Atmospheric turbulence within and above an Amazon forest

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Abstract

In this paper, we discuss the impact of a rain forest canopy on the statistical characteristics of atmospheric turbulence. This issue is of particular interest for understanding on how the Amazon terrestrial biosphere interact with the atmosphere. For this, we used a probability density function model of velocity and temperature differences based on Tsallis’ non-extensive thermostatistics. We compared theoretical results with experimental data measured in a 66 m micrometeorological tower, during the wet-season campaign of the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). Particularly, we investigated how the value of the entropic parameter is affected when one moves into the canopy, or when one passes from day/unstable to night/stable conditions. We show that this new approach provides interesting insights on turbulence in a complex environment such as the Amazon forest.

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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. Many aspects of this fragile and highly complex system remain unclear for the scientific community. 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 interface vegetation-air. 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. While most researchers agree that the basic physical aspects of the mechanically generated turbulence are described by the Navier-Stokes equations, limitations in computer capacity make it impossible to directly solve these equations for high Reynolds numbers turbulent flows (fully developed turbulence), specially in a complex environment such as the canopy of a rain forest.

Traditionally, the properties of turbulent flows are studied from the probability density functions (PDFs) of fluctuating quantities (velocity differences \( v_r(x) = v(x) - v(x + r) \), for example), at different separation scales \( r \). It is a well known characteristic of turbulent flows that, at large scales, these PDFs are normally distributed. However, at increasingly smaller scales, they become strongly non-Gaussian and display tails fatter than expected for a normal process. This is the signature of the intermittency phenomenon: strong bursts in the kinetic energy dissipation rate. Since the sixties, many PDFs models have been proposed to take into account this feature \([1,2]\). Most of these models are based on refined versions of Kolmogorov’s original phenomenology for isotropic inertial subrange turbulence, such as in the lognormal \([3]\), multifractal \([4]\), log-Poisson \([5]\), and Levy \([6]\) models.

Recently, a new PDF model based on the non-extensive thermostatistics (NETS) formalism has been introduced \([7]\). Since then, the connection between NETS and turbulence is attracting a growing interest \([8,9,10,11,12,13,14,15,16]\). NETS is a generalization of classical Boltzmann-Gibbs thermostatistics \([17]\), through the introduction of a family of non-extensive entropy functionals \( S_q \), with a single parameter \( q \). These functionals reduce to the Boltzmann-Gibbs entropy as \( q \to 1 \).

Within the context above, the objective of this paper is twofold. First, to study the atmospheric turbulence in a complex environment such as the Amazon forest. In particular, we focus on the impact of the rain forest crown on the statistical characteristics of the atmospheric turbulence, and on how this characteristics are affected when one moves into the canopy, or when one
passes from day/unstable to night/stable conditions. We also investigate the connection between coherent structures and intermittency on the statistical distribution of turbulence fluctuations. Our second goal is to test the validity of the PDF model based on NETS, and whether this approach can provide new insights to the study of atmospheric turbulence in the tropics. To achieve these goals, we use fast-response experimental data obtained during the wet-season campaign of the Large Scale Biosphere-Atmosphere Experiment in Amazonia (known as the LBA Project), carried out during the months of January to March of 1999, 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 contains the theoretical background. Results are presented and discussed in Section 4. Finally, in Section 5 we present our conclusions.

2 Data and Experimental Site

The experimental site is located in Rondonia, Brazil, roughly 3000 kilometers northwest from Rio de Janeiro, inside the Jaru Biological Reserve, 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, using sonic anemometers and thermometers. The data was gathered during an intensive micrometeorological campaign, part of the wet-season LBA project. The experiment was carried out during the months of 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, specially deforestation, in these functions, and analyzing the interactions between Amazonia and the Earth system.

The measurements were made with the help of a 66 meters 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 pm, 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 pm 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 [18]. We also checked the validity of Taylor’s hypothesis verifying the turbulence intensity inside the inertial subrange [19]. Finally, since we were primarily interested in the statistical characteristics of turbulence within the inertial subrange, we checked
our data for the existence of a sizable scaling range. We also computed the approximate extension of the inertial sub-range using the value of the isotropy coefficient (which shall be close to one within the inertial sub-range) [20].

3 Theoretical Background

In this paper, we adopt a generalization of the model used in our previous works [7,8,13], assuming that the PDF \( p_q(v_r) \) of turbulent velocity differences \( v_r \) (and also temperature differences \( T_r \)) is given by [14]:

\[
p_q(v_r) = [1 - \beta (1 - q) |v_r|^{2\alpha} - C \text{sign}(v_r)(|v_r|^\alpha - \frac{1}{3} |v_r|^{3\alpha})]^{1/(1-q)}/Z_q, \quad (1)
\]

where \( C \) is a small skewness correction term, and \( Z_q \) is given by

\[
Z_q = \frac{a^{m_0+1}}{\alpha} B(\phi_0, \chi_0), \quad (2)
\]

with \( B(\phi_0, \chi_0) = \Gamma(\phi_0)\Gamma(\chi_0)/\Gamma(\phi_0 + \chi_0) \), \( \phi_0 = (1 + m_0)/2 \), \( \chi_0 = l - \phi_0 \), \( l = \frac{1}{q-1} \), \( m_0 = \frac{1-\alpha}{\alpha} \), and \( a = \sqrt{l/\beta} \). The parameter \( \alpha \) was chosen according to the empirical formula \( \alpha = 6 - 5q \). The main advantage of eq. (1) is to permit the use of the same PDF model for handling both velocity and temperature turbulent fluctuations.

Neglecting the skewness correction term, we obtain for the PDF \( n \)-th moment:

\[
< |v_r|^n > = a^{m_n-m_0} B(\phi_n, \chi_n) \frac{B(\phi_0, \chi_0)}{B(\phi_0, \chi_0)}, \quad (3)
\]

where \( \phi_n = (1 + m_n)/2 \), \( \chi_n = l - \phi_n \) and \( m_n = \frac{(n+1)-\alpha}{\alpha} \).

The parameters \( q \) and \( \beta \) determine the shape of the PDF and are obtained through eq. (3), measuring the values of two moments (or related quantities) at each scale (for example, the variance, \( < |v_r|^2 > \) and the kurtosis, \( K_r = \frac{<|v_r|^4>}{<|v_r|^2>^2} \)).

The parameter \( q \) depends on \( K_r \) through the equation:

\[
K_r = \frac{B(\phi_4, \chi_4) B(\phi_0, \chi_0)}{B(\phi_2, \chi_2)^2}, \quad (4)
\]
Particularly for \(<|v_r|^2| = 1\), \(\beta\) is given by

\[
\beta = \left[ \frac{B(\phi_2, \chi_2)}{B(\phi_0, \chi_0)} \right]^{2/(m_2-m_0)},
\]

We remark that the kurtosis depends only on the entropic parameter. It is well known that large values of \(K_r\) are a signature of intermittency [2]. Thus, \(q\) can be used as a measure of intermittency in turbulent flows [15].

We also note that if we assume a scaling of the moments \(<|v_r|^n>| of \(v_r\) as \(r^{s_n}\) (which is valid for inertial subrange scales, for sufficiently high Reynolds number), the scale variation of \(q\) and \(\beta\) can be computed (rather than measured). For this, we shall use the scaling relation together with equations (3) and (4) to extrapolate the experimental values of \(q\) and \(\beta\), at a given reference scale (say, the Kolmogorov scale, \(\eta\)). This extrapolation procedure can be extended over a much wider range of scales [15] with respect to the inertial subrange, by using the concept of extended self-similarity proposed in [21]. This approach requires to numerically solve the Kolmogorov equation using, as initial condition, the observed value of \(q\) and \(\beta\), at a reference scale.

4 Results and Discussions

4.1 Wind Velocity Data

Figures 1 and 2 present semilogarithmic plots of probability distributions of daytime normalized vertical velocity differences \(v_r = w(x) - w(x + r)\), at four different scales, properly rescaled and vertically shifted for better visualization. Figure 1 data was measured above the canopy, inside the transition sub-layer. Figure 2 data was measured approximately 14 meters below the canopy top. Overall, we observe that the theoretical results (solid lines) are in good agreement with measurements across spatial scales spanning three orders of magnitude and a range of up to 10 standard deviations, including the rare fluctuations at the tail of the distributions. The transition from large-scale Gaussian behavior to a power-law form as \(r\) decreases is quite evident and well reproduced by the model. At small scales, the distributions have tails larger than that expected for a normal process and a spiky shape near the origin, an indicative of intermittency. We obtained similar agreement for the PDFs of longitudinal velocity \(u\) differences (not shown in the text).

Comparing the histograms of Figures 1 and 2, we note that the kurtosis is consistently higher within the canopy under diurnal conditions, regardless the scale. To investigate with more detail this behavior, we plot in Figure 3, the
Fig. 1. Standardized experimental and theoretical (solid lines) probability distributions of vertical velocity differences at the four spatial scales, for daytime above canopy data.

Fig. 2. The same as in Figure 1, but for within canopy data.
scale variation of the entropic parameter for \( u \) and \( w \) data, above and within the canopy, under diurnal and nocturnal conditions. A few points can be highlighted from these results.

First, we remark that all curves display a similar pattern: from a saturation value, the entropic parameters \( q_u \) and \( q_w \) decrease as \( r \) grows. Theoretically, \( q \) should tend to 1 at the integral scale and beyond. A similar trend has also been observed in a Couette-Taylor flow experiment [14].

Second, we note that the statistical characteristics of \( u \) and \( w \) wind-velocity components are not the same, mainly at larger scales. This result was somehow expected considering that our data was measured in a "noisy" real atmosphere, close to a very complex surface, such as the Amazon rain forest canopy.

Third, we observe that, indeed, under diurnal conditions, the entropic parameter is consistently higher within the canopy. However, this bias towards higher levels of intermittency found in low level data disappears under nocturnal conditions, as shown in Figure 3b. In order to explain this behavior, it is essential to examine the cyclic variation in the thermal stability regimes above and within the canopy along a typical day, and the role of the forest.
canopy in this process.

Schematically, during the day, dense forest canopies store heat in their highest parts due to incoming solar radiation flux. Hence, under daytime conditions, the above canopy region is hotter than the surroundings, and, thus, unstable. On the other hand, the region within the canopy is stable. There is a downward flux of turbulent kinetic energy (TKE), which is mostly produced by mechanical shear of the flow next the canopy. During the night, the energy budget is dominated by long-wave infrared radiation. Thus, the forest crown looses heat, the stability profile is reversed and stable conditions predominate above the canopy, and lightly unstable conditions may occur within the canopy. Next to the ground, there is a small upward flux of TKE generated by thermally induced local flows. This cyclic process determines variations on the thermodynamic structure of the canopy, which influence the turbulent transfer processes in this environment. This analysis suggests a simple scenario to explain the different intermittency regimes observed in the data. In this scenario, the forest crown act as a filter, breaking down large vortices while allowing smaller ones to pass through the canopy. This filtering process also explains why stable regions have a higher intermittency level than unstable ones. We remark that such eddy-filter character of forested canopies has already been observed by other authors [22,23,24].

In order to test this scenario, we high-pass filtered the original daytime above-canopy signal, and measure at each scale, the corresponding entropic parameter. As we can see Figure 4, this procedure increases the signal kurtosis, resulting in PDFs that are more similar to those found within the canopy during the day. This result provides evidence that indeed the forest crown has a filtering effect on large eddies, what impacts the intermittency level of the remaining velocity field. Naturally, the real scenario is much more complex than that, and is difficult to establish a general and simple pattern for all turbulent fluctuations in the actual atmosphere. For example, the momentum exchange process between the atmospheric flow above and within the canopy is not continuous in time but characterized by strong intermittent transfers, associated with the action of the so-called coherent structures, and characterized by a sweep and an ejection phases [25].

4.2 Temperature Data

We also tested the PDF model given by eq. (1) with temperature data. To illustrate, in Figures 5 and 6 we compare the theoretical PDFs with the experimental histograms of daytime normalized temperature differences, above and within the canopy, at four different scales. Again, for each scale, we estimated the variance and the kurtosis, and then computed the parameters $q$ and $\beta$. 

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Overall, we observe that the theoretical results (solid lines) are in good agreement with measurements, mainly at the smaller spatial scales. The transition from a power-law form at smaller scales to large-scale Gaussian behavior, as the scale increases, is less evident than in the velocity histograms but is also present. Comparing both histograms, we also note that, at smaller scales, they are quite similar, but at larger scales, the above canopy data appears to be more spiky, with heavier tails.

As we did previously, we study this trend plotting in Figure 7, the scale variation of the entropic parameter for temperature data, above and within the canopy, under nocturnal and diurnal conditions. Again, we observe that velocity and temperature curves display a similar pattern: from a saturation value, \( q \) decreases as one goes to larger scales. However, we also remark that, under both diurnal and nocturnal conditions, the entropic parameter is higher above the canopy. In other words, the temperature signal appears to be more intermittent above the forest crown, regardless the stability conditions. In this case, it is worthwhile to ask why this behavior is different from that observed in the velocity data, which display different patterns for day and night.

One possible answer is the existence of large-scale, ramp-like, coherent structures in the temperature fields. These structures are responsible for most of the sensible heat transport through the canopy [26]. Since the strongest shear and
Fig. 5. Standardized experimental and theoretical (solid lines) PDFs of temperature differences at four spatial scales, for diurnal above canopy data.

Fig. 6. The same as in Figure 5, but for within canopy data.
Fig. 7. Scale variation of the parameter $q$ for longitudinal velocity ($u$) and temperature ($T$) measured above and within the canopy, under diurnal conditions (top) and nocturnal conditions (bottom).

thermal gradients are located above the forest crown, we expect that ramp-like structures will be more apparent above vegetated canopies than within them [27]. These large scale, coherent structures are influenced by the local boundary conditions and, through their interaction with smaller scales, affect inertial sub-range properties measured by $q$. If correct, this scenario suggest that a “universal model” of turbulence intermittency is very difficult to be defined or may even not exist for canopy flows. These findings have implications in the development of subgrid model of Large Eddy Simulation (LES), now widely used to assess $CO_2$ exchange [28], which are primarily based on Kolmogorov type cascades or simplistic energy backscatter corrections [29], as they are not capable to capture the effect of large-scale motion on canopy sublayer inertial range.

The impact of such large scale, coherent structures can be well illustrated decomposing the turbulent data, by means of Haar wavelet filtering [30], in a coherent, intermittent part, and an incoherent, structureless part. This is performed by removing from the original signal all wavelet coefficients that are larger than a given threshold. Comparing the experimental histograms of the original signal (Figure 8) and the remaining incoherent signal (Figure 9), we observe that the incoherent, decorrelated velocities display PDFs that are roughly Gaussians, where the effect of intermittency has almost disappeared.
Naturally, the corresponding power spectrum (not shown here) is much more similar to that of a white noise.

Although the values of $q$ for velocity and temperature are highly correlated, they also convey information about different aspects of the turbulent flow: $q_w$ about the momentum exchange process through the canopy, and $q_T$ about the transport of sensible heat. Thus, properly combining the information on the two entropic parameters, make it possible to assess the stability conditions of the atmosphere. In Figures 10 and 11, we plot pairs of $q_w$ and $q_T$, simultaneously measured at different scales, for daytime and nighttime conditions, above and within the forest canopy. As we can see, two different stability regimes are clearly visible.

Above the canopy (Figure 10), the atmosphere is thermally unstable during the day ($q_w < q_T$), and almost stable at large scales during the night ($q_w \approx q_T$), although there are evidence of instabilities at smaller scales. On the other hand, within the forest (Figure 11), the atmosphere is slightly unstable during the night ($q_w < q_T$) and stable during the day ($q_w \approx q_T$). In contrast with the usual stability criteria [31,32], which are essentially global, the main advantage of the present approach is to assess the local atmospheric conditions, at different range of scales.
Fig. 9. Histograms of the filtered decorrelated wind-velocity data.

Fig. 10. Pairs of $q_w$ and $q_T$, simultaneously measured at different scales, for daytime and nighttime conditions, above the forest canopy.
5 Conclusions

In this paper, we discussed the impact of a rain forest canopy on the statistical characteristics of atmospheric turbulence. This issue is of particular interest for understanding on how the Amazon terrestrial biosphere interact with the atmosphere. For this, we used a probability density function (PDF) model of velocity and temperature differences based on Tsallis’ non-extensive thermostatistics (NETS). This new approach allow us to use a single PDF model to describe both the turbulent velocity and temperature differences in the turbulent flow.

We compared theoretical results with experimental data measured in a 66 m micrometeorological tower, during the wet-season campaign of the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). We investigated in detail how the value of Tsallis’ entropic parameter is affected when one moves into the canopy, or when one passes from day/unstable to night/stable conditions. We observed that the forest crown break down large vortices, allowing only smaller eddies to pass through the canopy, what increases the intermittency level of the remaining turbulent velocity data. We also found that large-scale, ramp-like, coherent structures in the temperature fields affect inertial sub-range properties increasing the kurtosis of the temperature signal above the canopy. Finally, we showed that combining the information on $q_w$ and $q_T$...
make it possible to assess the stability conditions of the atmosphere within
and above the canopy.

In conclusion, we might say that the new approach described in this paper,
based on NETS, provides interesting insights on different aspects of the atmo-
spheric turbulence in an complex environment such as an Amazon rain forest.
In this context, Tsallis' entropic parameter emerges as a measurable quantity
which can be used to objectively quantify intermittency buildup in turbulent
atmospheric flows.

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