Local Correlations and Multi-Fractal Behaviour in Marine Boundary Layer Cloud Dynamics

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Introduction

The marine boundary layer (MBL) cloud dynamics is studied through a statistical analysis of time series of the cloud base height, one of the macro-physical cloud parameters. The cloud base height profiles (CBHP) are known to have highly fluctuating and irregular structure. The dynamics of the CBHP evolution is determined by variety of processes in the atmosphere. This irregular structure is a benchmark for nonlinear dynamics. In this report we present an analysis of the local correlations and the multi-affine properties of CBHP with respect to their diurnal evolution. The measurements are made with a ground-base laser ceilometer, having temporal resolution of 30 seconds. For the purposes of our analysis we have chosen data measured at the Azores Islands during the Atlantic Stratocumulus Transition Experiment (ASTEX). The multi-fractal behaviour of the diurnal cloud evolution is revealed through the intermittent and the multi-affine properties of the analyzed CBHP. The results are oriented toward understanding and modelling of the dynamical behaviour of the MBL cloud evolution. They are also of great interest for the investigation of the reflectivity of electromagnetic waves from an irregular boundary such as the cloud base height.

The data, used in this study, obtained from the Atmospheric Radiation Measurement (ARM) Program archive (http://www.archive.arm.gov), are registered during the ASTEX conducted in June 1992, in the vicinity of the Azores and Madeira Islands in the northeastern Atlantic. The goal of ASTEX was to study the type and amount of marine stratocumulus clouds and determine how these clouds are regulated. ASTEX combined coordinated satellite, airborne, island, ship, and buoy observations with modeling activities to investigate the consequences to the atmosphere and ocean of marine stratocumulus clouds and their life-cycle variations, including the important broken cloud regimes (ASTEX Operations Plan 1992). CBHP measured on June 5, 1992, is plotted in Figure 1.

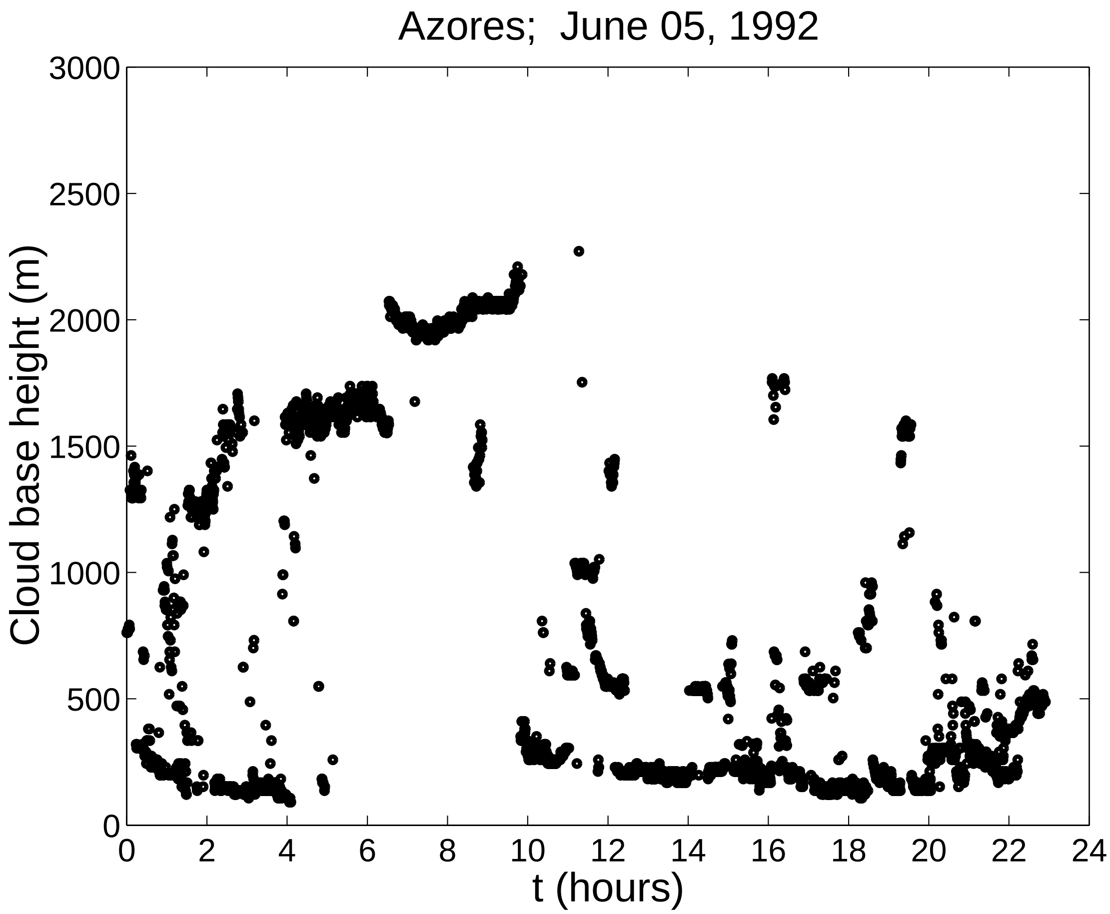

Figure 1. MBL CBHP, measured on June 5, 1992, in the Azores Islands between 0 and 23h.

CBHP have complex structure and exhibit erratic fluctuations in time and space. Such a complexity is due to the variety of processes that take place in the MBL (Garratt 1992) like: turbulent motions, entrainment, radiative transfer, and cloud microphysical structure.

The objectives of this study are using statistical analysis of the CBHP temporal evolution:

- determine the character of the local correlations in the MBL cloud dynamics
- characterize its multi-fractal behavior.

Methods of Analysis

Spectral Analysis

The spectral analysis method aims at testing for existence of periodic, quasi-periodic or the overall scaling behaviour of the signal. The power spectrum of the data series is obtained as a Fourier transform (Körner 1988) of the signal y(t), i.e.,

$$S(f) = \frac{\lim}{T \to \infty} \frac{1}{T} \left| \int_{-T}^{T} e^{2\pi i f t} \; y(t) dt \right|^2$$

Detrended Fluctuation Analysis (DFA) Method

The DFA method searches for the long-range correlations in time series and it consists of (Peng et al. 1994; Ivanova and Ausloos 1999):

- Dividing a random variable sequence y(n) of length N into N/t non-overlapping boxes, each containing t points.
- The local trend z(n) = an+b in each box is computed using a linear least-square fit to the data points in that box.
- The detrended fluctuation function F(t) is then calculated following.

$$F^2 \; (t) = \frac{1}{t} \sum_{n=kt+1}^{(k+t)t} [(y(n) - z(n)]^2 \qquad k = 0,1,2.. \left(\frac{N}{t} - 1 \right)$$

- Averaging $F^2(t)$ over the N/t intervals gives the fluctuations $\langle F^2(t) \rangle$ as a function of t

$$\left\langle F^2 \; (t) \right\rangle^{1/2} \propto t^a$$

Depending on the value of the α exponent the data series y(n) is random uncorrelated or short range correlated for $\alpha = 0.5$. Value of $\alpha \neq 0.5$ for certain values of t implies existence of long-range correlations in that time interval as, for example, in fractional Brownian motion.

Multi-Fractal Techniques

The **multi-affine** properties of y(t) can be described by the so-called “q-th” order structure functions (Davis et al. 1994; Ivanova and Ackerman 1999).

$$C_q = \left\{ \left| y(t_{i+r}) - y(t_i) \right|^q \right\}, \quad i = 1,2,..N-r$$
$$\tau = t_{i+r} - t_i \quad r > 0$$

$$C_q(\tau) \propto \tau^{qH(q)}, \quad q \geq 0$$

where the H(q) spectrum, needed to rescale such a signal. This also implies that local roughness exponents H(γ) exist (Vandewalle and Ausloos 1998).

$$N_\gamma(\tau) \propto \tau^{-h(\gamma)}$$

$$\gamma(q) = \frac{d(qH(a))}{dq}$$

$$h(\gamma_q) = 1 + q\gamma(q) - qH(q)$$

where $N_\gamma(\tau)$ is the density of the points that have the same roughness exponent (Vandewalle and Ausloos 1998).

The **intermittency** of the signal is studied using the singular measure analysis (Davis et al. 1994; Ivanova and Ackerman 1999).

$$\left\langle \delta\varepsilon(r,l)^q \right\rangle \propto r^{-K(q)}, \quad q \geq 0$$

where generating function is

$$\delta\varepsilon(1,l) = \frac{\left|\Delta\gamma(1,l)\right|}{\left\langle \Delta\gamma(1,l) \right\rangle}, \quad l = 0,1,...N-1$$

and $\Delta\gamma(1,l) = \gamma(t_{i+1})$ -$\gamma(t_i)$ is the small-scale gradient field $\left\langle \Delta\gamma(1,l) \right\rangle = \frac{1}{N}\sum_{l=1}^{N-1} \left|\Delta\gamma(1,l)\right|$. Therefore,

$$\delta\varepsilon(r,l) = \frac{1}{r}\sum_{l'=1}^{l+r-1} \delta\varepsilon(1,l'), \quad l = 0,....N-r$$

$$0 < l < N-r$$

$$r = 1,2,4,...,N = 2^m$$

Results and Discussion

We first test the scaling properties of the signal and the range in which they hold.

A power law dependence $S(f) \sim f^{-\beta}$ with $\beta = 1.24$ for about two decades in time suggests existence of self-affine properties of the CBH profile (Figure 2). However, it is the multi-fractal analysis that can reveal whether or not these properties are multi- or mono-fractal. Since $1<\beta<3$, the CBH signal is a nonstationary process with stationary increments (Peng et al. 1994; Ivanova and Ausloos 1999).

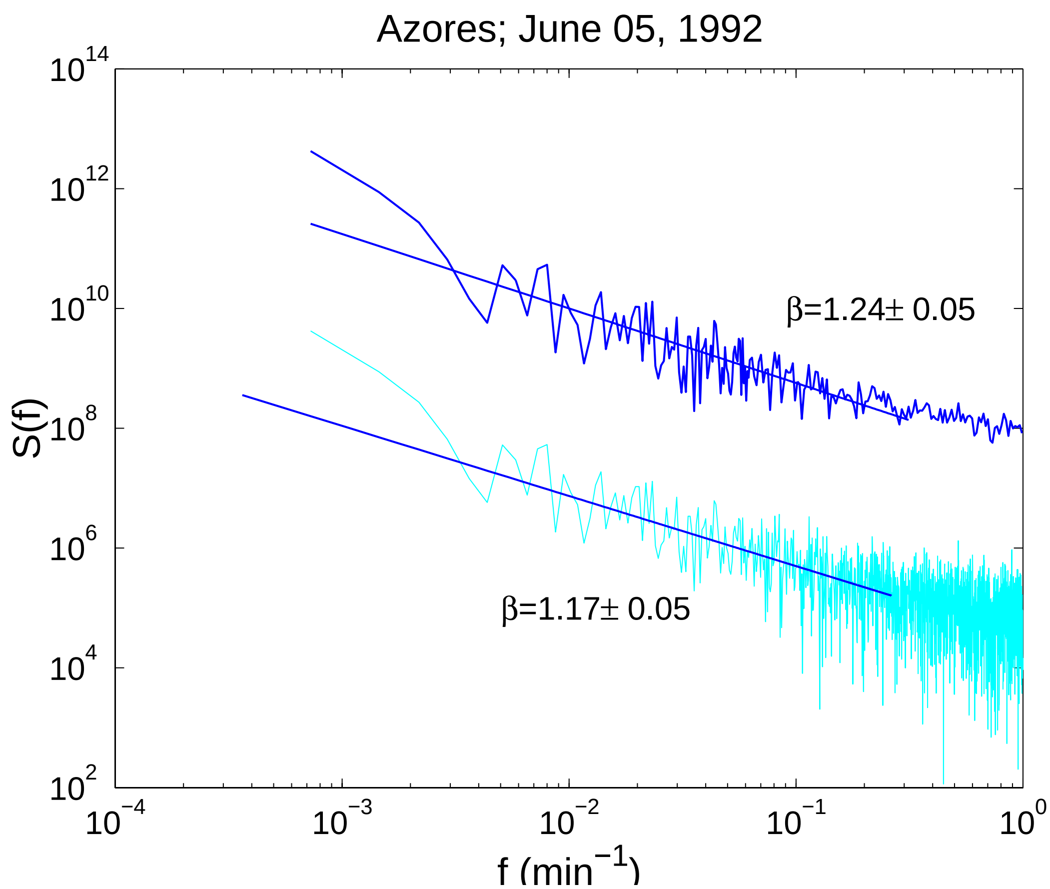

Figure 2. Power spectrum S(f) of the Azores MBL cloud base height signal measured on June 5, 1992, and characterized by $\beta = 1.17 \pm 0.05$. The upper curve represents the smoothed spectra, vertically displaced by two decades, that scales with a spectral exponent $\beta = 1.24 \pm 0.05$.

In order to test how the scaling properties of the CBH profile change along its length, we applied the DFA technique within an "observation box" with width size w of 7h, which is moving with a step $\Delta w = 30$min (60 points) from the beginning toward the end of the data sequence. The local similarity exponent α is calculated for that box. The evolution of the local α is plotted in Figure 3b.
The α exponent values are within the limits of the anti-persistent behaviour with ($\langle\alpha\rangle = 0.28 \pm 0.01$ for June 5) transitions between different levels of anti-persistence in the underlying dynamics.

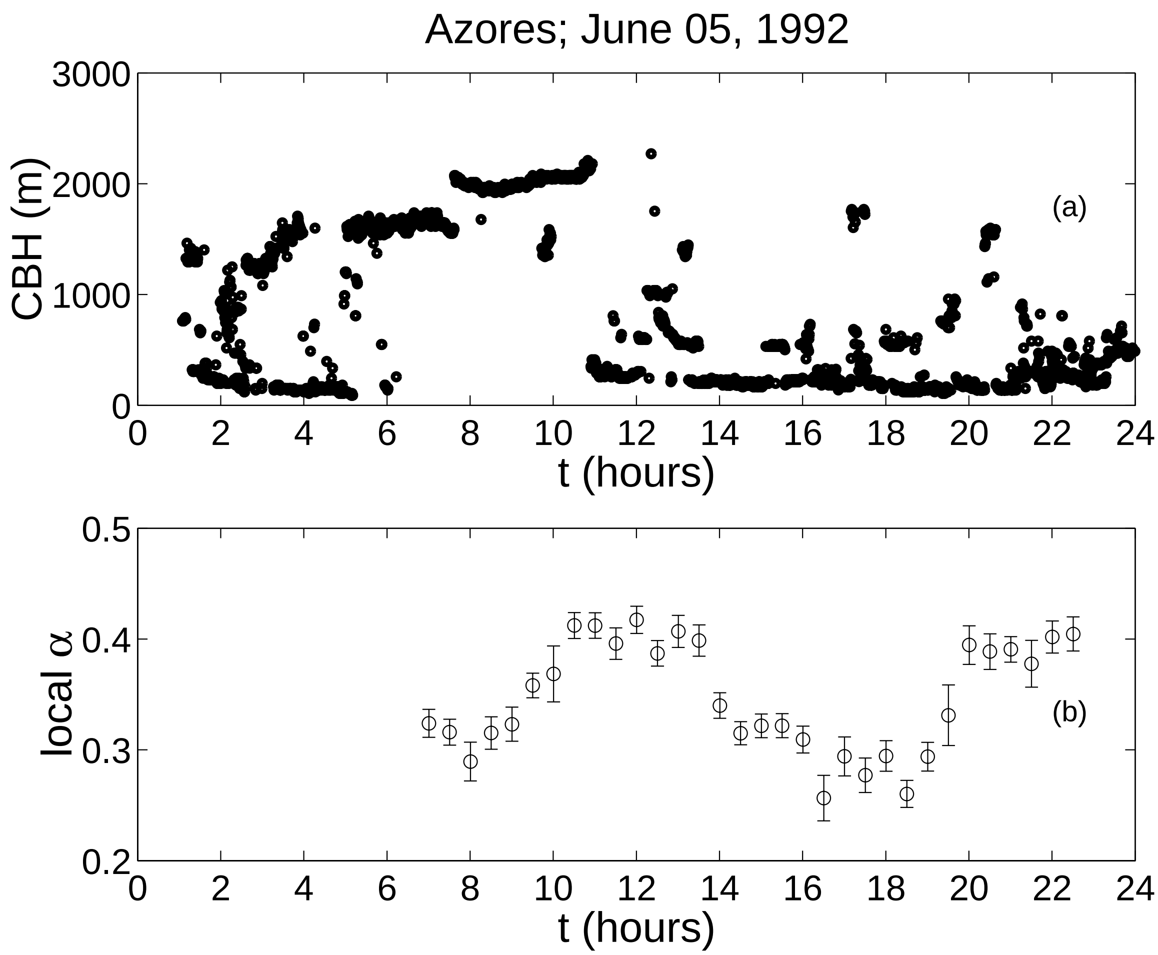

Figure 3. (a) Azores MBL CBH fluctuations for June 5, 1992; (b) the local α exponent. Note the two regions around 10-13h and 16-24h, characterizing the two CBH levels of different height by approximately the same value of $\alpha \approx 0.40 \pm 0.02$.

The temporal evolution of the local similarity exponent α, characterizing the local cloud base height correlations suggests a multi-fractality of the fluctuations. We apply the singular measures and q-th order structure functions analysis to the CBHP to quantify the correlations of order q that exist in the profiles. Results are plotted in Figure 4. Thereby the intermittent and multi-affine properties of the studied dynamics are determined and quantified by the $\xi(q)$ and $K(q)$ functions. In first order these properties are assed by the roughness exponent H_1 and the intermittency exponent C_1. The high values of the intermittency exponent C_1 ($C_1 > 0.10$) reflect the intermittent character of process of decoupling and recoupling of the MBL.

The multi-fractal properties of the CBH signal are further characterized by the $h(\gamma)$ function, empirically determined from the data (Figure 5). Its nonlinear dependence on γ implies that a set of exponents are necessary for rescaling the signal, thus its multi-fractal structure.

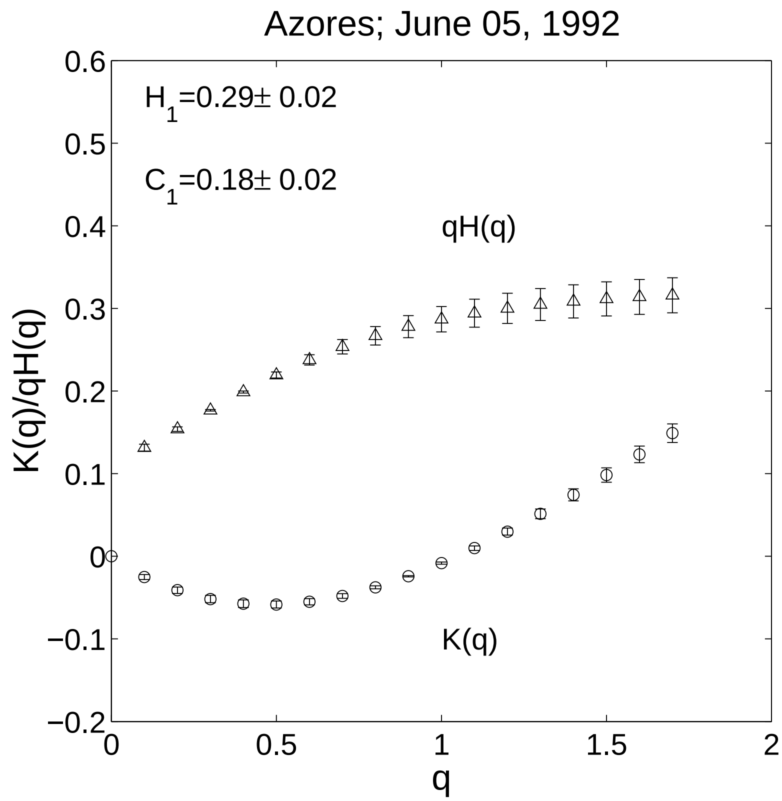

Figure 4. $\xi(q) = qH(q)$ and $K(q)$ functions for the MBL CBHP Azores data taken on June 5, 1992.

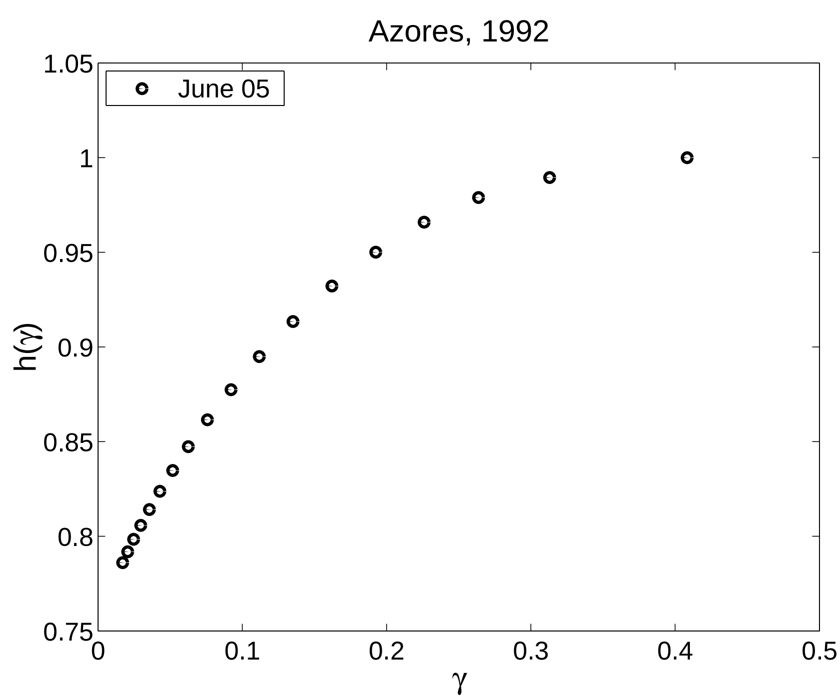

Figure 5. The $h(\gamma)$-curves for Azores MBL CBHP data taken on June 5 and 11, 1992.

Conclusions

Anti-persistent local correlations hold with well established day-night evolution of local α related to dominant thermodynamical or turbulent processes. The transition between processes with different level of anti-persistence, which are revealed by the trend in local α evolution, could be used for trace parameter of CBH dynamics. The multi-affine structure of the CBH data is demonstrated by the sets of local roughness exponents h(γ). These findings can be useful for including in global circulation models.

Acknowledgements

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