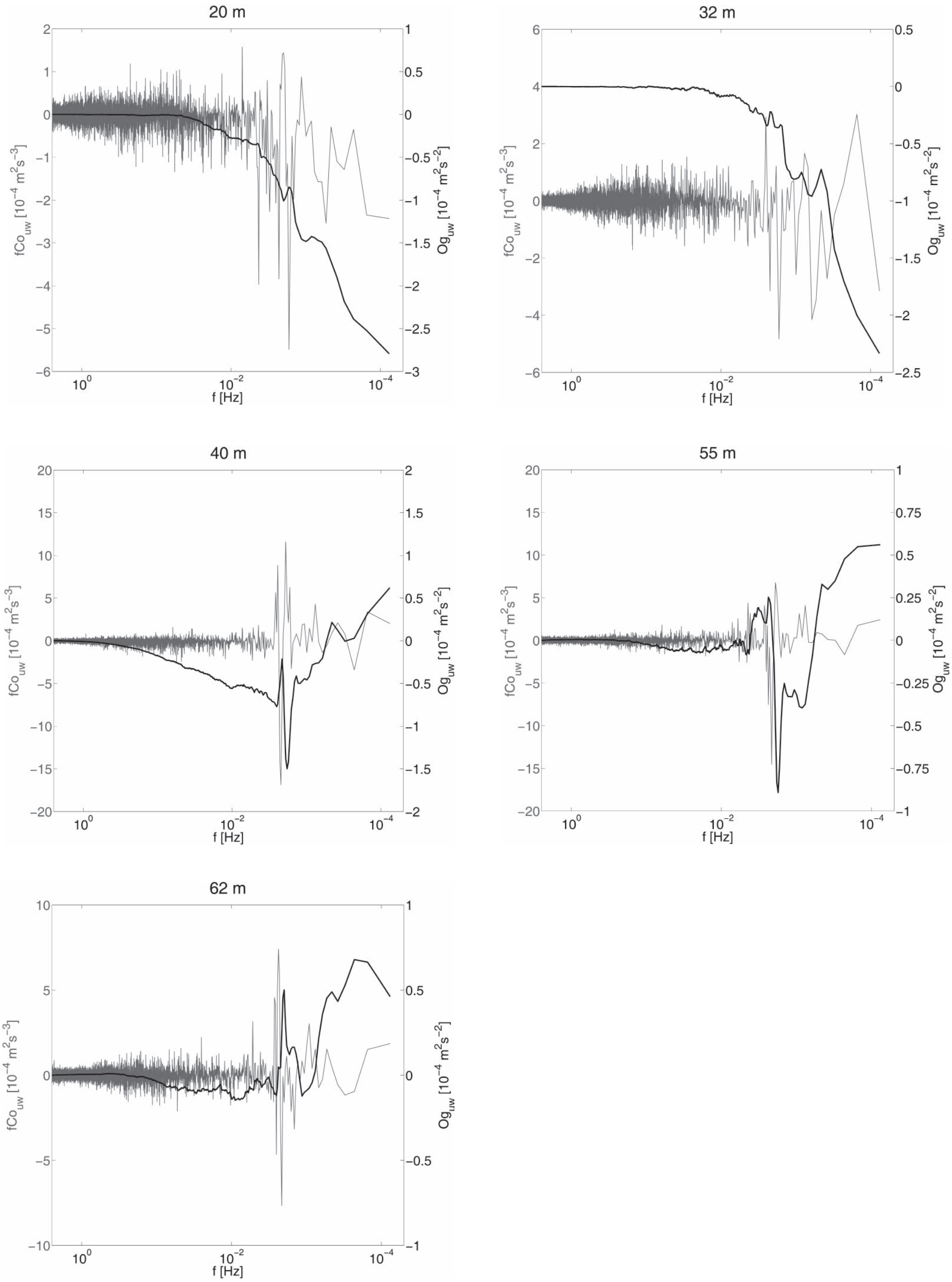

Figure 8. Absolute ogives of the momentum flux (black, right y-axis) and corresponding cospectra (grey, left y-axis) as a function of frequency at the five measured heights (indicated on the top *x*-axis).

11.5 min (Tab. 2), both of which can be found within spectral gap scales estimated by the first method.

These results indicate that total turbulent flux was reached within a time period shorter than 30 min. This is in accordance with the results found by Foken et al. (2006) for their Case 2, which occurred in the transition time with non-steady state conditions or in periods with low fluxes. As can be discerned from Tab. 2, the location of the spectral gap's high-frequency end in the u spectrum (Fig. 6; Tab. 1) corresponds well with f_c. Nevertheless, considering very low flux cospectra values and ogive functions that do not show a convergence from a certain frequency, this case is not very easy to investigate. Moreover, what seems undeniable is an influence of certain process that has a time period of approximately 7 min since the spectrum of streamwise velocity component and cospectrum of both, kinematic heat and momentum fluxes show and energy peak that correspond to this time period. This underlines the fact that examination of stratified turbulence in atmospheric boundary layer is complicate task to perform since it is influenced by multiple physical processes such as clear air radiative flux divergence, elevated shear associated with low level jets, meandering motions, gravity waves, slope flows and surface heterogeneity.

Table 2. Positions of local maximal values of the ogive function (given in minutes) for the kinematic heat flux and for the momentum flux according to Figs. 7 and 8.

Level	20 m	32 m	40 m	55 m	62 m
f_c ($Og_{w\theta}$) [min]	10.4	7.8	9.9	7.5	11.5
f_c (Og_{uw}) [min]	10.4	7.8	7.7	7.3	8.4

5. Summary and conclusions

The aim of this preliminary study was to estimate the integral time scale τ that may be used for calculating turbulent fluctuations, that is, a time scale appropriate for the filtering process or mean removal process for the nocturnal stable ground-based layer. This operation is important in transforming intrinsically non-stationary atmospheric data into time series that are statistically stationary.

In this study, we use two different methods, both based on Fourier analysis, to estimate the turbulence averaging interval. The first method involves calculating a spectrum of wind components and sonic temperature. The second method used for estimation of time scale is based on the inverse frequency associated with the location of the local maximum value of the kinematic heat flux and momentum flux cospectrum ogive functions. Each time scale was evaluated using three-dimensional ultrasonic anemometer data acquired at five levels of a meteorological mast located in the industrial part of Kutina. The data were analyzed during a 4-h period when stable conditions were observed between 00 and 04 LST on 22 December 2008.

It is interesting that for the investigated time interval, a spectral gap scale was found in stable conditions which are characterized by a weak and intermittent turbulence. The gap, defined by position of peak frequencies, was found at all levels except at 32 m. At the height of 20 m, a spectral gap occurred between the periods of 30 and 7 min, while a gap was observed between 22 and 7 min at 40, 55 and 62 m. An interesting feature is the occurrence of a strong peak at all levels except at 32 m at approximately $f \approx 2.4 \times 10^{-3}$ Hz, which possesses more energy than any other peak in the spectrum. This peak corresponds to the period of oscillations present in the wind direction, which have been observed at three lower levels and are associated with west to northwest directions. These oscillations will be examined in more detail in future work. The second ogive method employed uses cospectra of kinematic heat flux and momentum flux. The results obtained from the ogive method show that f_c defines the high-frequency end of the observed gap in the u spectrum. Owing to the very low values of the kinematic heat flux and also momentum flux, however, this case is very difficult to investigate using the ogive method. Moreover, the ogive function does not reach a constant value after a certain frequency, as has been suggested by theory. Instead, it shows several local maximum values between which the ogive values decrease. It seems that in this case, without deploying a first method, the ogive method itself would not lead to any conclusive results.

We do not have any explanation for the different behavior of the spectrum of the streamwise velocity component at 32 m a.g.l. compared to spectra at other heights. Since quality control did not reveal any errors in measured data, in further work it would be desirable to perform same calculations at larger datasets.

At the first glance, the erratic behavior of ogive functions, which are not monotonically increasing with increasing frequency, can be attributed to very weak turbulent fluxes. To our knowledge, other studies applying ogive functions and obtaining more monotone patterns (e.g., Oncley et al., 1996; Foken et al., 2006), do not investigate wintertime stable boundary layers.

Our preliminary results obtained for the one case of the nighttime, stable boundary layer suggest turbulence averaging time scales between 7 and 11.5 minutes. In order to minimize possible contribution of mesoscale flows in the calculated turbulent fluxes in very weak turbulence conditions (Mahrt and Vickers, 2006), we selected the smallest among obtained values (that is, 7 min) as the most appropriate turbulence averaging time scale. It would also be desirable to conduct an analysis of more time intervals in the same atmospheric conditions to estimate the integral time scale for stable boundary layer turbulence.

Acknowledgements – We thank reviewers for useful suggestions. The study was supported by the Croatian Ministry of Science, Education and Sports (grants No. 119-1193086-1323 and 119-1193086-1311).

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SAŽETAK

Određivanje turbulentne skale usrednjavanja u noćnom graničnom sloju na temelju Fourierove analize

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Gibanja u atmosferskom graničnom sloju su statistički nestacionarna te ih se stoga nužno mora transformirati u statistički stacionarne vremenske nizove. (Statistička svojstva stacionarnih nizova se ne mijenjaju u vremenu.) Ova transformacija se izvodi postupkom uklanjanja srednjaka, čime se definira vremenska skala turbulentnih fluktuacija. U ovoj studiji uspoređujemo dvije metode pomoću kojih ocjenjujemo fizikalno relevantne turbulentne vremenske skale u stabilnom, zimskom noćnom graničnom sloju. Ova vremenska skala se koristi za uklanjanje nestacionarne srednje komponente u vremenskom nizu bilo koje od mjerenih meteoroloških varijabli. Prva metoda uključuje primjenu Fourierove analize, kako bi u računanju vertikalnih tokova turbulentnih kovarijanci utjecaj mezoskalnih gibanja bio isključen. Druga metoda korištena za određivanje relevantne turbulentne vremenske skale usrednjavanja predstavlja kumulativni integral kospektra kinematičkog toka topline ili toka impulsa (eng. *ogive* metoda). Za ocjenu ove vremenske skale koriste se trodimenzionalni podaci soničnih anemometara postavljenih na pet visina meteorološkog tornja (20, 32, 40, 55 i 62 m iznad tla), koji se nalazi u industrijskom dijelu grada Kutine. Rezultati upućuju na to da na svim visinama, izuzev 32 m, postoji procjep u spektru komponente vjetra usmjerene niz srednje strujanje. Spektralni procjep se uočava na periodima između 30 i 7 minuta na visini od 20 m, te između 22 i 7 minuta na ostalim visinama. Vremenska skala turbulentnog usrednjavanja dobivena pomoću druge metode se temelji na pronalaženju frekvencije, pri kojoj se javlja lokalni maksimum u kumulativnom integralu kospektra kinematičkog toka topline i toka impulsa. Druga metoda daje vremenske skale koje definiraju visokofrekventni kraj spektralnog procjepa.

Ključne riječi: stabilni granični sloj, integralna vremenska skala, spektralni procjep, ogiva funkcija

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