The 9th Experimental Chaos Conference – ECC9
May 29 - June 1, 2006, São José dos Campos, São Paulo, Brazil

Searching chaos and coherent structures in the atmospheric turbulence above the Amazon forest

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In this work the possible chaotic nature of the atmospheric turbulence, above a densely forested area in the Amazon region, is investigated. To this end, we use high resolution temperature data obtained during a micrometeorological measurement campaign in the Brazilian Amazonia. The existence of chaos in the atmospheric boundary layer is confirmed by estimates of the correlation dimension ($D_2 = 3.50 \pm 0.05$) and of the largest Lyapunov exponent, ($\lambda_1 = 0.050 \pm 0.002$). Our findings indicate that this low-dimensional chaotic dynamics is associated with the presence of the coherent structures within the boundary layer right above the canopy top, and not to the atmospheric turbulence *per se*, as previously claimed.

Keywords: Atmospheric turbulence; coherent structures; deterministic chaos; correlation dimension; Lyapunov exponent.

1. Introduction

Amazonia is one of the last great tropical forest domains, the largest hydrological system in the planet, and plays an important role in the function of regional and global climates. A subject of great relevance for understanding how the Amazon terrestrial biosphere interact with the atmosphere is the correct modeling of the turbulent exchange of heat, humidity, greenhouse gases, and other scalars at the vegetation-air interface. However, this issue, as many other aspects of this fragile and highly complex system, remains unclear for the scientific community. This is partly due, on one hand, to the lack of high-frequency, detailed *in situ* measurements, and, on the other hand, to the fact that turbulence has been a notoriously difficult problem to grasp.

In the last decades, several studies have handled the problem of turbulence - and of atmospheric turbulence, in particular - with the tools of chaos theory. Perhaps the most paradigmatic example of this approach is the work of E. N. Lorenz (Lorenz (1963)), based on a simplified model of the dynamics of a convective fluid layer. Soon after this landmark paper, it was conjectured that the atmosphere might also be governed by a low-dimensional chaotic attractor (Weber *et al.* (1995)). Since then,

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various works reported the existence of low-dimensional chaotic attractors based on the analysis of climatic or weather time series (Nicolis & Nicolis (1984); Fraedrich (1986); Fraedrich & Leslie (1989); Göber *et al.* (1992); Poveda-Jaramillo & Puente (1993); Fraedrich (1986); Xin *et al.* (2001); Gallego *et al.* (2001)). However, in spite of the growing empirical evidence, the subject remains controversial. Grassberger (1986) objected to the validity of some early findings because of the small number of data points used in the analyses. Later, Weber *et. al* (1995) found no evidence of a low-dimensional attractor on wind velocity turbulent time series with several million data points long. Lorenz himself found unlikely that weather or climate systems possess low-dimensional attractors because of their intrinsic complexity (Lorenz (1991)). In his opinion, however, positive claims were not meaningless but resulted from the fact that the atmosphere "might be viewed as a loosely coupled set of lower-dimensional subsystems". In other words, as speculated by Ruelle and Takens (1971), although the phase spaces of many dynamical systems in nature are infinite-dimensional, the dynamical invariant sets responsible for many observable phenomena of physical interest may lie in some low-dimensional manifold (Lai *et al.*, (2003)).

Within the context above we set two objectives to this work. First, investigate the existence (or not) of a low-dimensional chaotic attractor in the atmospheric turbulence above a densely forested area in the Amazon region. Second, examine the role played by coherent structures (or eddies) - here viewed as the lower-dimensional subsystems conjectured by Lorenz (1991) - in the predictability properties of the atmosphere. Turbulent flows in canopies are dominated by such coherent structures of whole canopy scale (Finnigan (2000)), which might be responsible for up to 75% of the turbulent fluxes in the atmospheric surface layer (Krushe & Oliveira (2002)). Under convective conditions, coherent structures are recognized in time series of temperature and other scalars by the presence of ramp-like patterns, i.e. a gradual rise in the signal, followed by a sudden fall (Antonia *et al.* (1979)). To attain our goals, we used fast-response experimental data obtained during a field campaign of the large-scale biosphere-atmosphere experiment in Amazonia (known as the LBA project), carried out during the wet season (January-March), in the southwestern part of the Brazilian Amazonia.

This paper is organized as follows. In Section 2 we describe the data and the experimental site. Section 3 describes the analytical tools used on the data, and the corresponding results are presented and discussed. Finally, in Section 4 we present our conclusions.

2. Data and Experimental Site

The experimental site is located in Rondônia, Brazil, roughly 3000 kilometers northwest from Rio de Janeiro, inside the Jaru Biological Reserve (10°46'S, 61°56'W), a densely forested area with 270 thousand hectares. Fast response wind speed measurements, in the three orthogonal directions, and temperature measurements were made at a sampling rate of 60 Hz, over periods of 30 minutes, using sonic anemometers and thermometers. The data was gathered during an intensive micrometeorological campaign, part of the LBA project. The experiment was carried out during wet season, from January to March 1999. The LBA Project, acronym for Large Scale Biosphere-Atmosphere Experiment in Amazonia, is an international initiative led by Brazil, aimed at understanding the climatological, ecological, biogeochemical, hydrological functioning of Amazonia, studying the impact of land use change, especially deforestation, in these functions, and analyzing the interactions between Amazonia and the Earth system.

The measurements were made with the help of a micrometeorological tower, simultaneously at three different heights: above the canopy, at 66 m; at the canopy top, at 35 m; and within the canopy, at 21 m. Two distinct measurement periods have been selected: from noon to 1:00 p.m., when the forest crown is heated by the sun, the top of the canopy is hotter then the surroundings, and thus the above canopy region is unstable; and from 11:00 p.m. to midnight, when we have the opposite condition, and the above canopy region is stable. In order to verify the data quality, we applied the quality control procedure proposed by Vickers and Mahrt (1997). Since we were primarily interested in the dynamical characteristics of fully-developed turbulence, we checked our data for the existence of a sizable inertial sub-range. Finally, we also checked the validity of Taylor's hypothesis verifying the turbulence intensity inside the inertial sub-range.

3. Methods and Results

(*a*) *Selection and Filtering of the Data*

The first step of our analysis was to select among the set of available time series those that presented clear signs of ramp-like patterns, an unequivocal evidence of the presence of coherent structures in the flow, and that obeyed minimal requirements of quality and stationarity. Figure 1 (top) shows the only time series selected by this procedure (called here "tS1200"), that corresponds to more than $100,000$ temperature data points, measured above the canopy, during daytime (under convective, unstable conditions). Two other temperature time series, measured simultaneously with "tS1200" but that do not display ramp-like patterns, were also considered: "tM1200", measured at the canopy top; and "tI1200", below the canopy.

The second step was to decompose "tS1200", using Haar wavelet transform, into a coherent, low-frequency signal and a high-frequency, apparently incoherent one. The so-called coherent part bears the main features that characterize the ramp-like patters present in the original time series, while the incoherent, structureless part looks like a random sequence of temperature fluctuations (see Figure 1, middle and bottom).

Figure 2 presents the corresponding Global Wavelet Spectra (GWS) of the three parts. Note that these spectra present all a "broad band" aspect, with no dominant frequency. This is a necessary but not sufficient condition for a time series being related to chaotic dynamics (Tufillaro *et al.* (1992)). Remark also that even the incoherent part has a power-spectrum with a clear $-5/3$ scaling, typical of fully-developed turbulence. This result shows that the phenomenon of turbulence permeates all scales of the original time-series, and that the apparently random part is not just a "colored" noise. This result is consistent with other studies that used a similar procedure to decompose a turbulent signal into coherent and incoherent parts (Farge *et al.* (2001); Ramos *et al.* (2004)). The rationale behind our decomposition approach is straightforward: in case of finding a low-dimensional chaotic

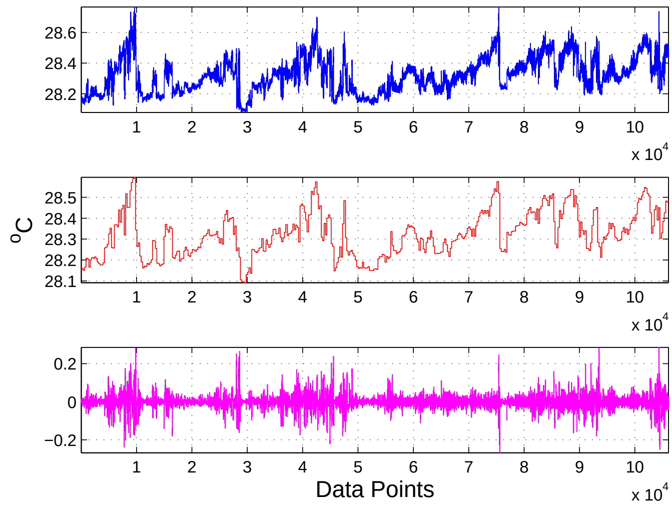

Figure 1. Original (top), coherent (middle) and incoherent (bottom) temperature time series.

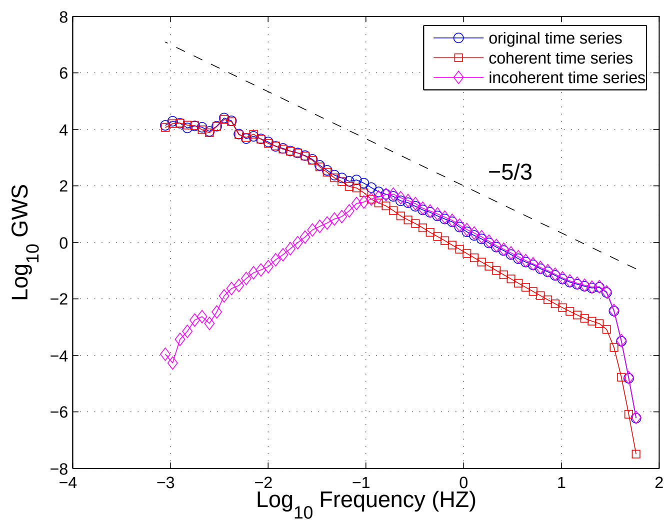

Figure 2. Global Wavelet Spectra of the original, coherent and incoherent time series.

attractor in the original time series, it will be possible to attribute it to the presence of coherent structures in the flow, to the atmospheric turbulence, or to both.

(*b*) *Phase-space reconstruction*

The technique of phase-space reconstruction is a powerful tool in the analysis of nonlinear dynamical systems with chaotic behavior. The basic theorem behind this technique (Takens (1981)) states that in the phase-space formed by the axes $x(t), x(t+\tau), x(t+2\tau), \dots, x(t+(m-1)\tau)$, where τ is a suitable time delay, the reconstructed attractor is topologically equivalent to the system's unknown one, of which only a discrete record of the state variable x is known.

(i) *Choosing the time delay* τ

Takens (Takens (1981)) demonstrated that for an infinite time series of x and in the absence of noise, the choice of the time delay τ is in most cases arbitrary. Experimental time series, however, are finite in size and usually contaminated with noise. In practical applications, thus, the correct choice of τ is crucial. Several works have considered this issue (Fraser & Swinney (1986)). The most popular criterion, also used in this work, sets τ as a modest fraction (say, 1/20) of the first zero-crossing of the autocorrelation function (Baker & Gollub (1996)). Applying this criterion to the original, coherent and incoherent time series we found $\tau = 369$, $\tau = 402$ and $\tau = 3$, respectively (in discrete time-steps units).

(ii) *Computing the correlation dimension* D_2

The correlation dimension D_2 is one of the main tools used to identify the existence of chaotic dynamics. Deterministic chaos might exist *in a stationary series* if the slope of the correlation integral $C(r)$ converges to a saturation value, as $r \to 0$ and the embedding dimension m increases (Grassberger & Procaccia (1983)). The correlation integral counts the relative frequency in which two vectors $\vec{\xi}_i = (x(t_i), x(t_i+\tau), \dots, x(t_i+(m-1)\tau)$ in phase-space are separated by an Euclidian distance no larger than r; for small values of r, it behaves as a power law $C(r) \approx r^{D_2}$. In deterministic time series with chaotic behavior, the value of D_2 reaches a maximum value due the low-dimensional dynamics of the system. In other words, D_2 is a good approximation of the fractal dimension D_0, and through the relation $m \geq 2D_0 + 1$ (Takens (1981)) may be used to estimate the value of the embedding dimension m that allows the system's attractor to be adequately unfolded, avoiding any trajectories crossings.

Figure 3 shows the curves $C(r)$ versus r for the original, coherent and incoherent time series, for embedding dimensions ranging from 1 to 10. The corresponding D_2 values, estimated by linear regression, are presented in Figure 4. As expected, D_2 for a purely random process (white noise) grows linearly with m. The correlation dimension for the incoherent signal does not saturate too. On the other hand, the curves for the original and coherent time series converge to the values (averaged over 5 realizations) of $D_2 = 3.50 \pm 0.05$ and $D_2 = 3.21 \pm 0.04$, respectively. Accordingly, the associated attractor is well represented in an embedding space of dimension $m = 8$. Note that we have $D_2 < D_{2_{\max}} = 2\log_{10} N$, where $N \approx 100{,}000$ is the number of points of the time series, and $D_{2_{\max}}$ is the maximum value that can reliably be estimated from a data set of size N (Eckmann & Ruelle (1992)). Our D_2 results compare well with those published in the literature, for similar weather-related time series (see Table 1). More important, they imply that the fingerprint of a low-dimension chaotic dynamics in our data does not come from the atmospheric turbulence but from the presence of coherent structures in the flow.

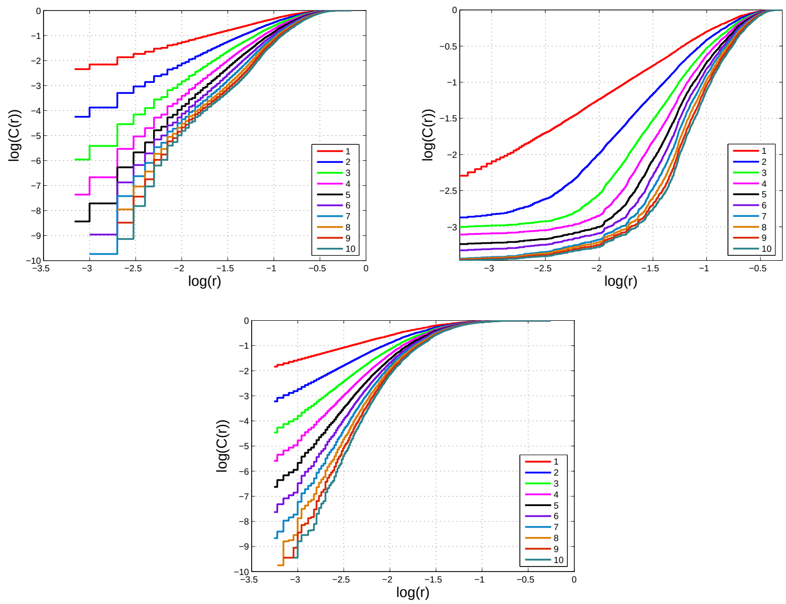

Figure 3. Correlation integral for the original, coherent and incoherent time series.

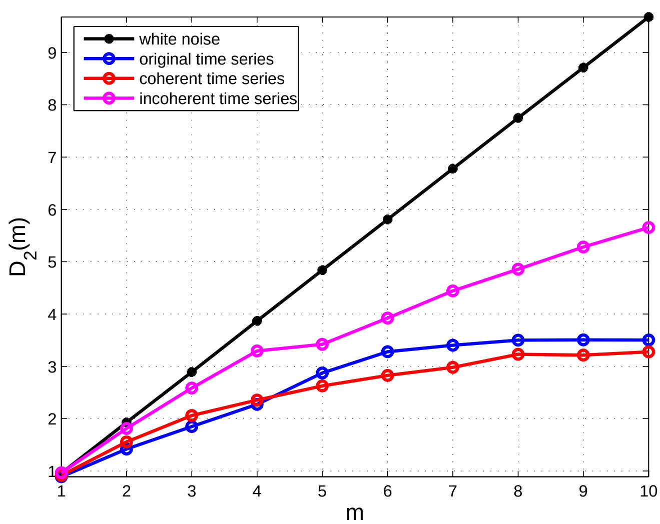

Figure 4. Correlation dimensions of the original, coherent and incoherent time series, and a white noise.

It is well known that certain "colored" noises may also generate correlation dimensions that converge to a finite value (Osborne & Provenzale (1989)). To check this possibility, we also computed the correlation dimension for surrogates of the original and coherent time series, after randomly shuffling their phases in the Fourier space, a procedure that does not modify the power-spectra of the signals (Provenzale *et al.* (1992)). Now the correlation dimensions, presented in Figure 5, do not converge to a finite value anymore, which represents an additional evidence of the existence of low-dimensional chaotic attractor in our data.

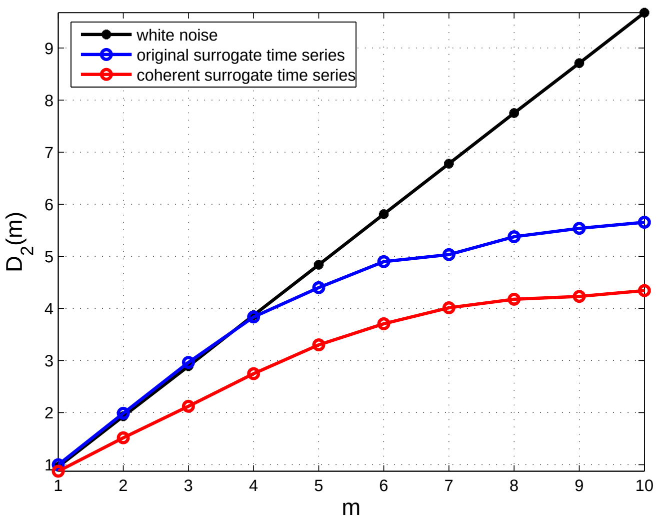

Figure 5. Correlation dimensions for the original and coherent surrogate time series, and a white noise.

(iii) *Computing the Lyapunov exponents*

Lyapunov exponents contain information about the average rate at which trajectories exponentially diverge or converge within the attractor. A chaotic system is characterized by an exponential divergence of nearby initial conditions, and therefore possesses at least one positive Lyapunov exponent. Here, with the value of embedding dimension estimated previously ($m = 8$), we applied Wolf's algorithm (Wolf *et al.* (1985)) to compute the largest Lyapunov exponent λ_1 of the original and the coherent time series, for different regions of the corresponding attractors. The values we obtained, respectively, $\lambda_1 = 0.050 \pm 0.002$ and $\lambda_1 = 0.011 \pm 0.001$, are small but positive (even considering the error bars), what confirms the presence of a low-dimensional chaotic dynamics in both series. Again, a comparison with Lyapunov exponents estimated by other authors under similar conditions (see Table 1) does not present large discrepancies.

(iv) *Recurrence plots*

As a final check of our data, we prepared recurrence plots (Eckmann *et al.* (1987)) of the original, coherent and incoherent time series. The resulting plots are shown in Figure 6. We observe that, while the incoherent part produced a homogeneous, structureless plot typical from high-dimensional stochastic processes, the plots of the original and coherent time series display patterns commonly found

Table 1. *Correlation dimensions D_2 and largest Lyapunov exponents λ_1 for different turbulent time series.*

Type of data	D_2	λ_1	Reference
Temperature (original series)	3.50	0.050	this work
Temperature	4.50	0.155	Povedo-Jaramillo & Puente (1993)
Longitudinal wind velocity	3.50	0.195	Povedo-Jaramillo & Puente (1993)
Temperature	3.26	0.047	Xin *et al.* (2001)
Longitudinal wind velocity	3.43	0.120	Xin *et al.* (2001)
Vertical wind velocity	5.35	0.058	Gallego *et al.* (2001)

in deterministic chaos, such as the small diagonal structures above and below the main diagonal (Thiel *et al.* (2004)).

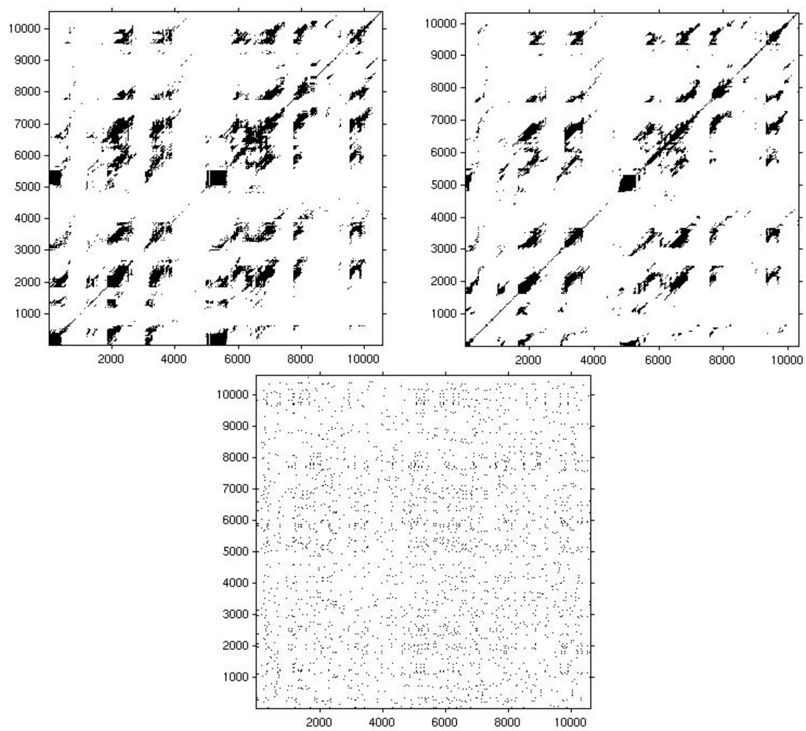

Figure 6. RP of the original time serie with $m = 8$ and $\varepsilon = 0.9507$; RP of the coherent time serie with $m = 8$ and $\varepsilon = 0.8390$; and RP of the incoerent time serie with $m = 1$ and $\varepsilon = 0.030$.

4. Conclusions

In this work the possible chaotic nature of the atmospheric turbulence above a densely forested area in the Amazon region was investigated. The analyses carried out here, based on high resolution temperature data obtained during a micrometeorological measurement campaign in the Brazilian Amazonia, suggest the existence of a low-dimensional chaotic attractor in the atmospheric boundary layer, with a correlation dimension of $D_2 = 3.50 \pm 0.05$. The existence of chaotic dynamics in the data is confirmed by the estimation of a positive largest Lyapunov exponent, $\lambda_1 = 0.050 \pm 0.002$. More important, our results indicate that this chaotic dynamics is associated with the presence of coherent structures within the boundary layer right above the canopy top, and not to the atmospheric turbulence *per se*. This claim was evidenced by the process of filtering, using Haar wavelets, applied to the experimental data, which allowed us to separate the contribution of the coherent structures from the turbulent background signal. It is important to remark that two other turbulent temperature time series ("tM1200" and "tI1200"), which do not possess the ramp-like patterns displayed by "tS1200", were also analyzed, and in both cases we found no evidences of the existence of a low-dimensional chaotic attractor.

Our findings corroborate a conjecture made by Lorenz (Lorenz (1991)), stating that the connection between chaos and weather (or climate) found by many authors were not simply artifacts but the result of the existence in the atmosphere of low-dimension chaotic subsystems weakly coupled to a higher-dimensional system, more complex and non chaotic. Within the context of the present work, these low-dimensional subsystems are the coherent structures commonly found in canopy flows under convective conditions. Naturally, the higher-dimensional system is the complex and turbulent atmospheric boundary layer. The results obtained in this work, for the correlation dimension D_2 and the largest Lyapunov exponent λ_1, are consistent with those published in literature, where evidences of a low-dimensional attractor in the atmosphere were also detected (Xin *et al.* (2001); Povedo-Jaramillo & Puente (1993); Gallego *et al.* (2001)). Although the presence of coherent structures is not clearly mentioned, a careful reading of these works provide some indications that ramp-like structures may also be present in their data (see, for example, Figure 5 in Povedo-Jaramillo & Puente (1993)).

Acknowledgements

This work is part of the large-scale biosphere-atmosphere experiment in Amazonia (The LBA project) and was partially funded by the Fundação do Amparo à Pesquisa do Estado de São Paulo (FAPESP)/Brazil. This work has also been supported by CNPq and CAPES, Brazil.

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