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# WAVELET ANALYSIS OF INTERMITTENT TURBULENCE IN A VERY STABLE NOCTURNAL BOUNDARY LAYER: IMPLICATIONS FOR THE VERTICAL MIXING OF OZONE

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**Abstract.** Turbulence in the very stable nocturnal boundary layer is weak, patchy and intermittent. Near the surface isolated bursts of turbulent activity, characterised by abrupt changes in vertical velocity variance, have been shown to play an important role in determining the vertical transport of pollutants. However, there is little consensus as to the most appropriate methods for identifying or analysing the characteristics of intermittent turbulence that are of direct relevance to air quality studies. This paper presents an original technique, based on wavelet analysis, to objectively isolate intermittent turbulent 'bursts' within vertical velocity time series. The technique permits the quantitative description of global intermittency and can be used to assess the duration and strength of turbulence within a time series. The technique is applied to a dataset from a summer field experiment in the Lower Fraser Valley, British Columbia, 1998. A very stable nocturnal boundary layer was observed in this region of complex terrain during anticyclonic synoptic conditions. During the 11 nights studied turbulent activity was characterised (within each 30-min time series) by three to four individual bursts persisting for less than 10 min in total. The implications of these results for air quality studies are discussed within the context of the vertical mixing of ozone (stored within the residual layer) to the surface. Results show that, despite the complexity of the processes determining nocturnal surface ozone concentration, the strength and duration of turbulent bursts can play an important role in determining local surface concentrations.

**Keywords:** Air quality, Intermittent turbulence, Ozone, Vertical mixing, Very stable nocturnal boundary layer, Wavelet analysis.

## Introduction

Observational studies have shown that turbulence in the very stable nocturnal boundary layer (NBL) is typically dominated by intermittent bursts of activity lasting 5–30 min (Weber and Kurzeja, 1991; Poulos et al., 2002). Turbulent activity is often found in isolated layers or pockets within the very stable NBL (Mahrt et al., 1998a) and characterised by abrupt changes in variance (often by as much as an order of magnitude) (Coulter, 1990; Howell

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and Sun, 1999). However, although well studied, the structure and underlying causes of this intermittent turbulence remain poorly understood (Koracin and Berkowicz, 1988; Mahrt et al., 1998a).

In the very stable NBL turbulence is typically caused by local and non-local processes that generate shear (such as mesoscale thermo-topographical wind systems, low-level jets (LLJ), density currents, solitary waves or breaking internal gravity waves) (Mahrt, 1985; Stull, 1988; Sun et al., 2003). Near the surface, the turbulence observed may be unrelated to the surface characteristics and is primarily determined by the interaction between dynamic dampening caused by local thermal stability and the processes generating turbulence aloft (Bange and Roth, 1999). The penetration of these active instabilities into the surface layer has important implications for local air quality. For example, the temporary coupling of the residual and surface layers facilitates the vertical transport of scalar quantities (such as air pollutants), which may otherwise have been stored in the residual layer, to the surface (Beyrich, 1994; Howell and Sun, 1999).

Although it is increasingly recognised that a significant portion of the vertical transport of pollutants in the very stable NBL occurs as a result of these intermittent bursts of turbulent activity (Corsmeier et al., 1997; Poulos et al., 2002; Salmond and McKendry, 2002), there is little consensus in the literature as to the most appropriate method for identifying turbulent thresholds or quantifying the characteristics of intermittent turbulence within this context. Given the heterogeneity of pollutant concentrations with time in the residual layer (Salmond and McKendry, 2002, 2005), such detailed knowledge of the characteristics of intermittent bursts may play a key role in understanding surface pollutant concentrations.

Traditional analytical tools (such as Fourier analysis) and boundary-layer theory, which look at the global characteristics of a dataset, cannot be easily applied to the analysis of turbulent time series from the very stable case as only a small portion of the data from any given sampling period is likely to be turbulent (Finnigan et al., 1984; Derbyshire, 1994; Rogers et al., 1995; Chen and Hu, 2003). Thus not only are a limited number of eddies sampled (reducing the statistical validity of results), but the local turbulent event(s) of interest are obscured within the descriptions and analysis of the entire (or global) characteristics of the dataset. As a result it is very difficult to determine from standard descriptive statistics whether intermittent turbulence is present and all information regarding the number, timing, duration or strength of individual turbulent bursts is obscured. Thus the intermittent turbulent parameters of direct relevance to air quality studies are very difficult to evaluate or quantify for the very stable NBL (Koracin and Berkowicz, 1988).

In this paper a new technique based on wavelet analysis is developed to provide an objective, statistically robust threshold to isolate and quantitatively analyse turbulent bursts from vertical velocity time series observed in the very stable NBL. Wavelet analysis offers an alternative approach to traditional analytical tools for the analysis of turbulent time series. It is a local, two-dimensional transform that facilitates the retention of information about the temporal location of frequencies within the dataset. As such it is an analytical tool that 'encompasses many desirable features of traditional conditional sampling techniques' (Hagelberg and Gamage, 1994b).

The technique is applied to turbulence data collected near the surface during a field campaign in the Lower Fraser Valley, an urbanised region of complex terrain located on the south-west coast of British Columbia in Canada, in the summer of 1998. Its potential to elucidate further the relationship between intermittent turbulent bursts and surface air quality is explored using local surface ozone ($O_3$) data and vertical profiles of $O_3$ concentration. Given that the emphasis here is on the potential application of this technique to vertical transport and air quality applications, no attempt is made to describe the statistical properties of intermittency within or between time series using functions such as the Hurst exponent that are commonly used in hydrology or engineering applications.

## 2. Methodology

### 2.1. Field observations

The site chosen for the field experiment was the Canadian Forces Station (CFS) Aldergrove located at 49°4.5′ N, 122°28′ E (100 km east of Vancouver and 18 km west-north-west of Abbotsford) in the Lower Fraser Valley, British Columbia, Canada. This location is situated in the middle of the valley away from the immediate influence of tributary valleys and in a region of comparatively simple terrain.

An 8-m steel-framed triangular lattice (0.25 m wide) tower was installed at this grassland site to support micrometeorological sensors used to measure turbulent fluxes. The Source Area Model developed by Schmid (1994, 1997) was used to calculate an appropriate height for the instruments, given a minimum homogeneous fetch (consisting of tall grasses (1.4 m in height) with occasional small trees and shrubs) to the tower of 500 m. Due to the close proximity of a few buildings (100 m to the south-east), data collected when the prevailing wind direction was between 140° and 160° were not used in analysis.

It was not possible to calculate the roughness length from the data available, and it was therefore estimated to be 0.3 m based on Davenport et al. (2000) and Wieringa (1993). This value, which is at the high end of the range of values given for tall grassland regions interspersed with obstacles, was chosen to take into consideration the heterogeneous characteristics of the local morphology and the impact of isolated trees on wind flow patterns (Fujita and Wakimoto, 1982). Thus a Gill three-axis ultrasonic anemometer (sonic) was mounted on the tower at 5.05 m above the ground using a 2-m steel boom to measure the turbulent fluctuations in the wind field ($u$, $v$, and $w$) and temperature. Data from the sonic anemometer were collected at 21 Hz and stored in 30-min blocks using a Pentium 1 series desktop computer from 1230 July 17, to 2400 September 3, 1998 (all times given are in Pacific Daylight Time, PDT).

In order to establish the relationship between local bursts of turbulence and $O_3$ concentration, nitrogen dioxide ($NO_2$), nitrogen monoxide (NO) and $O_3$ monitors were situated near the base of the tower. Mean $O_3$ concentrations were recorded at a height of 4 m at 5-min intervals using a Monitor Labs 9811 ML analyser. The monitor was tested and calibrated prior to, and following the field season, with minimal drift recorded; the instrument is considered accurate to within 1 ppb in the 0–600 ppb range. Data were collected between 1540 July 7 and 1035 September 16 1998.

The data presented here are from intensive observation periods (IOPs) chosen between July and September 1998 (July 21–23, July 26–29, August 8–10, August 12–14, August 30–September 1). In each case, measurements commenced during the afternoon on the first day and ceased around noon on the last day. IOPs were chosen to coincide with periods when anticyclonic conditions were well developed over the region. The associated clear sky conditions resulted in strong radiative heat losses at night promoting the development of a very stable nocturnal boundary layer.

During the IOPs an Atmospheric Instrumentation Research Inc. model tethersonde balloon system, equipped with a radiosonde meteorological sensor and a KZ-ECC ozonesonde (EN-SCI Corporation), was used to document vertical characteristics of the boundary layer. Flights were made approximately hourly between 1700 and 1100 throughout the IOPs; flights typically lasted 45–60 min and ascended to an altitude of between 500 and 800 m depending on the conditions and flight restrictions imposed by Air Traffic Control. Overall, an ascent rate of between 0.25 and 0.5 m s$^{-1}$ was achieved, which, with an instrument response time of 10 sec, enabled a minimum vertical resolution of 5 m.

Although conditions varied during the nights chosen for analysis due to the presence of intermittent turbulence, the surface layer was characterised by mean wind speeds $< 2$ m s$^{-1}$ and a friction velocity of 0.1 m s$^{-1}$ (see Table I). Tethersonde data show the consistent development of a shallow, very stable boundary layer by 2230. Throughout the course of the tethersonde observations the depth of the stable boundary layer (as determined by the height of the temperature inversion) varied between 50 and 150 m. This is illustrated in

TABLE I

Characteristics of the very stable nocturnal boundary layer as observed at CFS Aldergrove during the IOPs.

| | Wind speed ($m\ s^{-1}$) | Friction velocity ($m\ s^{-1}$) | Heat flux ($W\ m^{-2}$) | Obukhov length (m) | z/L |
|---|---|---|---|---|---|
| Maximum | 1.8 | 1.3 | 54.9 | 2.4 | 8.8 |
| Minimum | 0.3 | 0.02 | −137.5 | −9.1 | −8.7 |
| Mean | 0.9 | 0.10 | −3.2 | −0.3 | −0.07 |
| Standard deviation | 0.32 | 0.18 | 25.1 | 1.8 | 3.7 |

the typical profiles of wind speed, potential temperature, Brunt–Vaisala frequency, ozone concentration and Richardson number through the nocturnal boundary layer given in Figure 1 for 0055 July 27, 1998.

The prevailing conditions observed during the IOP periods were also associated with high daytime surface $O_3$ concentrations (Salmond and McKendry, 2002). During the nocturnal periods, $O_3$ concentrations in the residual layer were highly variable in time (Salmond and McKendry, 2002, 2004) and with height (as demonstrated in Figure 1d).

In this paper emphasis is placed on a case study (the night of August 31–September 1, 1998), which is considered representative of conditions observed during the field campaign. However, data from other nights throughout the study period are also drawn upon to illustrate the variety of

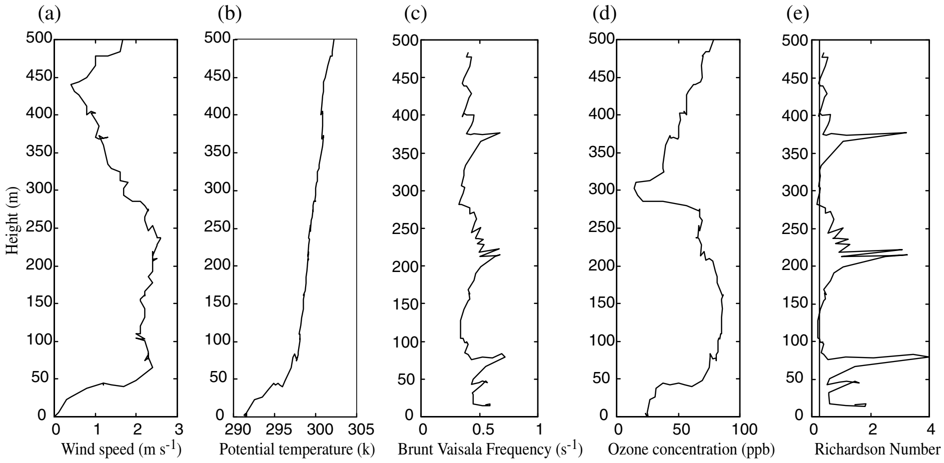


*Figure 1.* Typical vertical profiles through the very stable NBL for: (a) wind speed; (b) potential temperature (K); (c) Brunt–Vaisala frequency; (d) ozone concentration; (e) Richardson number as observed 0055 July 27.

conditions observed and demonstrate the versatility of the technique proposed.

### 2.2. Quantification of global intermittency using wavelet analysis

Many different attempts have been made to quantify the intermittent behaviour of natural systems (Hagelberg and Gamage, 1994a). Qualitatively, intermittency refers to the non-periodic, temporally irregular fluctuations between two polar states over a defined period of time. Intermittent behaviour can thus be quantified as a ratio between the time when the process was turned on (or off) and the total length of the time series. This ratio is commonly called the intermittence factor. The precise time the system or process changed state, the time interval between changes and the number of changes per time period may also be of interest in studying intermittency.

Two types of intermittency are often identified with regards to turbulence: local intermittency, which refers to the variation within a turbulent eddy, and global intermittency (of interest here), which refers to the separation of clusters of turbulent eddies in time or space (Mahrt, 1989). One of the particular challenges facing the quantitative definitions of intermittency with regards to atmospheric turbulence is that a threshold must be selected to identify and isolate turbulent ‘events’ or bursts from the time series. This may be done visually or computationally, based on the magnitude of a particular feature in physical space or the selection of a frequency threshold (Hagelberg and Gamage, 1994b). To date there are no accepted, objective and systematic methods for distinguishing between instrumental noise and plausible physical behaviour (Vickers and Mahrt, 1997). Thus the criteria for identifying the boundary between turbulent and non-turbulent portions of the signal are often determined by eye and subject to personal bias, inconsistencies and are frequently contested (Bange and Roth, 1999).

Once the criteria have been established, global intermittency can be defined by comparing the turbulent and non-turbulent portions of the signal. However, there is little consistency as to how this may be effectively achieved. Mahrt et al. (1998b) define a global intermittency index for each eight-min section of the record, comparing the local standard deviation of the flux with the standard deviation of the 30-min record length. Other indices include ratios of the time period of the turbulent and non-turbulent sections of the record (Hagelberg and Gamage, 1994b). As a result, quantitative indices of intermittency range from the ratio of flux time (structure or event component) to time series length (Hagelberg and Gamage, 1994b), to the ratio between the standard deviation of 5-min fluxes to the total flux of the time series (Mahrt et al., 1998b). However, neither of these definitions describe the individual or relative temporal placement of turbulent events.

Wavelet analysis offers an alternative approach to the analysis of turbulent time series. It is considered to be both a departure from, and extension of, Fourier analysis. Perhaps the most significant difference between the two techniques is that wavelet analysis provides a two-dimensional representation of the signal in time and frequency space. Thus it retains a time localisation associated with the frequencies identified and provides information about how the dominant frequency modes vary through time (Torrence and Compo, 1998). In this way, it can be used to 'point to important features of a process and reveal structure not apparent from direct observation that are a key component of process understanding' (Kumar and FoufoulaGeorgiou, 1997). This property can also be exploited to locate and quantitatively analyse the turbulent component of time series enabling the temporal placement of turbulent bursts within a time series and the analysis of their duration and strength.

## 2.3. Wavelet analysis

The continuous form of the wavelet transform* of a time series $x_n$ is given by (Torrence and Compo, 1998),

$$W_n(S) = \sum_{n'=0}^{N-1} \boldsymbol{x}_{n'} \psi^* \left[ \frac{(n' - n)\delta t}{S} \right], \tag{1}$$

where $\psi^*(t)$ is the complex conjugate of the wavelet function (normalised to have unit energy) for time step $\delta$t at a localised time index $n$ and at scale $s$. The Morlet wavelet (shown in Figure 2) was used in this analysis, the relation for which is (Lafreniere and Sharp, 2003),

$$\psi(t) = \pi^{-1/4} e^{i6t} e^{-t^2/2}. \tag{2}$$

This non-orthogonal, complex wavelet was chosen since it is a symmetric wavelet and therefore is coherent at the edge of any transition effectively defining the start of the change in conditions (Hagelberg and Gamage, 1994b). This enabled efficient identification of the start and end points of the intermittent turbulent periods. The Morlet wavelet is also a compact wavelet and is well defined in Fourier space. Good resolution in the frequency domain was important if a scale separation between turbulent fluctuations and other longer scale motions was to be achieved when identifying intermittent turbulent bursts.

The data were divided into 30-min time series and normalised by dividing each time series by the standard deviation prior to analysis. The Morlet

* The code for the basic Morlet wavelet transform used here was modified from Torrence and Compo (1998) (available at http://paos.colorado.edu/research/wavelets/).

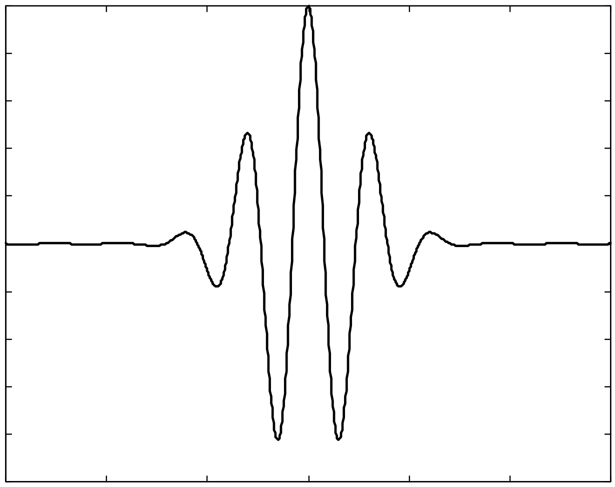

*Figure 2.* The Morlet wavelet.

wavelet was applied to the time series using a discrete set of 13 scales of fractional powers of two:

$$S_j = S_o 2^{j\delta j}, \quad (3)$$

where $S_o = 0.125$ s and $\delta j = 0.5$. This gave a range of scales between 0.125 and 1024 s ($\approx$ 17 min). For the Morlet wavelet the relationship between scale (the width of the analysing wavelet) and period (the approximate Fourier equivalent that corresponds to the oscillations within the wavelet at that scale) is

$$\text{period} = 1.03 \times \text{scale}. \quad (4)$$

Thus here the two terms are used interchangeably.

Following Torrence and Compo (1998) the statistical significance of the wavelet coefficients was assessed using a 95% confidence interval. The test is wavelet specific and uses the lag–1 autocorrelation of the time series to generate a theoretical red noise spectrum specific to each time series (Torrence and Compo, 1998). This procedure was originally developed for stationary signals and is based on an underlying assumption that the variance and covariance of the dataset have a chi-squared distribution (almost certainly violated for atmospheric turbulence data). However, the test has been successfully applied by e.g. Galmarini and Attie (2000) and Attie and Durand (2003), to reveal interesting spatial and temporal patterns embedded within atmospheric turbulence time series and provides a useful insight into the data.

Figure 3 illustrates the wavelet power spectra (average of the absolute wavelet coefficients squared) plotted as a scalogram for the vertical velocity

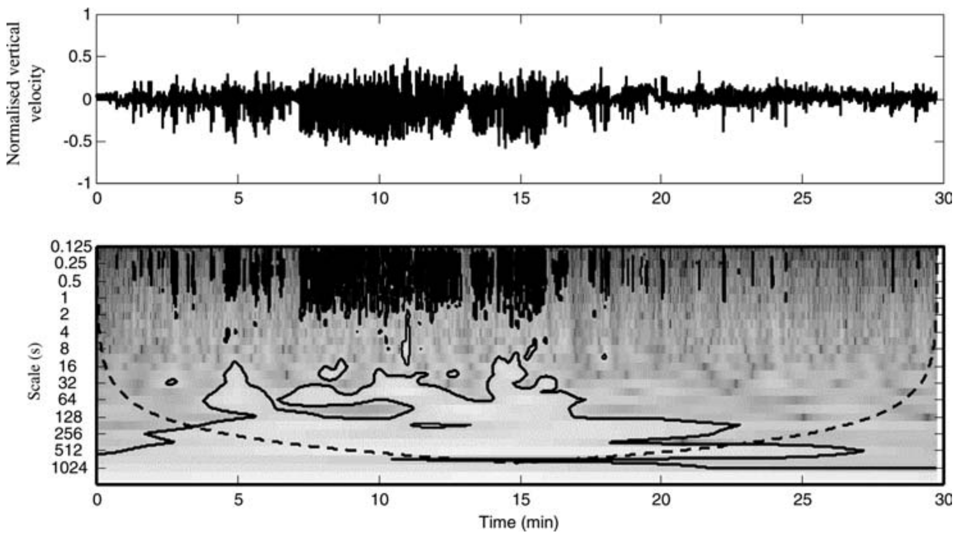


*Figure 3*. Scalogram to illustrate the dominant frequencies identified using wavelet analysis of a 30-min time series of vertical velocity observed between 0000 and 0030 September 1, 1998. Dashed line represents the cone of influence and areas where the wavelet power is considered to be significantly different to that expected due to red noise are encapsulated within the solid black line. (See text for further explanation.)

time series observed between 0000 and 0030 September 1, 1998. The areas where the wavelet power is considered to be significantly different to that expected due to red noise are encapsulated within the solid black line. Due to the high temporal resolution of the scalogram these appear as lines at high frequencies.

The relationship between wavelet coefficients and the red noise spectrum can be assessed with time across a variety of different scales. Here, the objective is to accurately and objectively identify periods when turbulence was active at the surface in the NBL, so the focus is on the smaller scale wavelet coefficients that are representative of the turbulent component of the time series.

Given that during the field experiment observed depths of the stable boundary layer were typically 50–150 m, measurements were made at 5.05 m and mean wind speeds were 2 m $s^{-1}$ or less, the characteristic eddy time scale ($z/u$) is approximately 2.5 s. It can be seen from Figure 3 that there is a strong relationship between periods of increased turbulent activity within the time series and sections of the power spectrum that are significant at time scales between 0.125 and 2 s. Analysis of a large number of scalograms repeatedly revealed a clear scale separation at this level. Whilst it is recognised that this scale separation is in part an artefact of the range of scales chosen, and that turbulent structures are likely to exist at much larger scales, it becomes more difficult to separate turbulence from more wave-like motions and gravity wave–turbulence interaction at larger scales. Thus five scales (ranging from 0.125 to 2 s) were considered representative of turbulent activity and chosen for further analysis of intermittent turbulence.

The mean modulus of the wavelet coefficients at scales between 0.125 and 2.0 s for each time series was compared with the calculated red noise spectra assessed at the 95% significance level. The purpose of this analysis was to identify intermittent bursts of sustained periods of turbulent activity or the global intermittency of turbulence within the time series. A turbulent burst was identified and defined by the length of time the mean modulus of the wavelet coefficients remained significant.

In order to limit the noise introduced within the mean modulus of the wavelet coefficients by the local intermittency of the turbulent burst (local variations in turbulent strength within turbulent eddies), the wavelet coefficients were smoothed using a 30-s running mean. This removed the effect of isolated data points within turbulent bursts that dropped below the significance line. Analysis of the dataset showed that such isolated points were more consistent with local variation of turbulent strength within an eddy rather than an indication of the cessation of a turbulent burst. The effect of this smoothing is shown in Figure 4, where the raw mean modulus is provided in Figure 4a, and the smoothed data for the same time period are given in Figure 4b. Sensitivity tests for different averaging periods showed little affect on the results. Given that the emphasis here is on the identification of turbulent bursts that are likely to be significant in terms of vertical transport events, rather than identifying individual turbulent eddies that may occur in isolation, bursts of less than 0.01 min in duration were excluded from the analysis.

This method is similar to previous attempts to isolate the local intermittence of convective turbulence using wavelet analysis (Collineau and Brunet, 1993; Gao and Li, 1993; Hagelberg and Gamage, 1994a, b). However, these studies rely on the choice of specific criteria to isolate the coherent turbulent structures of interest. Unfortunately the characteristics of the turbulence in the very stable nocturnal boundary layer make it very difficult to identify a consistent structure associated with nocturnal turbulent activity. Thus the advantage of the methodology proposed here is that not only does it provide an objective means of isolating the turbulence from more wave-like activity, it is also based on a statistically rigorous technique used to distinguish between the signal and noise in the time series.

In order to ascertain the effectiveness of the technique in isolating the turbulent component of the time series the wavelet spectra of the turbulent and non-turbulent sections of each time series were analysed. Mahrt and Gamage (1987) demonstrated that the $-5/3$ slope seen in the inertial subrange

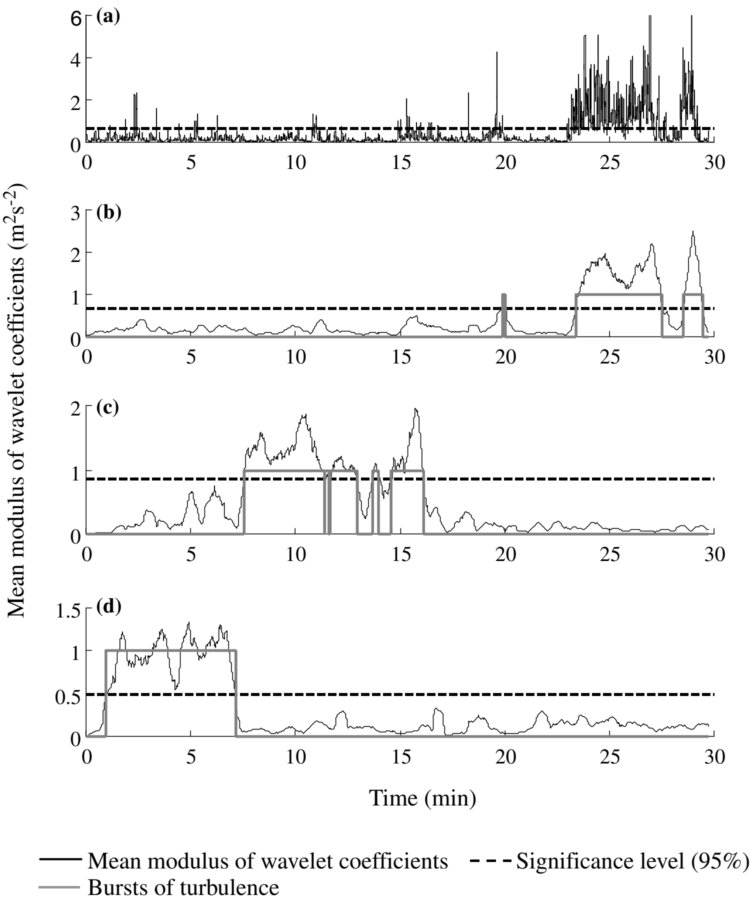


*Figure 4*. Average wavelet coefficients for scales 0.125–2.0, red noise significance level (dash line) and identification of turbulent events for: (a) 2330–0000 August 31 (unsmoothed); (b) 2330–0000 August 31 (smoothed); (c) 0000–0030 September 1, 1998 (smoothed); (d) 0030–0100 September 1, 1998 (smoothed).

of well-developed turbulence is absent in weak, poorly developed turbulence, which is often characterised by a slope of −1. Hagelberg and Gamage (1994a, b) subsequently proposed that two universal structures exist within intermittent turbulence. They suggested that the −5/3 slope resulted from the size and spacing of intermittent turbulent structures in the time series. Thus a turbulent time series could be slit into the structure and non-structure components with a −5/3 slope characteristic of spectra that contain the structure component of the signal, whilst a −1 to 0 slope is characteristic of the non-structure component.

Thus if the technique proposed above (to filter the data and focus on scales 0.125–2 s) captured the important turbulent structures in the time series, we

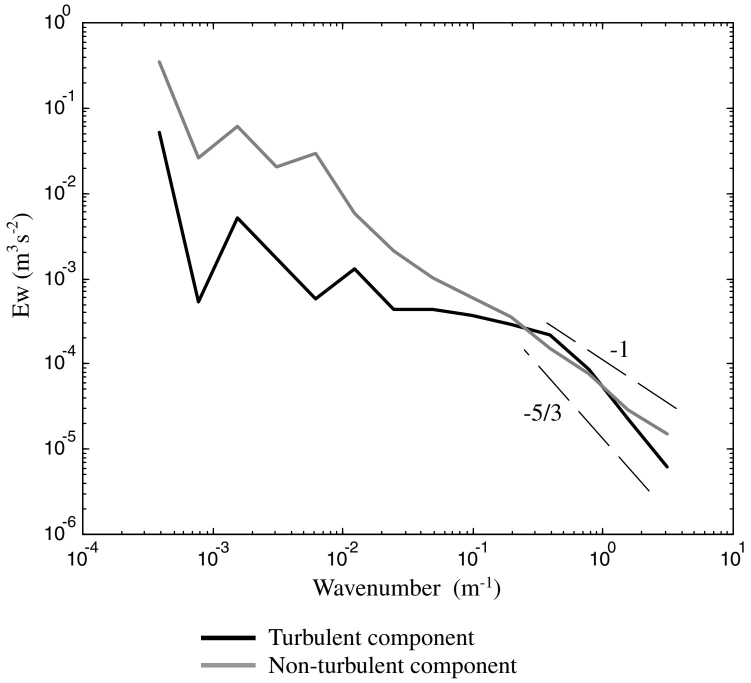


*Figure 5.* Energy spectra calculated using the haar wavelet transform for the turbulent (black line) and non-turbulent (grey line) components of the time series for 0300–0330 August 31, 1998.

should see −5/3 slope present in the structure component, and −1 or 0 slopes in the remaining part of the time series. Analysis of time series observed throughout the IOPs indicated that the turbulent component of the time series repeatedly showed the presence of a −5/3 slope in the inertial subrange, and typically a range of slopes with gradients of between −1 or 0 slope were observed in the non-turbulent component (Figure 5). Thus the technique can be considered to successfully isolate most of the turbulent structures characteristic of the time series.

## 3. Results

### 3.1. Identifying intermittent turbulence within a 30-min time series

Figure 6 illustrates three 30-min time series of vertical velocity (observed between 2330–0100, August 31 and September 1, 1998) that are typical of the data collected during the IOPs. The nocturnal traces clearly show three periods of marked increase in the magnitude of vertical velocities between 2350 and 0040 suggestive of intermittent turbulent ‘bursts’. These isolated

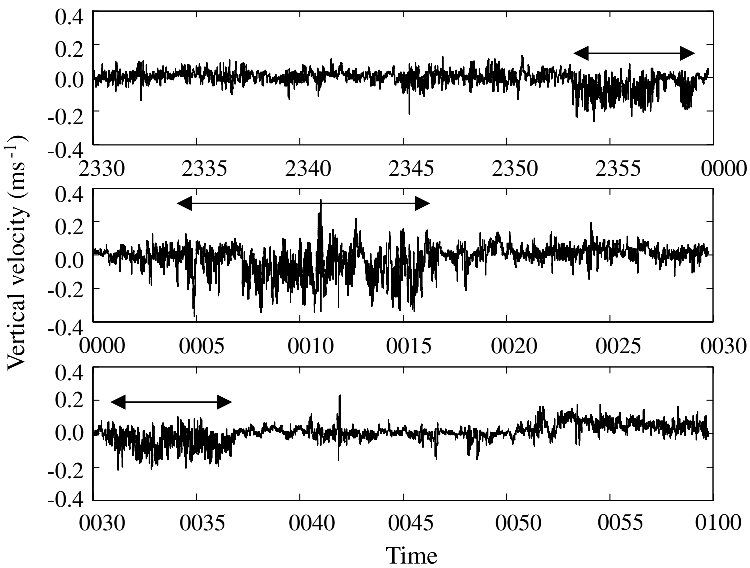


*Figure 6*. Variations in vertical velocity observed during three 30-min time series: (a) 2300–0000 August 31; (b) 0000–0030 September 1; (c) 0030–0100 September 1, 1998. (Arrows indicate approximate limits of three turbulent bursts.)

events in the time series are of primary interest here since they represent the more turbulent portion of the time series when vertical transport processes are likely to be active.

Visual inspection of the three time series reveals that the most intense burst of turbulence occurred between 0005 and 0020. Standard global scale statistics (or statistics referring to the complete 30-min time series) support this observation. For example, the standard deviation of time series 2 (0000–0030) is $\sigma_w = 0.11$ m $s^{-1}$, almost twice that of the other time periods (columns 2 and 3 of Table II). However, the visually apparent differences in the timing and characteristics of the turbulent bursts between time series 1 and 3 (2330–0000 and 0030–0100 ) shown in Figure 6 are largely masked in the global statistics. The vertical velocities of these two time series appear to have identical standard deviation values of ($\sigma_w = 0.064$ m $s^{-1}$).

Using the technique described above, however, it is possible to identify not only precisely when the bursts occurred but also to isolate the frequencies associated with just the turbulent portion of the time series. Figure 4b–d illustrates the coherent turbulent bursts identified by the technique for the 30-min vertical velocity traces observed between 2330 August 31 and 0100 September 1, 1998. Wavelet coefficients are considered to be significantly different (at the 95% level) to those expected due to red noise when they are greater than the dashed line (significance level) calculated for each individual

TABLE II
The global characteristics of turbulent time series and characteristics of turbulent bursts for select periods during the IOPs.

| | Standard deviation of vertical velocity of 30-min time series (m s$^{-1}$) | Mean vertical velocity of 30-min time series (m s$^{-1}$) | Standard deviation of vertical velocity of turbulent events (m s$^{-1}$) | Mean vertical velocity of turbulent events (m s$^{-1}$) | Average duration of turbulent event (min) | Total duration of turbulence within 30-min time series (min) | Intermittency (flux time/non-flux time) | Number of cases ($N$) |
|---|---|---|---|---|---|---|---|---|
| 2330–0000 PDT August 31, 1998 | 0.064 | −0.0065 | 0.079 | −0.018 | 1.7 | 5.2 | 0.213 | 1 |
| 0000–0030 PDT September 1, 1998 | 0.11 | −0.018 | 0.12 | −0.027 | 2.4 | 7.2 | 0.323 | 1 |
| 0030–0100 PDT September 1, 1998 | 0.064 | 0.0057 | 0.045 | −0.0081 | 6.2 | 6.2 | 0.261 | 1 |
| All 30-min nocturnal time series collected during IOPs | 0.076 | 0.003 | 0.047 | −0.003 | 0.94 | 2.86 | 0.120 | 196 |

time series. By comparing Figures 6 and 4, it is possible to show that this technique provides an effective way of isolating the turbulent bursts in the time series. If we statistically analyse the characteristics of the bursts (columns 3–6, Table II) the differences in duration, timing and intensity of the two series (2300–0000 and 0030–0100) become apparent. Stronger, shorter bursts of turbulence were observed between 2330 and 0000, with longer, weaker bursts observed between 0030 and 0100.

The duration (total and average), frequency and intermittency (flux time/total time) were then calculated for each 30-min turbulent time series collected between 2130–0630 during the IOPs. This time period was chosen since it represented the time period when daytime convective turbulence was no longer likely to be active and a stable boundary layer was well developed near the surface. The results (summarised in Table II) indicate that turbulent conditions typically prevail for a total of less than three minutes of each 30-min dataset. Typically three to four individual turbulent bursts or events, each lasting less than a minute, account for this mean total duration, and supports the underlying assumption that the surface layer can be classified as 'very stable'. These results are comparable to other studies of turbulence in the very stable nocturnal boundary layer. For example, Howell and Sun (1999) define a flux intermittency factor for their field experiment over grasslands in Kansas, which suggests that during very stable conditions turbulence persists for 1.25–4.0 min out of every 8-min dataset.

However, these figures are strongly weighted by the skewed distribution of the data points resulting from a large number of data files recording near-zero values. Thus, despite the prevailing stability, a wide range in turbulent conditions was observed (as reflected in the large standard deviation (2.4 min) in the dataset, with turbulence persisting on several occasions for more than eight (of the total 30) minutes of the time series.

### 3.2. Intermittent Bursts of Turbulence and Vertical Mixing Processes

Having established a technique to quantitatively evaluate the turbulent characteristics of the NBL, an attempt can be made to ascertain whether the nature of the turbulence provides an insight into the characteristics of vertical mixing of $O_3$ to the surface. $O_3$ is a highly volatile secondary pollutant, formed in the atmosphere as a result of the photo-dissociation of $NO_2$. This reaction can only take place in the presence of ultraviolet light, thus there are no known sources $O_3$ in the nocturnal boundary layer. Further, given the volatility of the gas, its rapid reaction with primary pollutants such as NO commonly emitted from vehicle exhausts (Vecchi and Valli, 1999) and its rapid deposition onto land surfaces (Broder and Gygax, 1985; Zaveri et al., 1995), $O_3$ concentrations near the surface typically remain near zero in the very stable boundary layer. In the absence of industrial NO emissions from chimney stacks, $O_3$ concentrations in the residual layer are likely to remain more constant with time. Thus increased $O_3$ concentrations observed at the surface in the very stable nocturnal boundary layer are likely to be generated by vertical mixing processes (Neu et al., 1994; Corsmeier et al., 1997; Kalthoff et al., 2000; Salmond and Mckendry, 2002).

Comparison of turbulence characteristics during nights when localised ozone maxima were observed at the site, with those nights when no significant increases in $O_3$ concentration were observed, reveals a small increase in the strength (as measured by the standard deviation) and total duration of the turbulent periods during nights when $O_3$ spikes were present (Table III). However, these differences are not statistically significant (assessed using standard measures based on independent samples *t*-test and ANOVA statistical tests).

This suggests that there was no difference between the mean turbulent characteristics of nights when ozone maxima were observed and nights when

TABLE III
The characteristics of turbulence associated with varied ozone concentration during IOPs.

| | Number of 30-min time series considered (*N*) | Average duration of turbulent 'bursts' (min) | Total duration of turbulence in the 30-min time series (min) |
|---|---|---|---|
| All nights | 196 | 0.94 | 2.86 |
| **Nights with ozone maxima** | **138** | **0.91** | **3.01** |
| Nights with no ozone maxima | 58 | 1.04 | 2.53 |
| **All periods when ozone concentrations increasing at the surface** | **41** | **0.96** | **3.38** |
| All periods when ozone concentration decreasing at the surface | 155 | 0.88 | 2.85 |
| **Periods when ozone concentration rapidly increasing by more than 6 ppb $h^{-1}$ at the surface** | **16** | **1.5** | **3.78** |
| Periods when ozone concentration rapidly decreasing by more than 6 ppb $h^{-1}$ at the surface surface | 23 | 0.68 | 1.77 |

they were not. This can be partly explained by the variability of ozone concentrations in the residual layer. For $O_3$ concentrations to increase at the surface turbulent transport processes must extend through the boundary layer to heights where increased concentrations of $O_3$ are found. Plumes of high $O_3$ concentration were intermittently advected over the site, at heights of 100–400 m as shown in Figure 7 (Salmond, 2001; Salmond and McKendry, 2002). Thus the availability of ozone aloft is likely to have had a marked impact on the efficiency of ozone transport processes.

A further explanation for the apparent similarity between turbulence characteristics during nights when ozone maxima were observed and those when they were not lies in the temporal scale of the turbulent processes. Ozone maxima typically lasted 1–2 h (Salmond and McKendry, 2002) and thus the associated changes in turbulent characteristics can be expected in only a small number of each of the time series observed during the course of the night. Further, for a surface peak in $O_3$ concentrations to be observed, local concentrations of pollutants that destroy ozone (such as NO) must be minimal throughout the profile and at the surface. Otherwise, $O_3$ transported to the surface will be rapidly removed from the system as a result of chemical titration processes and a consequent spike in surface concentration may not be observed. Thus periods of increased turbulence may have been observed during nights when increased surface $O_3$ concentrations were not observed due to low $O_3$ concentrations aloft or high surface NO concentrations, rather than due to the dynamic efficiency of the mixing process.

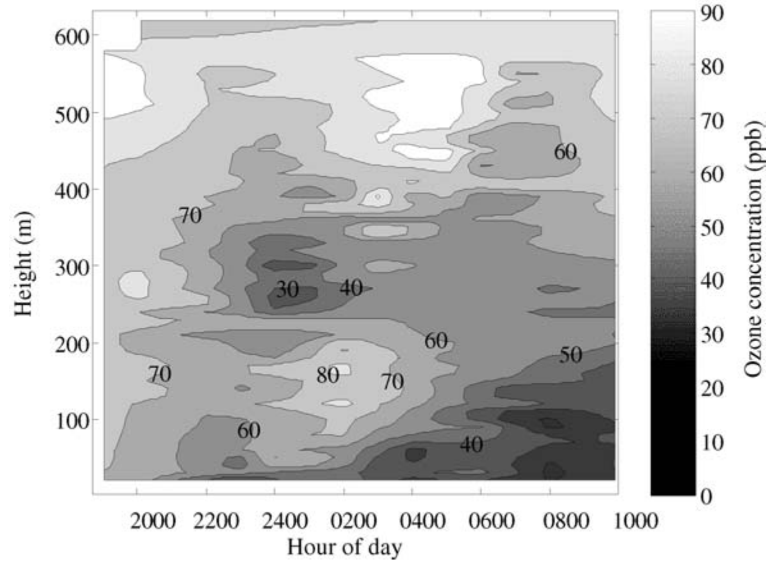


*Figure 7.* Contour plots of ozone concentration with time and height for the night of August 31–September 1, 1998.

To compare appropriate turbulent characteristics over appropriate time scales and reduce the influence of $O_3$ availability throughout the residual layer, all time series associated with increased surface ozone concentration were compared with those observed during periods of constant or decreasing ozone concentrations. Again no significant differences were observed between the two datasets (Table III). This may be due to the complexity of the system, which requires turbulence to coincide with both a vertical ozone gradient and absence of NO for an increase in ozone concentrations to be observed at the surface.

Thus to limit the variability due to ozone availability further, periods when marked increases in ozone concentration (more than 6 ppb $h^{-1}$) were compared with those observed when concentrations were decreasing at a rate of more than 6 ppb $hr^{-1}$. As shown in Table III the results show a much more significant difference between the average duration of the turbulence of both turbulent bursts and total turbulent activity in the time series of the datasets.

Despite the difficulties identified previously in establishing a generalised relationship between the characteristics of turbulence and increased $O_3$ concentration, analysis of $O_3$ spikes at a smaller scale reveals a good correlation between the characteristics of the turbulence and increased $O_3$ concentrations at the surface. This is further support by Figure 8, which reveals

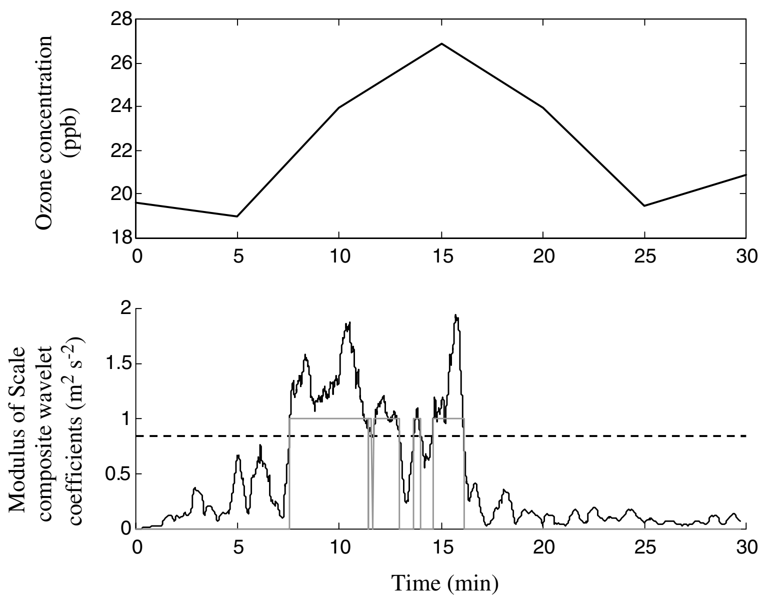


*Figure 8*. Comparison of surface ozone concentrations as recorded at 4 m by the ML 9811 ozone analyser with periods of turbulent activity recorded by the sonic anemometer and identified using wavelet analysis between 0000 and 0030 September 1, 1998.

that there is a good correlation between the timing of turbulent bursts observed between 0000 and 0030 September 1, and localised increases in surface $O_3$ concentration at a 5-min resolution. During this time period the tethersonde data show localised advection of a band of high $O_3$ concentrations at altitudes of 100–200 m above the site, as shown in Figure 7. Although detailed measurements of turbulence with height through the boundary layer were unavailable, with such a strong vertical gradient in concentrations close to the surface $O_3$ availability is unlikely to be a limiting factor. Surface concentrations of NO were also near zero at this time and no coincident changes in wind speed or direction were observed at the surface. This suggests that the technique provides an efficient way of identifying the turbulent bursts associated with the vertical mixing of $O_3$ to the surface under ideal conditions.

Further, a more detailed examination of nights when $O_3$ concentration remained comparatively homogeneous in the residual layer throughout the night and NO concentrations near zero, illustrates the strength of the relationship between the characteristics of the turbulent bursts and $O_3$ transport. For example, during the night of August 8–9, 1998 $O_3$ concentrations remained between 40 and 50 ppb in the residual layer. As shown in Figure 9

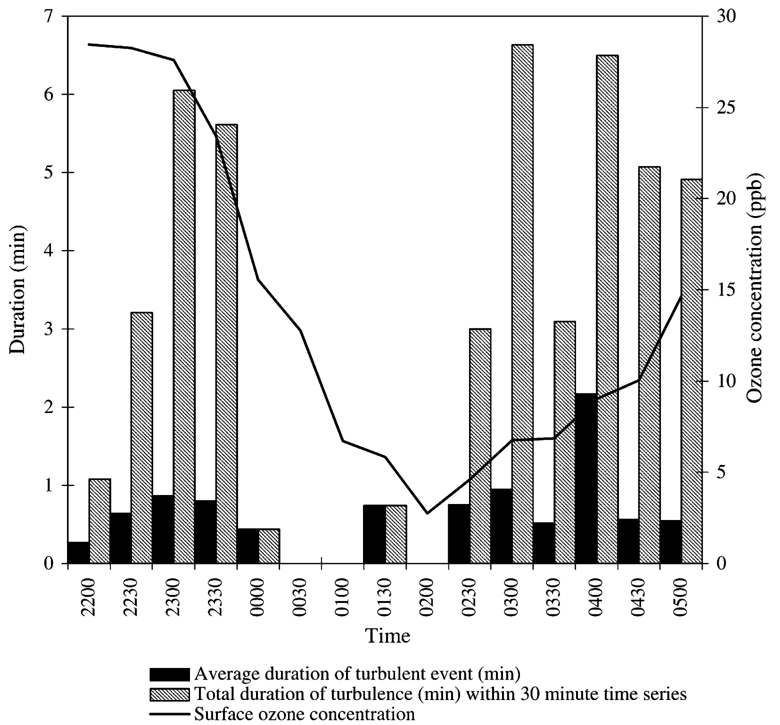


*Figure 9.* The relationship between average duration and total duration of turbulence and surface ozone concentrations August 8–9, 1998.

surface concentrations show a marked decrease in concentration with time as the stable layer develops from 2200 until 0200. Figures 9 and 10 indicate that during this period both the duration and intensity of the turbulent bursts decrease with time. From 0200 onwards $O_3$ concentrations start to increase and are coincident with both an increase in the duration and intensity of the turbulent bursts. Figure 10 also shows the global statistic for the standard deviation of the 30-min time series for comparison. It is interesting to note that, whilst this measure of the intensity of the turbulence decreases with time until 0030, it increases again before we see a coincident increase in surface $O_3$ concentration or the intensity of the turbulent bursts. This supports the underlying hypothesis that the technique effectively isolates bursts of turbulence associated with vertical mixing processes whilst the global scale statistics are affected by background (red and white) noise in the time series. This is likely to be particularly true during periods of very weak turbulence.

Unfortunately NO data were unavailable for the case study discussed above. However, the complexity introduced by varied $O_3$ concentrations in

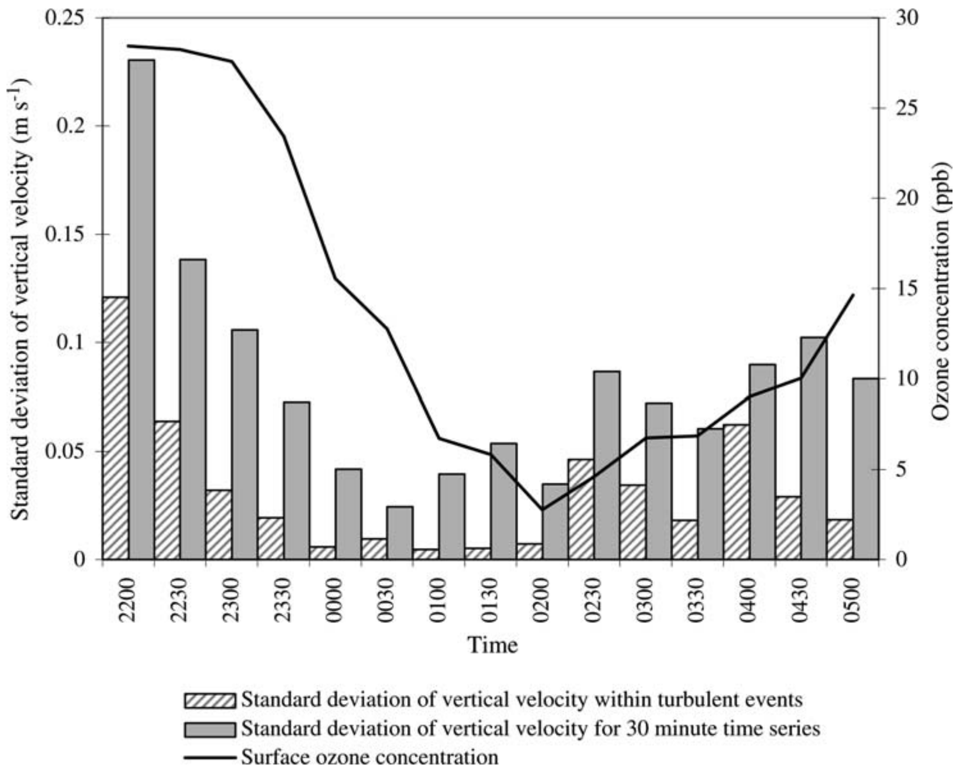


*Figure 10*. The relationship between standard deviation of mean vertical velocity, the mean vertical velocity of the turbulent component of the time series and surface ozone concentrations August 8–9, 1998.

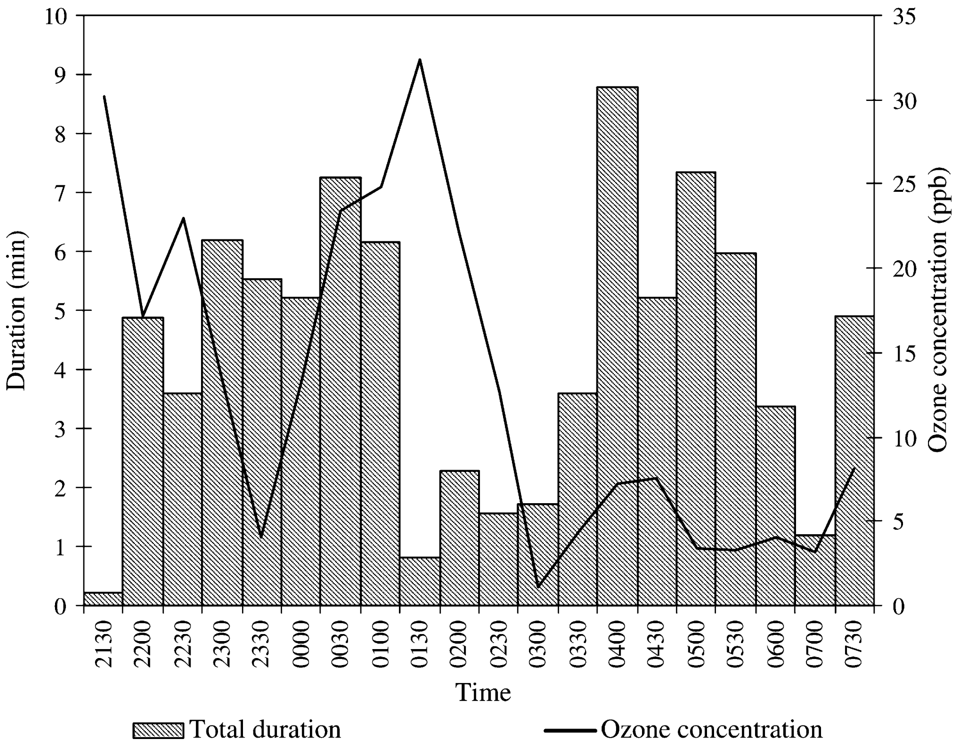


*Figure 11.* The relationship between total duration of turbulent events and surface ozone concentrations August 31–September 1, 1998.

the residual layer and NO concentrations near the surface is illustrated by returning to the primary case study of conditions during the night of August 31–September 1, 1998. Figure 11 illustrates the relationship between the total duration of the turbulent bursts and surface $O_3$ concentration and Figure 12 illustrates the intensity of the turbulence and surface NO concentrations. NO is primarily emitted by vehicular exhausts at the surface in this region, thus we would expect to see an increase in concentrations during very stable periods and decrease in concentration with increased turbulent activity as it is mixed through a deeper layer and reacts chemically with any ozone transported to the surface. This pattern is shown in Figure 12 and provides further evidence that the technique is accurately identifying periods of vertical mixing. Figures 11 and 12 also show that although from 2230 to 0100 we see an increase in the duration and strength of turbulent burst activity, $O_3$ concentrations do not start to increase near the surface until 2330. This may be accounted for in part by a localised increase in NO at the surface which occurs during the stable period prior to 2200, and partly due to the absence of high concentrations of $O_3$ in the boundary layer aloft (Figure 7). From 2330 advection of a band of high concentrations between 100 and 200 m

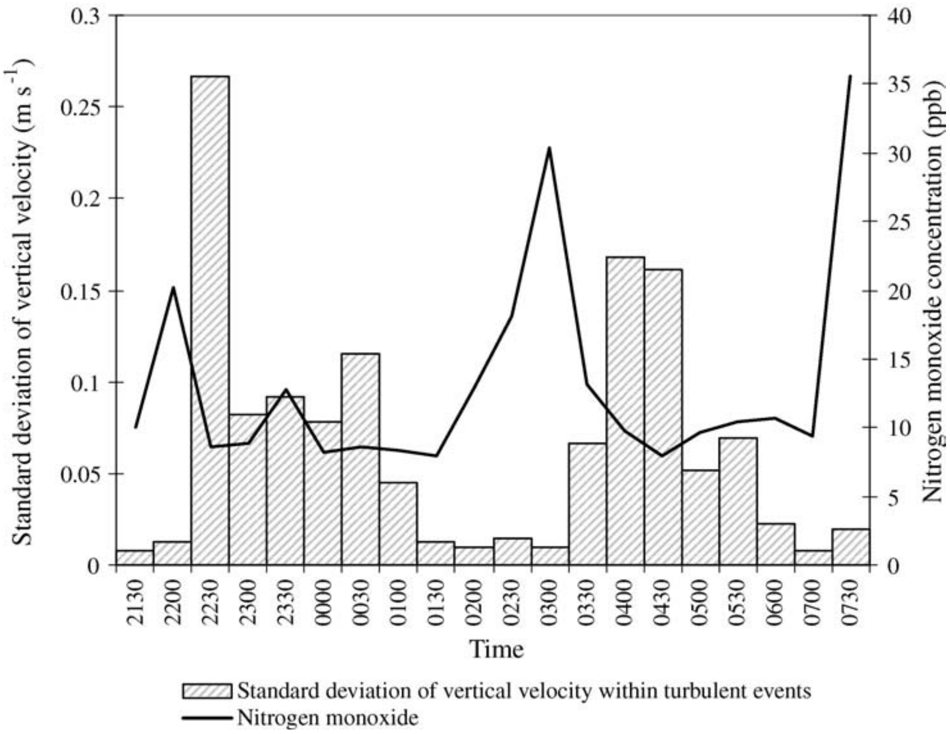


*Figure 12.* The relationship between standard deviation of mean vertical velocity of the turbulent component of the time series and surface nitrogen monoxide August 31–September 1, 1998.

coincides with the turbulent bursts and $O_3$ is mixed to the surface. Decreasing $NO_2$ concentrations (the likely by-product of the chemical reaction between $O_3$ and NO) during this period indicate both the absence of local sources of NO and increased dilution within the surface layer further supporting this argument. After 0100 turbulent activity decreases and a corresponding decrease in $O_3$ concentration and increase in NO concentration is observed. When turbulent activity increases again after 0300 an increase in $O_3$ concentrations is again observed. However, the net gain in $O_3$ concentration is reduced, and is likely to be, in part, a consequence of increased NO concentrations and in part by reduced $O_3$ availability within the profile.

These case studies suggest that the absence of a clear generalised relationship between turbulent characteristics of the boundary layer during periods of increased surface concentrations does not undermine the hypothesis that these events are the result of vertical mixing processes. It merely reinforces the importance of a complete understanding of the chemical and meteorological processes operating in the NBL. Clearly, whilst the technique appears to efficiently identify increased turbulence within the time series, the local surface chemistry and concentrations of $O_3$ aloft play as important a role in determining the characteristics of any resulting increase in surface $O_3$ concentration.

## 4. Conclusions

The complexity of the processes operating within the nocturnal boundary layer and the decoupling of forcing mechanisms from surface characteristics makes it very difficult to both describe and model turbulence in the very stable NBL (Stull, 1988). This paper presents a novel technique to describe the characteristics of intermittent turbulence observed near the surface in the very stable boundary layer. Application of the technique to observations made in the Lower Fraser Valley, British Columbia demonstrated that the turbulent component of vertical velocity time series could be efficiently and objectively isolated from a background of larger scale motions. Quantitative analysis revealed the presence of individual bursts of turbulence lasting 1–8 min within many of the 30-min time series.

A general relationship could not be identified between the characteristics of the turbulence (as determined by the duration and standard deviation of the vertical velocity of turbulent bursts) and the resulting vertical mixing of ozone to the surface. This is a result of the many processes operating in the nocturnal boundary layer that govern local transport and chemistry. For vertical mixing of $O_3$ to occur, $O_3$ must be available within the layer, and there must be turbulent activity to mix the $O_3$ to the surface. However, in the absence of other limiting factors the strength and duration of the turbulence appear to be important determinants of the concentration of $O_3$ mixed to the surface.

Clearly a larger, more detailed dataset is required to fully elucidate the relationship between the processes operating in the nocturnal boundary layer and the characteristics of the resulting turbulence in the surface layer. However, the efficient, objective technique developed provides a good basis for the quantitative description of intermittent turbulence characteristic of the very stable nocturnal boundary layer. Such analysis can provide insights into the complex relationship between air quality and intermittent turbulence. For example in the context of the data from the Lower Fraser Valley the results suggest that it is the absence of a marked vertical gradient in ozone concentrations rather than the absence of turbulent mixing processes that acts as a more consistent factor limiting the development of nocturnal ozone maxima at the surface. The technique developed here overcomes some of the limitations of traditional turbulent descriptive tools in the very stable boundary layer, and when applied to more extensive datasets has the potential to provide further insights into the characteristics of the turbulent processes operating in the nocturnal boundary layer.

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