

Influence of Atmospheric Stratification on the Integral Scale and Fractal Dimension of Turbulent Flows.

M. Tijera¹, G. Maqueda², C. Yagüe³

[1] Applied Mathematics Dpt. (Biomathematics). Complutense University of Madrid, Madrid, Spain.

[2] Astronomy, Astrophysics and Atmospheric Science Dpt. Complutense University of Madrid, Madrid, Spain.

[3] Geophysics and Meteorology Dpt. Complutense University of Madrid, Madrid, Spain.

Correspondence to: M.Tijera (mtijera@fis.ucm.es)

Abstract

In this work the relation between integral scale and fractal dimension and the type of stratification in fully developed turbulence is analyzed. Integral scale corresponds to that in which energy from larger scales is incoming into turbulent regime. One of the aims of this study is the understanding of the relation between the integral scale and the Bulk Richardson number, which is one the most widely used indicators of stability close to the ground in atmospheric studies. This parameter will allow us to verify the influence of the degree of stratification over the integral scale of the turbulent flows in the Atmospheric Boundary Layer (ABL). The influence of the diurnal and night cycle in the relationship between the fractal dimension and integral scale is also analyzed. Fractal dimension of wind components is a turbulent flow characteristic as it has been shown in previous works, where its relation to stability was highlighted. Fractal dimension and integral scale of the horizontal (u') and vertical (w') velocity fluctuations have been calculated using the mean wind direction as framework. The scales are obtained using sonic anemometer data from three elevations 5.8 m, 13 m and 32 m above the ground measured during the SABLES- 98 field campaign. In order to estimate the integral scales a method that combines the normalized autocorrelation function and the best gaussian fit ($R^2 \geq 0.70$) has been developed. Finally, by comparing,

1 at the same height, the scales of u' and w' velocity components it is found that almost
2 always the turbulent flows are anisotropic.

3

4 **1 Introduction**

5 The aim of this paper is to investigate the possible correlations between the integral
6 scale of the turbulent stratified flows in the Boundary Layer and parameters
7 characterizing topological features of the wind velocity field, such as fractal dimension
8 and its stability properties studied through the Bulk Richardson number. We are aware
9 that there is a lack of investigations between the integral scale and fractal dimension.

10 The size of the integral scale of the horizontal and vertical components and fractal
11 dimension of wind velocity near the earth's surface in boundary layer are determined.

12 Also, these magnitudes are compared between them and versus other parameters such as
13 the Bulk Richardson number. It is assumed that the turbulence is the primary agent that
14 causes changes in the boundary layer. In turbulent flows it is observed that time series
15 of meteorological variables as wind velocity, temperature, pressure and other
16 atmospheric mechanical magnitudes fluctuate in a disordered way with peaks extremely
17 sharp and irregular space and time variations. The complicated nature of these series
18 indicates that the motion of the air is turbulent. If we take a good look at the variety of
19 fluctuations of different periods and amplitudes observed in them we could explain the
20 complicated structure of turbulence. The irregularity of the time series obey to the
21 existence of different size and time scales and also to the nonlinear transfer of energy
22 that exists between them in the turbulent flows (Monin and Yaglom, 1971).

23 The irregular behavior of these flows is also due to waves and turbulence that are often
24 superimposed on a mean wind (Stull, 1998). If we filter the mean wind and waves in the
25 appropriate range we will only have turbulence. Some previous works present results
26 about this procedure (Tijera et al., 2008). In this work, the series of wind velocities in
27 the three directions x, y and z recorded by the anemometer are divided in series of five
28 minutes length. Each of these series applies the necessary transformation to get the
29 mean wind series (u horizontal component) and vertical velocity (w vertical component)
30 (Kaimal and Finnigan, 1994). During 5 minutes the average values of the magnitudes
31 in study remain constant. We filter horizontal and vertical mean wind velocity obtaining
32 the time series of fluctuations of the velocity in both directions ($u' = u - \bar{u}$, $w' = w - \bar{w}$).

1 When we observe these time series such as wind velocity, they vary in an irregular
2 shape and in spite of their complexity presents a self-similarity structure (Frisch,1995) .
3 This is a common property of the fractals, so that wind velocity could be considered as a
4 fractal magnitude. The modern physical notion of fractals is largely known due to
5 Mandelbrot (1977, 1985), but the mathematical notion of curves lines or sets having
6 noninteger dimensions is much older (Hausdorff, 1919, Besicovitch, 1929). An analysis
7 that compare the Hausdorff dimension and Kolmogorov capacities of self-similar
8 structure with non integer fractal dimensions (Kolmogorov capacity or box counting
9 dimension) was presented by Vassilicos (Vassilicos and Hunt, 1991). The wind
10 velocity versus time are irregular curves of this type, with noninteger dimensions. These
11 values correspond to the fractal dimension. A way of measuring the complexity of these
12 series is by means of fractal dimension. The Fractal Dimension of wind components is a
13 characteristic of turbulent flow as it has been shown in previous works where its
14 relation to stability was highlighted (Tijera et al., 2012)

15 In this paper the integral scale of u' and w' component are compared. The scales are
16 calculated using sonic anemometer data from three elevations 5.8 (~ 6), 13 and 32 m
17 above the ground at the main tower site of the Sables 98 field campaign. [Turbulent
18 motion of the atmospheric fluxes occurs through a broad range of scales from the
19 smallest scales that are usually defined as the scales at which the motion dissipates into
20 heat due to the viscosity of the fluid until the larger scales corresponding to the integral
21 scale.](#) The integral scale can be defined in several ways: the larger scale of the flow, the
22 scale above which the Fourier transform has a slope inferior a $-5/3$ slope, as which the
23 turbulent kinetic energy (TKE) is maximum. Micrometeorological studies have found
24 integral scale varying in a huge range, from around a hundred to a thousand meters
25 (Teunissen, 1980, Kaimal and Finnigan, 1994).

26 We study the anisotropy of the turbulent atmospheric flows in these scales comparing
27 integral scale of fluctuations of the velocity component along of the mean wind
28 direction and the vertical component at three different levels above the ground (5.8 m,
29 13.5 m, 32 m).

30

31 **2 Theoretical background**

32 The irregular behavior of the atmospheric turbulent fluxes in the boundary layer at large
33 Reynolds number leads us to be interested in calculating their fractal dimension. Fractal

1 dimension could help us to classify the irregularity of these flows. The more irregular
2 the flow the greater its fractal dimension. Turbulent flows are characterized by the
3 formation of many eddies of different length scales. These irregularities are due to the
4 superimposition of eddies of different sizes and it is related with a broad range of scales
5 which exist in turbulence. These scales vary from the smallest scales as dissipative scale
6 to larger scale as integral scale. This paper is concerned with the analysis of the
7 relationship between the integral scale and fractal dimension. As well as the relationship
8 between the integral scale with the Bulk Richardson number, this number provides a
9 measure of the intensity mixing, and of how a turbulent flow is prone to develop
10 instabilities. It is also used as a criterion for the existence or nonexistence of turbulence
11 in a stably stratified environment (a large positive value of $Ri > 0.25$ is indicative of a
12 decaying turbulence or a completely nonturbulent) (Arya, 2001).

13 In this section we describe the methodology applied to calculate the fractal dimension
14 and the integral scale. The estimation of the fractal dimension of time series has been
15 the most commonly used criteria to measure their chaotic structure, there exist different
16 works in that direction (Grassberger and Procaccia, 1982, Shirer et al, 1997). One of the
17 methods most commonly used to estimate to fractal dimension of atmospheric flows has
18 been the mean slope method through box-counting dimension using mean slopes of the
19 graph of $\ln N(L)$ versus $\ln(L)$ for small ranges of L , where $N(L)$ is the number of the
20 boxes of side L necessary to cover the different points that have been registered in the
21 physical space (velocity-time) (Falconer, 2000, Peitgen et al., 2004). As $L \rightarrow 0$ then
22 $N(L)$ increases, N meets the following relation:

$$23 \quad N(L) \cong kL^{-d} \quad (1)$$

24 The value d is the box-counting dimension that is an approximation of the Hausdorff
25 dimension and is calculated approximately by means of least-square-fitting of the
26 representation of $\log N(L)$ versus $\log L$ obtaining the straight line regression given by
27 the following equation:

$$28 \quad \log N(L) = \log k - d \log L \quad (2)$$

29 The fractal dimension d will be given by the slope of this equation as is shown in the
30 Fig.1.

31 In this paper we focus on calculating the integral scales for horizontal and vertical
32 component fluctuations u' and w' , and we studied their variations with respect to the

1 fractal dimension and with the Bulk Richardson number, a turbulent parameter of
 2 stability.

3 These integral scales have been estimated using the normalized autocorrelation function
 4 and a Gaussian fit. The velocity autocorrelation function as a function of τ (lags
 5 number) for u' component is:

$$6 \quad R(\tau) = \frac{\overline{u'(t)u'(t+\tau)}}{\overline{u'^2(t)}} \quad (3)$$

7 Integral time scale is:

$$8 \quad T_L = \int_0^{\infty} R(\tau) d\tau \approx \int_0^{\tau'} R(\tau) d\tau \quad (4)$$

9 The integral time scale provides a measure of the scales of eddies in the x direction of
 10 a flow field. In the Eq. (2) we observed that τ' denotes the last lag in the data series. In
 11 boundary layer observations this time scale can be related to a length by multiplying the
 12 mean wind velocity by time scale. This requires the assumption of frozen turbulence
 13 known as Taylor's hypothesis (Panofsky and Dutton, 1984). The integral length scale
 14 can be defined as:

$$15 \quad \lambda = \bar{v} T_L \quad (5)$$

16 The used method is based on Gaussian fit of the normalized autocorrelation function
 17 $R(\tau)$ and we calculated the value of τ that verifies the following equation:

$$18 \quad \tau - \int_0^{\tau} R(\tau) d\tau = \int_{\tau}^{\tau'} R(\tau) d\tau \quad (6)$$

19 The Fig. 2 shows the Gaussian fit for an example of a data series of wind velocities with
 20 τ that verifies Eq. 6. This value allows us to calculate the integral time scale
 21 multiplying it by the time interval between each lag.

22

23 **3 Description of Data**

24 The data set was recorded in the Research Centre for the lower Atmosphere (CIBA in
 25 the Spanish acronymus), located in Valladolid province (Spain) and were measured in
 26 the experimental campaign Sables-98. This research centre was set up primarily to study
 27 the atmospheric boundary layer. The campaign took place from 10th to 27th September
 28 1998 (Cuxart et al., 2000). This experimental site is a quite flat and homogeneous

1 which forms a high plain of nearly 200 Km², surrounded by crop fields and some small
2 bushes strewn over ground. Duero river flows along the SE border of the high plain.
3 The synoptic conditions during the period of study of eight consecutive days (from 14
4 to 21 September) were controlled by a high pressure terrain system which produces
5 thermal convection during the diurnal hours and from moderate to strong stable
6 stratification during the nights.

7 Here we analyze sonic anemometer data installed at 5.8 (~ 6), 13 and 32 m, these data
8 set are five minute series. During this period of study the series are obtained in a
9 consecutive period along the day every 30 minutes by a sonic anemometer and these
10 series have been divided into five minutes series and over them the mean wind velocity
11 of the horizontal and vertical components is calculated. At a rate of 20 data points per
12 second, sonic anemometers can resolve integral scales between about 10 m to 2000 m of
13 u' horizontal component and 1 m to 1000 m of the w' vertical component, depending on
14 the height in which the sonic anemometer is positioned and at the wind speeds typically
15 measured in the Sables-98 experiment. We detect vertical scales over a broad range of
16 scales from 1 m to 1000 m. The integral scales here are calculated based on the
17 autocorrelation function, the mean wind velocity and integral time scale and each of
18 them can be expected to vary significantly. As the integral scale are larger scales of
19 turbulent flows is it possible to detect vertical scales larger than heights at which the
20 sonic anemometer are located.

21

22 **4 Results**

23

24 **4.1 Fractal Dimension, integral scale and stability of stratification.**

25 In this paper we analyze the influence of stability of stratification on fractal dimension
26 and integral scale. Different atmospheric surface-layers data are separated into thermal
27 and dynamics stability classes based on a dimensionless parameter such as the Bulk
28 Richardson number Ri_B . This parameter represents the ratio of the production or
29 destruction of turbulence by buoyancy and by wind shear strain that is caused by
30 mechanical forces in the atmosphere:

$$Ri_B = \frac{g}{\theta} \frac{\Delta\bar{\theta}\Delta z}{(\Delta\bar{u})^2} \quad (7)$$

1 where g is the gravity acceleration and $\bar{\theta}$ the average potential temperature at the
2 reference level, the term $\frac{g}{\bar{\theta}}$ is known as the buoyancy parameter. Ri_B is positive for
3 stable stratification, negative for unstable stratification and approximate zero for neutral
4 stratification (Arya, 2001). The way to calculate this number is described next:

5 1. Calculation of the mean potential temperatures at height $z = 32$ m, and close to the
6 surface $z = 5.8$ m, namely $\bar{\theta}_{32}$ and $\bar{\theta}_{5.8}$ respectively. Being $\Delta\bar{\theta} = \bar{\theta}_{32} - \bar{\theta}_{5.8}$. The
7 potential temperature has been estimated as relative to ground level by using the
8 following formula: $\Delta\theta = \Delta T + \Gamma\Delta z$, $\Gamma = 0.0098 \text{ K m}^{-1}$ (Arya 2001)

9 2. Obtaining of \bar{u}_z the mean wind velocity module at the height $z = 32$ m and $z = 5.8$
10 m, denoted by \bar{u}_{32} and $\bar{u}_{5.8}$ respectively, where $\Delta\bar{u} = \bar{u}_{32} - \bar{u}_{5.8}$.

11 Once the values of $\Delta\bar{\theta}$, $\Delta\bar{u}$ and Δz have been obtained by means of Eq. (7) we
12 calculate the Bulk Richardson number in the layer between 32m and 5.8m.

13 In Fig. 3 we present the variation of the fractal dimension of the u' horizontal
14 component of the velocity fluctuations along time at the three considered heights: 5.8 m,
15 13 m and 32 m. The behaviour of these variations is similar at the three heights. The w'
16 component fluctuation presents an analogous behaviour. The fractal dimension values
17 are in a range between 1.30 to nearly 1.00. We have found that during the diurnal hours
18 the fractal dimension is bigger than at night (Tijera, 2012). We have no theoretical
19 reason to explain this result, but a possible explanation of why this happens could be
20 that fractal dimension is related with atmospheric stability and with the intensity of
21 turbulence. It is well known that the intensity of turbulence grows up as solar radiation
22 increases, producing instability close to the ground, mainly in the hours of noon.
23 Therefore, one of the possible reasons of the increase of FD is the instability of the
24 turbulent flow. In the other hand, during the nights a strong atmospheric stability
25 usually exists, so the fractal dimension is usually smaller than during the diurnal hours.

26 In Fig 4 it is observed how the integral scale varies versus time at the three heights.
27 There are some questions that have not been clarified yet. For example: How does the
28 diurnal and night cycle influence on the integral scale? Which is the mechanism
29 responsible for the growth of the integral scale? It has been observed in the previous
30 works that under certain conditions the turbulent flows self – organize and develop

1 large-scale structures take place through an inverse cascade that occurs in stably
2 stratified anisotropic flows (with or without rotation)(Marino et al., 2014, Smith and
3 Waleffe, 2002). The inverse cascade mechanism might also be responsible for the
4 growth of the integral scale in the stratified atmosphere. It is a fundamental issue that
5 we should clarify in a future research. As it is indicated in Fig 4 the integral scale for u'
6 component varies between around 100 m on their minor scales, until above 1500 m for
7 its major scales. The integral scales for w' component are slightly lower than u'
8 component. It is shown that these vertical scales can reach sizes between a few tens of
9 meters until 1000 m in some occasions. It is observed in each of the components that the
10 greater is the height at which is located the anemometer, greater is the integral scale in
11 turbulent flow. Usually, at 32 m these scales are, on average, greater than those of the
12 13 m and the latter higher than at 5.8 m height.

13 Although the conceptual model of turbulence as eddies of various sizes is useful, it is
14 difficult to obtain a correlation between the integral scale and fractal dimension in the
15 atmosphere if we consider values throughout the whole day. However, it is much easier
16 to find a relationship between the integral scale and fractal dimension of horizontal and
17 vertical components of the wind velocity if we separate the hours of the day and night,
18 and hence analyze the influence of diurnal and night cycle over these parameters.
19 Daylight hours are from 6-18 UTC and the night from 18-6 UTC. These data set are
20 analyzed in the three studied heights. Fig. 5 shows the variations of the integral scale
21 versus fractal dimension at the level of 5.8 m for horizontal component. As it can be
22 appreciated in Fig. 5 in the diurnal hours the average values of the integral scale versus
23 the fractal dimension can be adjusted to the straight regression line given by the linear
24 equation that appears on the top left of the graph. During those hours these values of the
25 integral scale increase from a few tens of meters until 400 m with increasing values of
26 the fractal dimension until 1.25. During the nights the average values of the integral
27 scale decreases with the increase in the fractal dimension. These values also fit a
28 straight regression line as it is indicated in Fig. 5. One of the possible explanations for
29 this behaviour is that during the diurnal hours the average values of the integral scale
30 increase due to the unstable stratification. During the nights, the existence of the stable
31 stratification decreases the integral scale with an increase in fractal dimension until the
32 approximate value of 1.2. This tendency appears also in the other two heights, at 13 m
33 and at 32 m as it is shown in Fig. 6. Although during the diurnal cycle at 32 m the linear

1 fit it is not so evident, the maximum scales are in the 1.15-1.20 range of the fractal
2 dimension as it is illustrated in Fig. 6 (c).

3 For the vertical component in the three studied levels, the behaviour is slightly different.
4 The averages values have fitted a quadratic function as it is indicated in Fig. 7. During
5 the diurnal hours the averages values of integral scale reach maximum scales around
6 the value of the fractal dimension of 1.15 at the three heights. From this value the
7 integral scale decreases when fractal dimension increases. These maximum integral
8 scales depend on the height. At the level of 5.8 m their sizes reach 50 m in average and
9 the scattering of the values shows higher values that could reach 100 m. At the level of
10 13 m the values are about 100 m, the dispersion of these scales can reach sizes of 200 m
11 and at the height of 32 m their larger average scales are approximately around 200 m
12 and due to the variances of the data set could reach sizes of 400 m. From the value of
13 the fractal dimension value of 1.15, the scales decrease until a few meters.

14 Throughout the night the average values of the integral scales decrease with the increase
15 of the fractal dimension in a parabolic way as it is indicated in Fig. 7. This happens due
16 to the stable stratification that occurs at nights. This behavior during the diurnal and
17 night hours for w' component of the integral scale is similar to the results obtained for
18 u' component, although the fits of averages values are parabolic and not linear. In all
19 these cases our R^2 values and confidence levels are high as it is indicated in Fig. 7.

20

21 **4.2 Relationship between integral scale and Bulk Richardson number**

22 Among the numerous parameters existing to characterize the degree of stratification in
23 the atmosphere we will use the Bulk Richardson number. The interpretation of this
24 number has already been mentioned in the previous section. Here, we analyze how the
25 integral scale of each one of the u' horizontal and w' vertical components varies with
26 the Bulk Richardson number in diurnal and night cycle in the studied period. These
27 results are shown in Fig. 8 for horizontal component and in Fig. 9 for vertical
28 component. During the daylight hours appear the three kinds of stratification: unstable,
29 neutral and stable as it is shown in the three graphs on the left side of Fig. 8 and the Fig.
30 9, each one corresponds to the different heights. In the stratification unstable and neutral
31 the integral scales are higher than the integral scales under the influence of the stable
32 stratification. At 5.8 m for the horizontal component these scales vary between 200 m

1 and values slightly higher than 400 m and in the case of neutral stratification could
2 increase until 600 m. This same behaviour occurs in the other two studied heights 13 m
3 and 32 m although their scales are slightly higher as it is illustrated in Fig. 8. During the
4 nights it is observed the biggest stability due to positive values of the Bulk Richardson
5 number.

6 The same results are obtained for the integral scales of vertical component, although
7 their sizes are smaller. At 5.8 m during the diurnal hours the average values reach about
8 50 m and during the night hours their values are below 50 m. At 13 m and 32 m in the
9 diurnal hours the average values could reach about 150 m and 200 m and at the night
10 hours are below 100 m and 200 m respectively.

11

12 **4.3 Analysis of the anisotropy with the integral scale**

13 In the last section we study the relationship between the integral scales of the horizontal
14 and vertical components at different heights: 5.8 m, 13 m and 32 m. In Fig. 10 we
15 represent the integral scale of u' component versus the integral scale of w' component at
16 three studied heights and we find linear relations with the averages values of these
17 scales. All integral scales measured during the period of study from 14 to 21 of
18 September appear in this figure. The linear fits obtained are acceptable, with high R^2
19 values at 13 m and 32 m, as it is indicated in Fig. 10. The linear regression appears on
20 the top left of each graph: at 5.8 m $L_{intu}(5.8\text{ m}) = 1.46 L_{intw}(5.8\text{ m}) + 178$, at 13 m
21 $L_{intu}(13\text{ m}) = 0.957 L_{intw}(13\text{ m}) + 275.6$ and at 32 m $L_{intu}(32\text{ m}) = 0.646 L_{intw}(32\text{ m}) + 370$,
22 being L_{intu} and L_{intw} the average values of the integral scale for horizontal and vertical
23 component respectively.

24 The data in Fig. 10 appear quite scattered and the average values could be representative
25 to find relationships between these scales. This scatter is due to the large number of
26 uncontrolled variables, nonlocal disturbance, the presence of waves, horizontal
27 inhomogeneity, low frequency disturbances, etc. These graphs are showing that the
28 scale measured at 32 m is nearly always larger than the integral scale measured at 5.8 m.
29 On the basis of the results obtained, we find slight differences between these
30 components, thus there is anisotropy in atmospheric turbulent flows. In isotropic
31 turbulence the integral scales of both components should be the same at the same

1 height. Only under certain conditions and over limited scales is isotropy a property of
2 turbulence in the stratified atmosphere (Thorpe, 2005).

3 4 **5 Conclusions**

5 We have calculated the fractal dimension and the integral scale of the horizontal and
6 vertical components using wind velocity data at three different heights: 5.8 m, 13 m and
7 32 m. The numerical results show light significant differences on the diurnal and night
8 cycle when the variation of the integral scale is analyzed versus the fractal dimension.
9 Atmospheric stratification is analyzed in the three heights through the Bulk Richardson
10 number, finding the three types of stratification during diurnal hours and at night hours
11 the stable stratification. It would be interesting for future works to study the growth of
12 the integral scale in stratified flows and if it could be due to the inverse cascade on both
13 diurnal and nighttime cycles. The main conclusions of this study are as follows.

14 Although all data appear quite scattered in this work, the averages values of these
15 magnitudes show interesting results. During the diurnal hours the averages values of the
16 integral scale of the horizontal component increases with the increase in fractal
17 dimension until around 1.25 at 5.8 m and 13 m height. At these heights we have found
18 linear fits between these magnitudes with high coefficients of correlation. While at 32 m
19 the linear fit is not so evident, the maximum scales are in the 1.15-1.20 range of the
20 fractal dimension. One of the possible explanations for this behaviour is that during the
21 diurnal hours the average values of the integral scale increase due to the unstable
22 stratification. During the night hours the average values of the integral scale decreases
23 with the increase in the fractal dimension. These values also fit a straight regression
24 line at the three analysed heights. During the nights the existence of the stable
25 stratification decreases the integral scale with an increase in fractal dimension until the
26 approximate value of 1.2.

27 For the vertical component of the integral scale the results are similar, even though with
28 slight differences. The averages values have fitted a quadratic function. During the
29 diurnal hours the averages values of integral scale reach maximum around the value of
30 the fractal dimension of 1.15 in the three heights. From this value the integral scale
31 decrease with the increase of the fractal dimension until a few meters. The different
32 degree of stratification along diurnal hours will be reflected in that different behaviour

1 from the value of 1.15. At nights when stability is normally major the integral scale
2 decrease with increasing the fractal dimension of a parabolic way.

3 In the unstable and neutral stratification the integral scales are higher than the integral
4 scales under the influence of the stable stratification.

5 To characterize the anisotropy of turbulent flows we have used the comparison of
6 integral scales of horizontal and vertical component showing that the scale of u'
7 component is almost always larger than the scale of the w' component at the same
8 height.

9

10 **Acknowledgements**

11 This research has been funded by the Spanish Ministry of Science and Innovation
12 (projects CGL2009-12797-C03-03). The GR35/10 program (supported by Banco
13 Santander and UCM) has also partially financed this work through the Research Group
14 “Micrometeorology and Climate Variability” (No 910437). Thank to participant teams
15 in SABLES-98 for the facilities with the data.

16

17 **References**

18 Arya S. P.: Introduction to Micrometeorology. International Geophysics Series,
19 Academic Press. 420 pp, 2001

20 Besicovitch A.S.: On linear sets of points of fractional dimension, *Mathematische*
21 *Annalen.*, 101, 161-193, 1929

22 Cuxart J., C. Yagüe, G. Morales, E. Terradellas., J. Orbe, J. Calvo, A. Fernández, M.R.
23 Soler, C. Infante, P. Buenestado, A. Espinalt, H.E. Joergensen, J.M. Rees, J. Vilà, J.M.
24 Redondo, I.R.Cantalapiedra, and Conangla, L.: Stable atmospheric boundary layer
25 experiment in Spain (SABLES 98): A report. *Bound.-Layer Meteorol.*, 96, 337-370,
26 2000

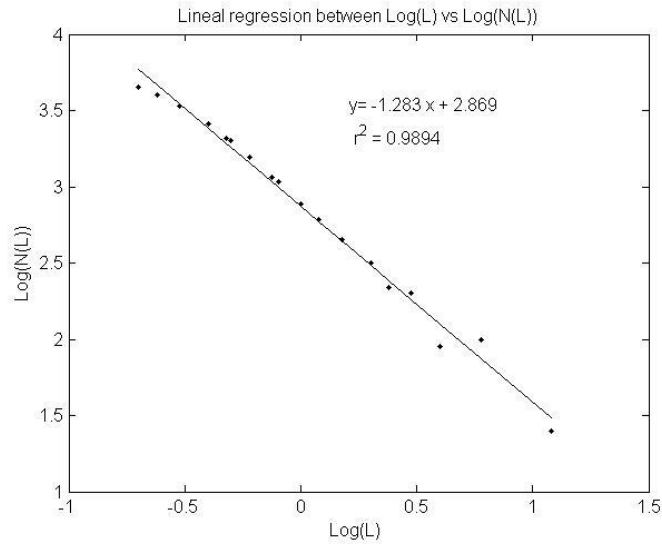
27 Falconer K. J.: *Fractal Geometry Mathematical Foundations and Applications.* John
28 Wiley & Sons, Ltd. 288 pp, 1990

29 Frisch, U.: *Turbulence.* Cambridge University Press, England, 296 pp, 1995.

- 1 Grassberger P. and Procaccia I.: Characterization of Strange Attractors. Phys. Rev Lett.
2 50, 346-349, 1983
- 3 Hausdorff F.: Math. Ann., 79, 157, 1919
- 4 Kaimal, J. C. and Finnigan J.: Atmospheric Boundary Layer Flows. Their Structure and
5 Measurement, Oxford University Press. 289 pp, 1994
- 6 Mandelbrot, B.B.: Fractal: Form, Chance and Dimension. Freeman, San Francisco, 1977
- 7 Mandelbrot, B.B.: The Fractal Geometry of Nature. Freeman, San Francisco, 1985
- 8 [Marino R, Mininni P.D., Rosenberg D. and Pouquet A.: Large-scale anisotropy in stably
9 stratified rotating flows. Phys. Rev. E 90, 023018, 2014](#)
- 10 Monin A.S. and Yaglom A.M.: Statistical Fluid Mechanics Mechanics Vol 1, Dover
11 Publications, 769pp, 1971
- 12 Panofsky H.A. and Dutton. : Atmospheric Turbulence, Wiley and Sons, 397 pp, 1984
- 13 Peitgen H., Jürgens H. and Saupe D.: Chaos and Fractals. Springer-Verlag 971pp, 2004
- 14 Shirer H.N., Fosmire C.J., Wells R., Suciú L.: Estimating the Correlation Dimension of
15 Atmospheric Time Series. Journal of the Atmospheric Sciences: 54, pp. 211-229, 1997
- 16 [Smith L and Waleffe F.: Generation of slow large scales in forced rotating stratified
17 turbulence. J. Fluid Mech. 451, 145-168, 2002](#)
- 18 Stull R. B.: An introduction to Boundary Layer Meteorology. Kluwer Academic
19 Publishers, 670pp, 1988
- 20 Teunissen H W.: Structure of mean winds and turbulence in the planetary boundary
21 layer over rural terrain. Boundary-Layer Meteorol 19, 187-221, 1980.
- 22 Thorpe S.A.: The turbulent ocean. Cambridge Universe Press. 439pp., 2005
- 23 Tijera, M., Cano J.L., Cano, D., Bolster, B. and Redondo J.M.: Filtered deterministic
24 waves and analysis of the fractal dimension of the components of the wind velocity.
25 Nuovo Cimento C. Geophysics and Space Physics 31, 653-667, 2008
- 26 Tijera M., Maqueda G., Yaque C., and Cano J.: Analysis of fractal dimension of the wind
27 speed and its relations with turbulent and stability parameters, Intech, Fractal Analysis
28 and Chaos in Geosciences, 29-46, 2012

1 Vassilicos J. C. and J. C. R. Hunt.: Fractal dimensions and spectra of interfaces with
2 application to turbulence. Proc. R. Soc. London Ser. A 435-505., 1991

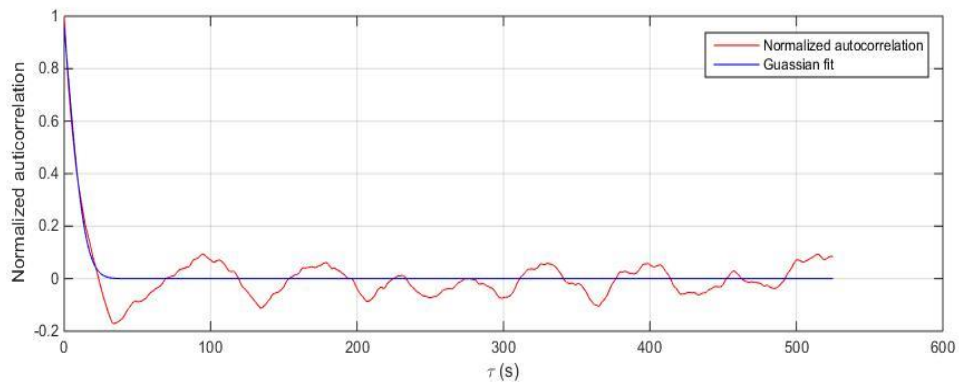
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32



1

2 **Figure 1.** Example of linear regression between number of not empty boxes and length
 3 side of the box. The slope (d) is the fractal dimension of the w' component, $d = 1.28 \pm$
 4 0.03 for a example of the w' component of the wind velocity.

5 I

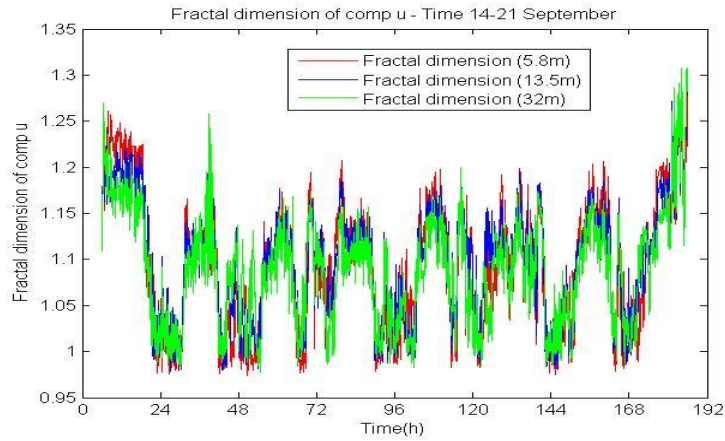


6

7 **Figure 2.** Gaussian fit for a data series of wind velocities u' component that allows us
 8 to calculate the integral scale.

9

10



1
2
3
4
5
6
7
8
9

Figure 3. Variation of the fractal dimension versus time for the u' component fluctuation at the three heights, showing the influence of the diurnal cycle.

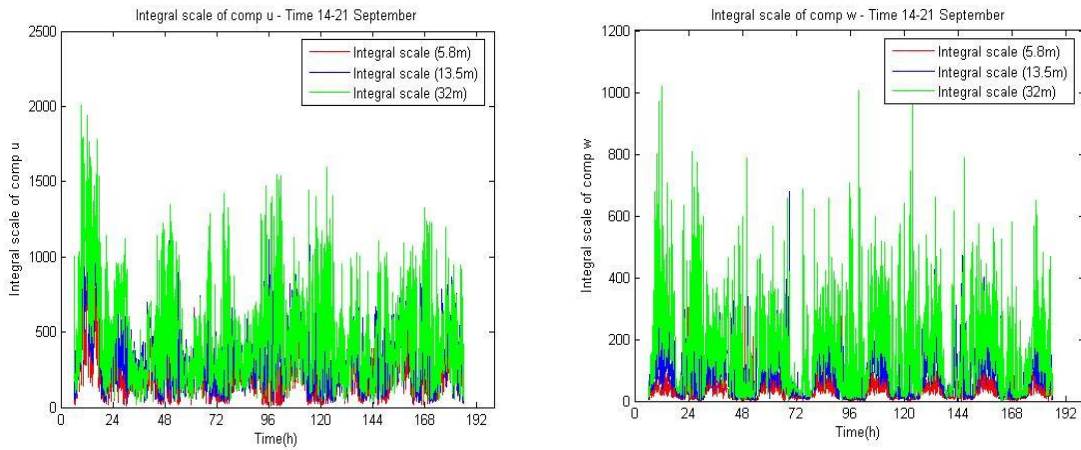
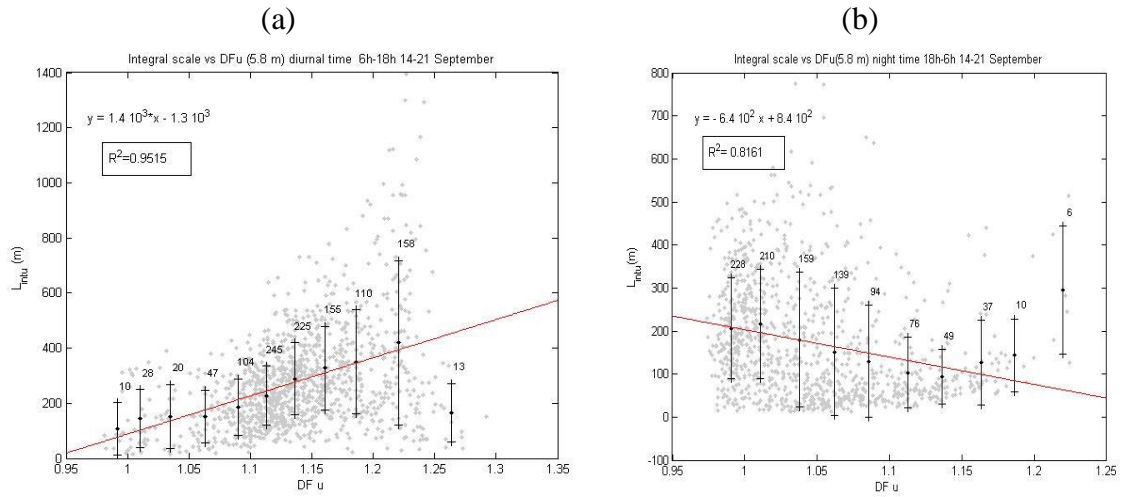


Figure 4. Variation of the integral length scale of horizontal and vertical components versus time at the three heights.

10
11
12
13
14

1



2 **Figure 5.** Variations of the integral scale versus the fractal dimension of u` component
3 of the wind velocity at 5.8 m. (a) diurnal hours 6h-18 h, (b) night hours 18 h - 6h. On
4 the top left of the each graph it is indicated the linear regression of the averages values
5 (a) $L_{intu}(5.8 \text{ m}) = 1.4 \cdot 10^3 DF_u(5.8 \text{ m}) - 1.3 \cdot 10^3$ (b) $L_{intu}(5.8 \text{ m}) = -6.4 \cdot 10^2 DF_u(5.8 \text{ m}) +$
6 $8.4 \cdot 10^2$, being L_{intu} and DF_u the integral scale and fractal dimension for u component
7 respectively.

8

9

10

11

12

13

14

15

16

17

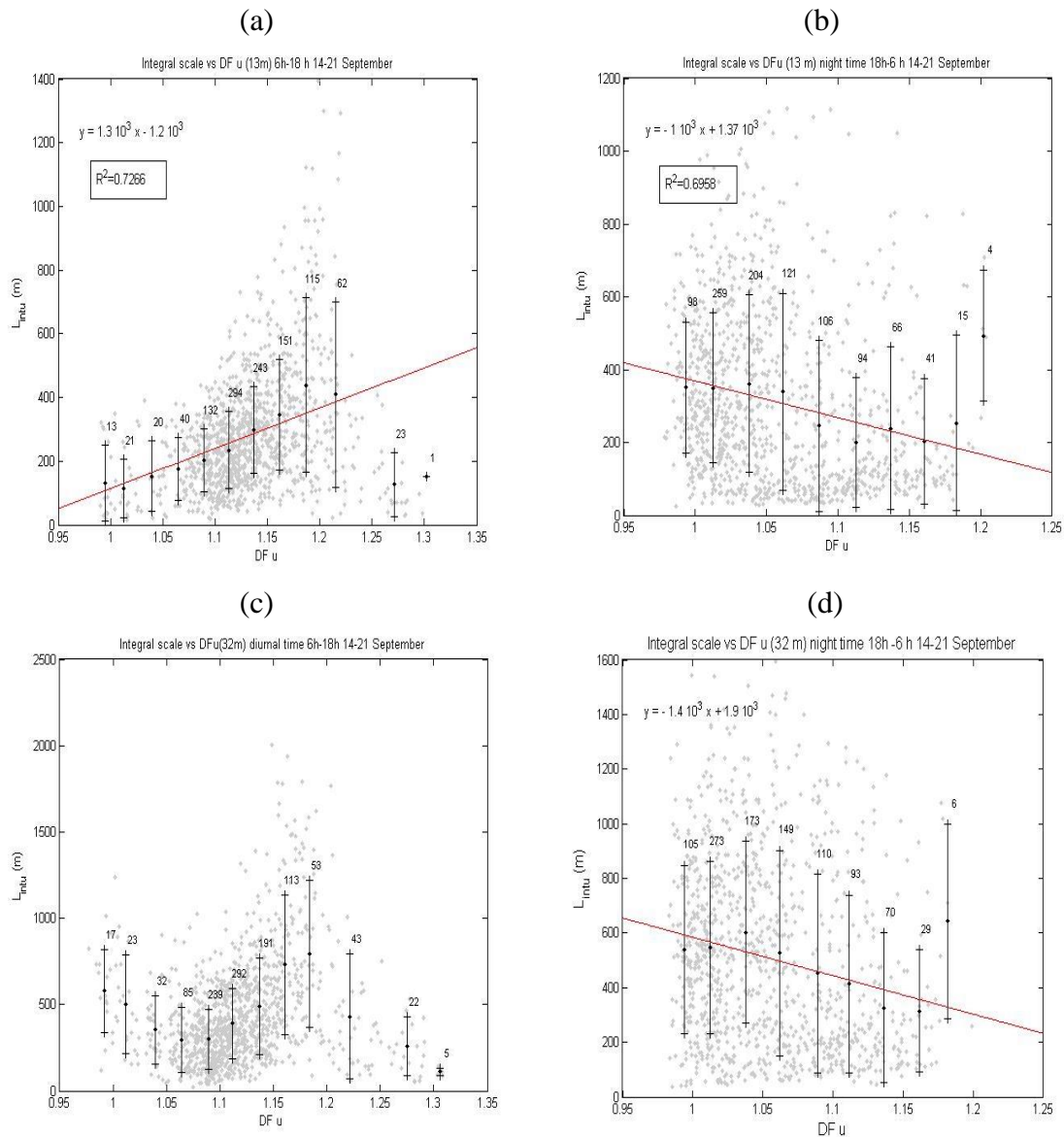
18

19

20

1

2

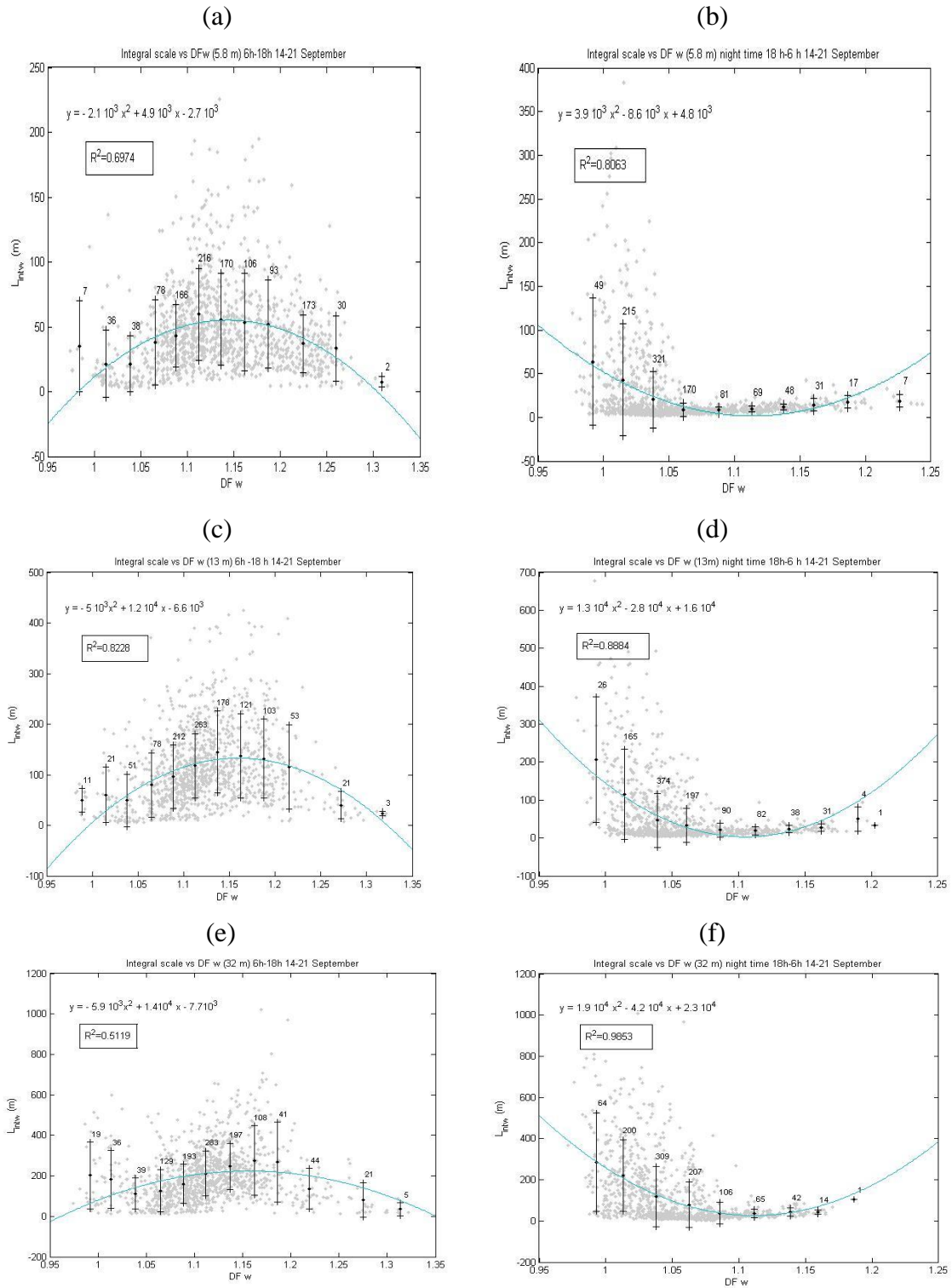


3 **Figure 6.** Variations of the integral scale versus the fractal dimension of the u'
 4 component at 13 m and 32 m. (a) and (c) diurnal hours, (b) and (d) night hours. In the
 5 same manner that in the figure 5 the linear fits are: (a) $L_{intu}(13\text{ m})= 1.3 \cdot 10^3 DF_u(13\text{ m}) -$
 6 $1.2 \cdot 10^3$, (b) $L_{intu}(13\text{ m})= -1 \cdot 10^3 DF_u(13\text{ m}) + 1.37 \cdot 10^3$, (d) $L_{intu}(32\text{ m})= -1.4 \cdot 10^3$
 7 $DF_u(32\text{ m}) + 1.9 \cdot 10^3$

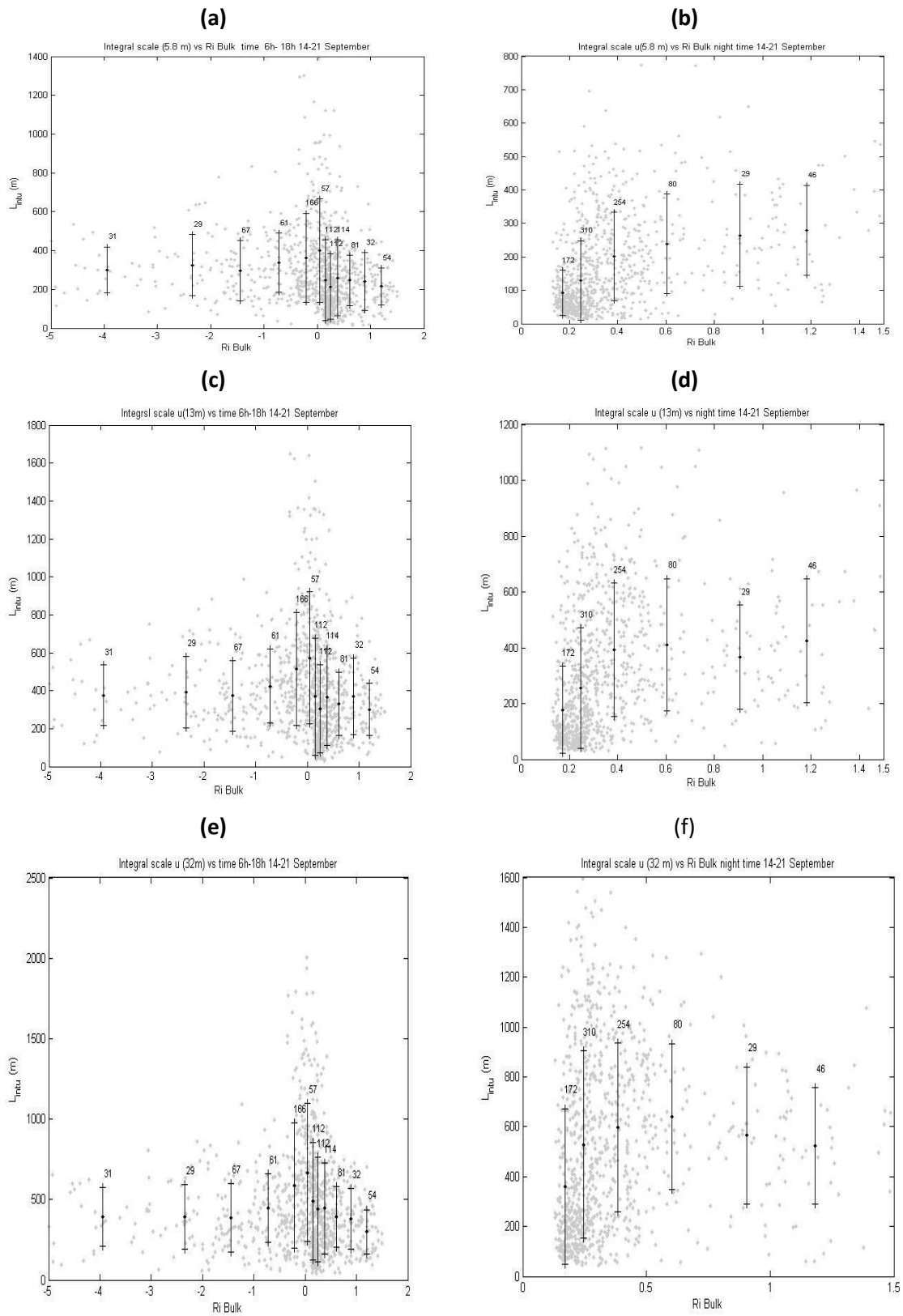
8

9

10

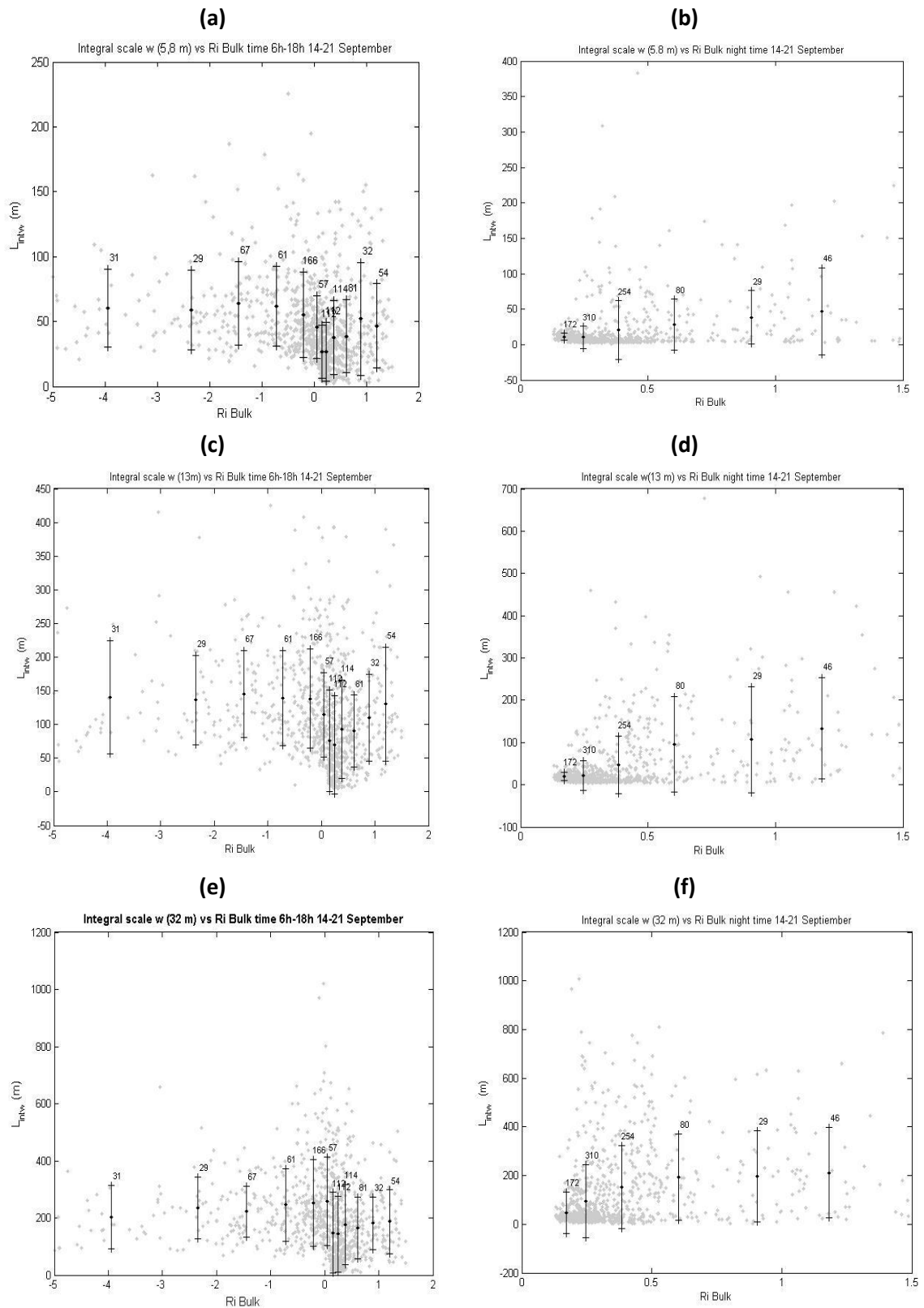


2 **Figure 7.** Variations of the integral scale versus the fractal dimension of the w`
 3 component at 5.8 m, 13 m and 32 m. (a), (c) y (e) diurnal hours, (b), (d) y (f) night.
 4 hours. The fits to a quadratic function of the averages values appear on the top left of
 5 the each graph, being y variable L_{intw} and x variable DF_w .



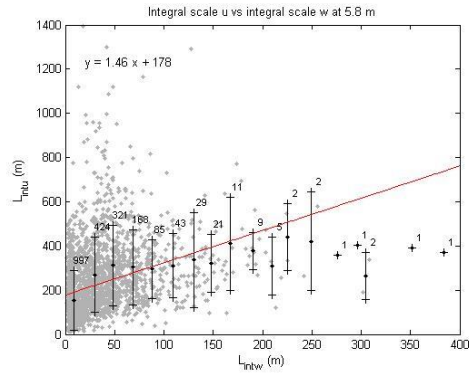
1 **Figure 8.** Integral length scales of u component plotted against the Bulk Richardson number
 2 at 5.8 m, 13 m and 32 m. (a), (c) y (e) diurnal hours, (b), (d) y (f) night hours.

3

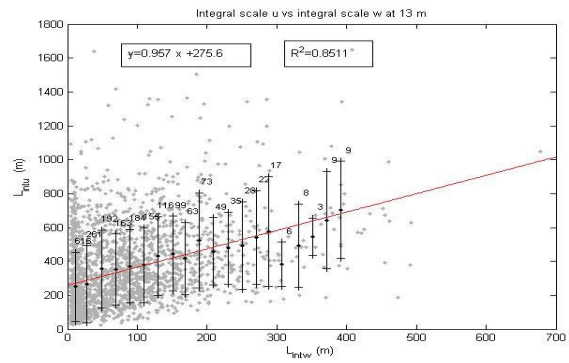


1 **Figure 9.** Integral length scales of w' component plotted against the Bulk Richardson
 2 number at 5.8 m, 13 m and 32 m. (a), (c) y (e) diurnal hours, (b), (d) y (f) night hours

(a)



(b)



(c)

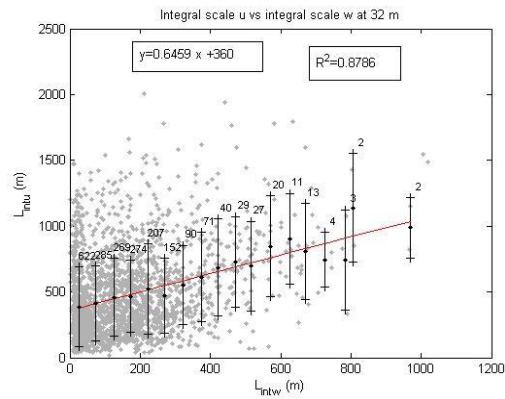


Figure 10. Comparison of integral scales of u' component and w' component (a) at 5.8 m, (c) at 13 m (c) at 32 m, showing that the averages values of these scales fit to the linear regression indicated on the top left each graph. Data set appear as a cluster around the straight line.