# TURBULENCE STRUCTURE OF THE ATMOSPHERIC BOUNDARY LAYER IN STABLE CONDITIONS

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## Abstract

Data from SABLES98 experimental campaign have been used in order to study the influence of stability (from weak to strong stratification) on the flux-profile relationships for momentum and heat: $\phi_m$ and $\phi_h$. Standard instrumentation, 14 thermocouples and 3 sonic anemometers at three levels (5.8, 13.5 and 32 m) were available from 10 to 28 September 1998 and calculations are done in order to extract structure functions and intermittency. The results show increasing values of $\phi_m$ and $\phi_h$ with increasing stability parameter and then values remain constant. As a consequence of these constant, but different values of $\phi_m$ and $\phi_h$ for strong stability, when linear similarity functions (Businger et al., 1971) are used to calculate surface fluxes of momentum and heat an important underestimation of the turbulent mixing is produced. The differences in structure and higher order moments between stable and neutral turbulence is studied in terms of turbulent intermittent mixing and velocity PDF's.

### 1. Introduction

Further results investigating the intermittency of atmospheric turbulence in strongly stable situations affected by buoyancy and internal waves are presented. It is found that the study of structure functions used to determines intermittency may be parametrized in terms of the Richardson's number as well as of the Monin-Obukhov lengthscale. The topological aspects of the turbulence affected by stratification reduce the vertical lengthscales to a maximum described by the Ozmidov lenthscale but intermittency and other higher order descriptors of the turbulence based on structure function and spectral wavelet analysis are also affected. The relationship between stratification, intermittency, $\mu$ and the fractal dimension, D, of the stable flows (Redondo 1990, Yague et al. 2006) and the relationships between the dispersion, the fractal dimension and the intermittency are discussed. The data analysed is from the high resolution experimental measurements of the campaign SABLES-98 (*period September 10 - 28 1998*) at the CIBA Valladolid at the north-west high Iberian Peninsula plateau.( Cuxart et al. 2000). Conditional statistics of the relationship between $\mu$(Ri) are confirmed and compared with laboratory experiments as well as other aspects of the turbulence.

### 2. Boundary layer analysis

For the small scale, as basic indicator of the potential energy to kinetic energy ratio we use the Flux Richardson number, also described as the Mixing efficiency, that may be derived From the turbulent kinetic energy comparing buoyancy with the production term

$$Rf = \frac{g}{r}\frac{\overline{r'u'}}{\overline{u'w'}\dfrac{\partial \bar{u}}{\partial Z}}$$

The use of Boussinesq relationships expressing the vertical mass and momentum fluxes in terms of the respective gradients of density and horizontal velocity leads to the relationship between the Flux and Gradient Richardson numbers.

$$Ri = \frac{K_h}{K_m} Rf$$

This is a highly non linear relationship as shown by Linden(1990). The intermittency may be appreciated as sharp spikes on the velocity values related to the higher order moments of the velocity differences and their differences. The relationship between kinetic Energy and the Richardson number is not univocal because stability is very sensible to small wind changes near the surface. Derbyshire and Redondo (1990)

A detailed analysis of the turbulence at small scale may reveal intermittent episodes in a stable atmosphere much clearly because of the high Kurtosis of the PDFs. In this case, under stable stratification conditions, we are able to obtain a better quantification of the intermittency than in a convective situation. A practical way in which to calculate intermittency as a single parameter may be done following Mahjoub et al.(1998), Mahjoub(2000) obtained using the sixth order structure function and the ß-model as $m = 2 - z_6$ where a practical relationship between the fractal dimension and the sixth order structure function may be expressed as:

$$z_6 = \frac{p}{3} + (3 - D)(1 - \frac{p}{3})$$

being p = 6 in this case the order of the structure function. Babiano et al.(1985).

### 3. Structure Function Analysis

Each set of values of a turbulent property has a certain fractal dimension, *D*, which expresses the level of self-similarity in space. Shertzer and Lovejoy (1986). This topological property may be studied horizontally or vertically, taking into account the evident anisotropy induced by stratification.

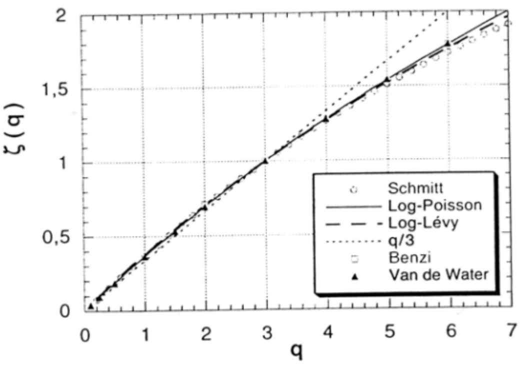


Figure1. Different theories for the deviation of the scaling exponents from Kolmogorov 1941 K41 Theory.

Then in relation to the images or data maps that contain spatial or temporal information on the velocity field, we apply the Box-Counting method built-in the ImaCal software (Grau, et al., 2003, Gade and Redondo 1999). For different observation scales (preserving self-similarity) and for different grey (velocity intensity) intervals (inside the total range so we avoid losing information of the intensity variation), we get then a multifractal characterization from the coverage of side *E* boxes (which contain the spatial or temporal information) with the boxes of the signal under study

$$D2 = -\frac{\ln N(E)}{\ln E}$$

By means of this methodology we calculate for every grey intensity level, the corresponding value of the fractal dimension having a description of the signal complexity for several intensity values. The multi-fractal cha-racterization in a particular unique area is possible Villermaux and Inocenti (1999). Every intensity reflects different physical processes. It is interesting to relate *D* to the frequency spectrum or to the spatial spectra obtained from the Fourier transform of the time or spatial correlation functions, usual in studies of turbulence. The reason is that from such frequency spectrum the corresponding fractal dimension may be derived, if the tracer scalar is passively advected by a turbulent flow. Then the fractal dimension might be related to the energy of the turbulence with a certain spatial or temporal dependence, then the frequency spectrum exponent, provided an inertial subrange exists, is a function of the box-counting fractal dimension as demonstrated by Redondo (1990)

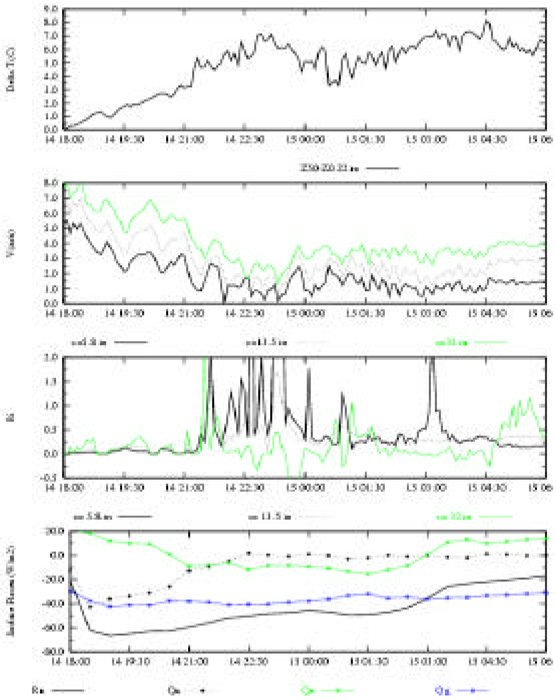

Figure 2. Evolution of different turbulent parameters versus time. T(50)-T(0), V, Ri. Surface Flux , from SABLES98.

## 4. Results

In order to evaluate the gradient of the mean potential temperature and wind speed, log-linear profiles were fitted to both variables using a least-squares procedure. For the SABLES98 data the levels used for potential temperature are: 0.22, 0.88, 2.00, 3.55, 5.55, 8.00, 10.88, 14.22, 18.00, 22.22, 26.88 and 32.00 m, and for wind speed: 3.0, 5.8, 10.0, 13.5, 20.0 and 32.0 m. The gradient of the mean wind direction has been evaluated from fitting a linear profile to the corresponding data at 5.8, 10.0, 13.5, 20.0 and 32.0 m. The method adopted for estimating these parameters from the data is dicussed in detail in Yague and Redondo (1995) and Cuxart et al.(2000).

It is clear that the transfer of heat and momentum as well as the TKE are well controlled by the gradient Richardson number. For very stable ranges the coefficients are almost of the order of 1/1000 . It is also interesting that Kh/Km is < 1 for strong stability. This could be an indication of internal-gravity waves activity which can produce transfer of momentum but little transfer of heat if these waves don't break. The turbulent parameters are also highly dependent on the friction velocity and on the inversion strength. Friction velocity controls the eddy transfer of heat and momentum and its relationship with the turbulence kinetic energy (TKE). The temporal evolutions of different variables along the night have been studied for SABLES98 data. Surface-based inversions and low-level jets are present. Intermittent turbulent peaks ocurred during these nights. These events are matched by low values of Ri and T50-0.22 and high values of TKE, Km, Kh, u* and H. (Tarradellas et al. 2001, Yague et al 2001)

Turbulent transfer seems to be very sensitive to surface wind. Although the synoptic conditions are similar along the whole period different evolutions are found. In Figure 2 we shown some variables for the 14-15 September night (wind speed, Richardson number, *TKE* and heat flux). This is probably the most stable night of all the period. Indications of gravity waves are also found this night: counter-gradient fluxes, high and oscillating values of *Ri* and Temperature differences in height, and these may be related to the intermittent maxima of the Potential Temperature r.m.s fluctuations.

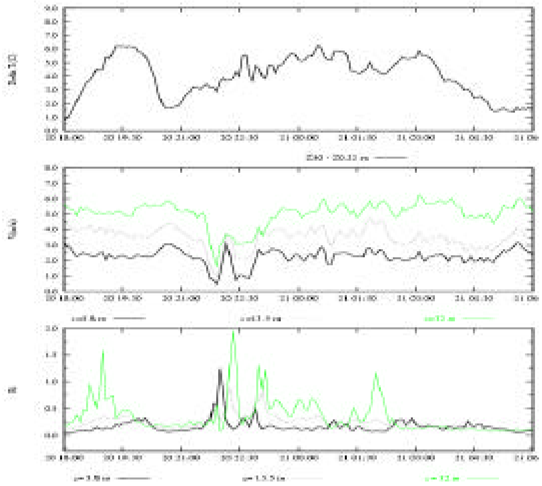

Figure 3. Evolution of different parameters for the 14-15 night. SABLES98.

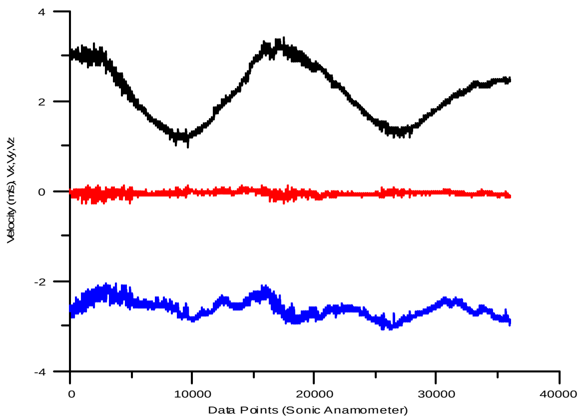


Figure 4. High resolution Sonic Data for a stable situation, 14-15 night. SABLES98.

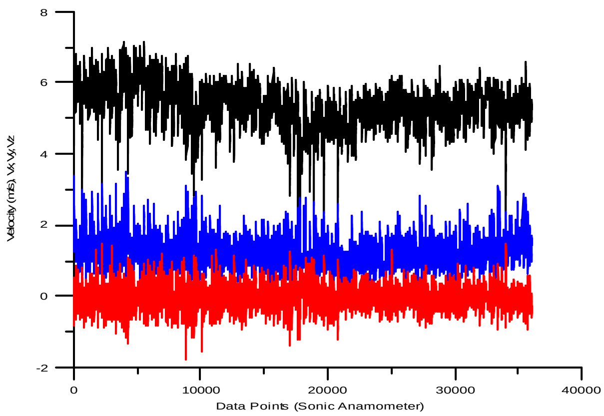


Figure 5. High resolution Sonic Data for a neutral situation, 21-22 night. SABLES98.

Figures 4 and 5 compare a stable and a neutral situation, in figure 4 the internal wave oscillations can be appreciated, as well as the lower wind values on stable situations.

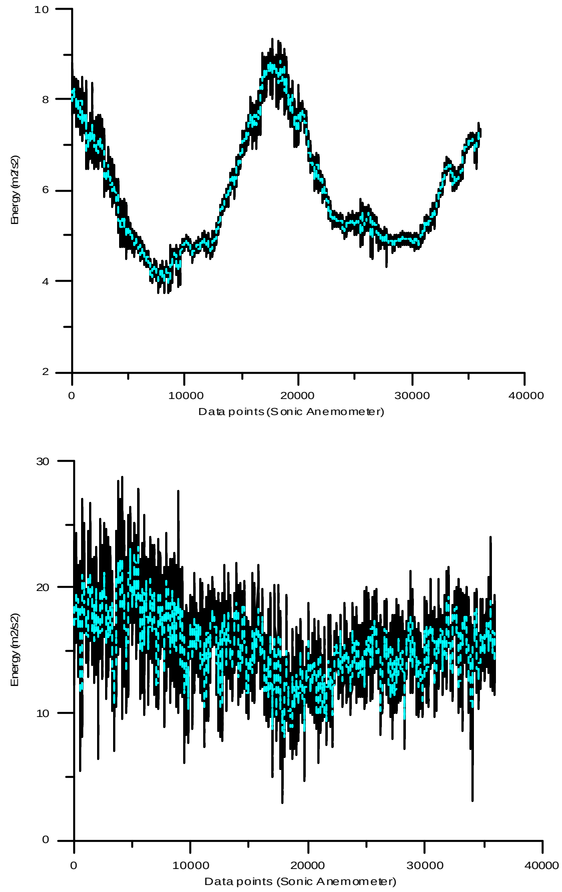


Figure 6 Turbulent Energy for a stable (top) and neutral (bottom) situations.

Figure 6 shows the turbulent kinetic energy in both stable and neutral situations. Considering the Ozmidov scale *(Lo)* and the integral lenghtscale of the turbulence *(l)* we can relate the Richardson number with the fractal dimension in a stratified fluid. A very interesting topic is to analyze the effect of stratification on the inverse turbulent Prandtl number, *Prt* which is a dimensionless number defined as the ratio of the eddy diffusivity for heat to the momentum *Kh/Km*. In Figure 2 it can be seen how this number decrease as stability (Richardson number) increases, showing the difference between the turbulent mixing of momentum and heat. Sometimes this difference is ignored for simplicity however this can lead to a low estimation of turbulent transport at stable conditions. Redondo et al.(1988)

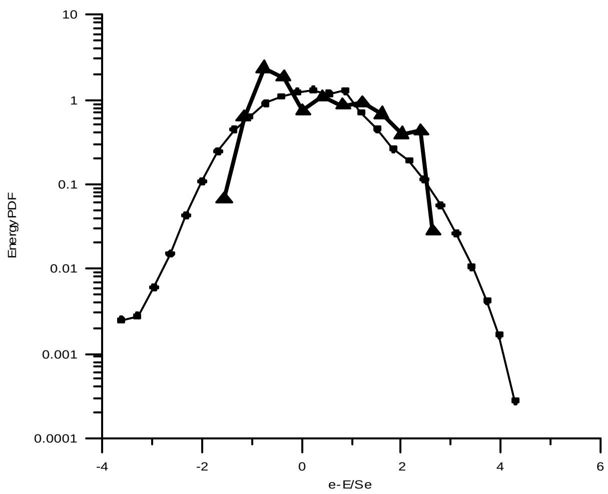


Figure 7. Comparison of PDF's for for a Stable 14-15 night and a neutral situation, 21-22 night. from STABLES98 data (a) Vane data from Yague et. al 2006). (b) Data from high resolution (25 Hz) Sonic anemometry from the same period? - Neutral situation ? - Stable situation.

## 5. Discussion and Conclusions

Atmospheric BL turbulence's behaviour is strongly affected by stability, it is possible to relate Richardson number to the geometrical aspect of a density interface using fractal geometry and the relationship between intermittency and fractal structure to the atmospheric data showing that intermittency clearly increases with higher stability. The observed behaviour supports the idea that under strong stable conditions (marked by high Richardson number, even greater than the critical 0.25) mixing of heat is inhibited to a greater extent compared to that of momentum. The role of internal gravity waves in this situation of intermittent and sporadic turbulence seems responsible for the more efficient transfer of momentum**.** Turbulent mixing and transfer are important topics in studies of the atmospheric boundary layer. This transfer can have complex features when the atmospheric boundary layer is strongly stratified. Then different processes appear, as intermittency of turbulence due to the lack of stationarity the presence of internal gravity waves and their interaction with turbulence. The behaviour of the turbulent vertical transport in the stable atmospheric boundary layer has been compared for a wide range of stabilities. A similar relationship between the Kurtosis or flatness of velocity differences and of potential temperature is found between the measurements and the laboratory experiments, in both cases Kurtosis increase with Richardson numbers up to values of 30, ten times larger than those of a Gaussian PDF distribution.

The friction velocity plays a key role in turbulent mixing in the stable boundary layer. It has been found that u* controls the eddy transfer coefficient for heat and momentum and the turbulent kinetic energy. Turbulent mixing is highly inhibited for increasing stability. The eddy transfer coefficients for heat and momentum show an important decrease for Richardson number between 0.01 and 0.2. The analysis of time evolutions shows different behaviour for similar synoptic situation, being the local stability (evaluated from the Richardson number) very important.


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## References


Babiano, A., Basdevant, C. and Sadourny, R. 1985 Structure functions and dispersion laws in two-dimensional turbulence. *J. Atmos. Sci.* **42**, 107-131.

Ben-Mahjoub O., Babiano A. y Redondo J.M. 1998 Velocity structure and Extended Self Similarity in non-homogeneous Turbulent Jets and Wakes. *Journal of flow turbulence and combustion* . **59** , 299-313.

Ben-Mahjoub, O. 2000 Intermittency and non-local dynamics *PhD Thesis* UPC. Barcelona

Ben-Mahjoub O., Redondo J.M., and R. Alami, 1998: Turbulent Structure Functions in Geophysical Flows, *Rapp. Comm. int. Mer Medit*.**, 35**, 126-127.

Businger, J. A., Wyngaard, J. C., Izumi, Y., and Bradley, E. F.: 1971, 'Flux-Profile Relationships in the Atmospheric Surface Layer', *J. Atmos. Sci.* **28**, 181–189.

Carrillo, A.; Sanchez, M.A.; Platonov, A.; Redondo, J.M. 2001.Coastal and Interfacial Mixing. Laboratory Experiments and Satellite Observations. *Physics and Chemistry of the Earth*, vol.B, 2**6**/4.

Cuxart, J., Yagüe, C., Morales, G., Terradellas. E., Orbe, J., Calvo, J., Fernandez, A., Soler, M. R., Infante, C, Buenestado, P., Espinalt, A., Joergensen, H. E., Rees, J. M., Vilà, J., Redondo, J. M., Cantalapiedra, I. R. and Conangla, L.2000 Stable Atmospheric Boundary Layer Experiment in Spain (SABLES 98): A report, *Bound-Layer Meteor.*, **96**, 337-370, 2000.

Derbyshire, S.H. and Redondo, J.M. 1990 "Fractals and Waves, some Geometrical Approaches to Stably-Stratified Turbulence". *Anales de Física*, Serie A, **86**, 1990.

Gade, M. y Redondo J.M., 1999. Marine pollution in European coastal waters monitored by the ERS-2 SAR: a comprehensive statistical analysis. *IGARSS 99*, Hamburg. **III**, 1637 - 1639, pp. 308-312.

Grau J. 2004 Multifractal analysis of clouds, *PhD Thesis* UPC, Barcelona. 2004.

Kolmogorov, A.N., 1941. Local structure of turbulence in an incompressible fluid at very high Reynolds numbers. *Dokl. Accad Nauk*. URSS, **30**:299-303.

Kolmogorov A. N: A refinement of previous hypotheses concerning the local structure of turbulence in a vis 1962ous incompressible fluid at high Reynolds number, *J. Fluid Mech.*, **13**, 82-85, 1962.

Linden P.F. 1980, Mixing across a density interface produced by grid turbulence, *Jour. Fluid Mech* **100**, part 4, pp. 691-703.

Redondo, J.M. 1990 The structure of density interfaces, *PhD Thesis.* Cambridge University. 1990.

Redondo, J.M. and Linden, P.F. 1988 "Geometrical Observations of Turbulent Density Interfaces". Cambridge. 1988.

Redondo J.M., Sanchez M.A. and Cantalapiedra I.R. (1998) Confined and Unbounded Mixing in Stratified Flows *IMA series*, **63**. Mixing an dispersion in stably stratified flows. Ed. P.A. Davies.

Schertzer, D. and Lovejoy, S. Generalised Scale Invariance and Anisotropic Inhomogeneus Fractals in Turbulence. *Fractal in Physics*.1986.

Terradellas, E.; Morales, G.; Cuxart, J. and Yagüe, C. 2001 "Wavelet Methods: Application to the Study of the Stable Atmospheric Boundary Layer under non-Stationary Conditions". *Dynamics of Atmospheres and Oceans*. **34** 225-244.

Villermaux, E. and Innocenti, C., 1999 "On the Geometry of Turbulent Mixing". *Jour. Fluid Mech*. (1999), vol. 393, pp. 123-147.

Yagüe, C.; Maqueda, G. and Rees, J.M. "Characteristics of Turbulence in the Lower Atmosphere at Halley IV Station, Antartica". *Dynamics of Atmospheres and Oceans.* **34** (2001) 205-223

Yagüe, C.and Redondo, J.M. 1995 "Characteristics of Turbulence in the Antartica". *Antartic Science*. **7**, 421-433, 1995.