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SATELLITE ECOHYDROLOGY AND MULTIFRACTALS: PERSPECTIVES FOR UNDERSTANDING AND DEALING WITH GREENHOUSE GAS EMISSIONS FROM HYDRORESERVOIRS

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RESUMO

O presente artigo caracteriza a primeira tentativa em identificar ramos científicos que conjuntamente possam fornecer soluções técnicas para melhor compreender e lidar com as emissões de gases de efeito estufa de reservatórios de água no Brasil. Os conceitos de Ecohidrologia são descritos na primeira seção. Em seguida aplica-se a abordagem ecohidrológica, através do uso de sistemas automáticos de aquisição de dados, para avaliar evidencias da ação de frentes chuvosas sobre as liberações de bolhas de metano e os fluxos de dióxido de carbono. Finalmente, a técnica *Multifractal Detrended Fluctuation Analysis* (MFDFA) é aplicada sobre dados de fluxo de gases na interface água-ar de reservatórios hídricos como uma orientação para simulações futuras de longo termo.

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ABSTRACT

The present article characterize a first attempt to identify scientific branches that together may assign technical solutions to better understand and deal with greenhouse gas emissions from hydroreservoirs in Brazil. The concepts of Ecohydrology are described in the first section. In the following is provided an ecohydrologic approach by using automated data acquisition systems to evaluate evidences of rainy fronts acting upon bubble methane releases and carbon dioxide fluxes. Finally, it is shown a Multifractal Detrended Fluctuation Analysis (MFDFA) of greenhouse gas fluxes at the water-air interface of hydroreservoirs as a direction for future long term simulations.

SUMMARY

FIGURE LIST

1. INTRODUCTION TO ECOHYDROLOGY

Ecohydrology is a neologism arising from merging the expressions “hydrology” and “ecology”. It was first proposed in Ireland in 1992 at the International Conference on Water and Environment (Zalewski et al., 1997) and suggests an integrated hydrographic basin approach by linking biological and physical sciences, with the aim of better understand and manage aquatic ecosystems.

The Ecohydrology concept tries to develop the consciousness of engineers and physicists in hydrology to further ecological methods and vice versa. In point of fact, the cooperation between hydrologists and ecologists would result in accurate answers for understanding and managing aquatic environments. In particular, *the ecohydrologic concept may also be applied for the awareness and attempting of reducing greenhouse gas emissions from manmade hydroreservoirs*.

Figure 1 presents a diagram condensing main ideas on Ecohydrology (Zalewski, 1997). Alike to dynamical system theory, Ecohydrology considers the hydrographic basin as a network of interconnected aquatic living systems, where feedback loops are naturally developed. Thus environment functioning and dynamics must be understood, especially in the following aspects (Zalewski and McClain, 1998):

- The knowledge of hydrosystems and comprehension of their responses to climatology, hydrology, water chemistry, toxicology, biology, geology, physical as well as biological processes, and anthropogenic effects;
- The integration of computational models based on this knowledge (process-based models); and
- The prediction of changes in hydrosystems by modeling, contrasting to long-term data, and management policy effects.

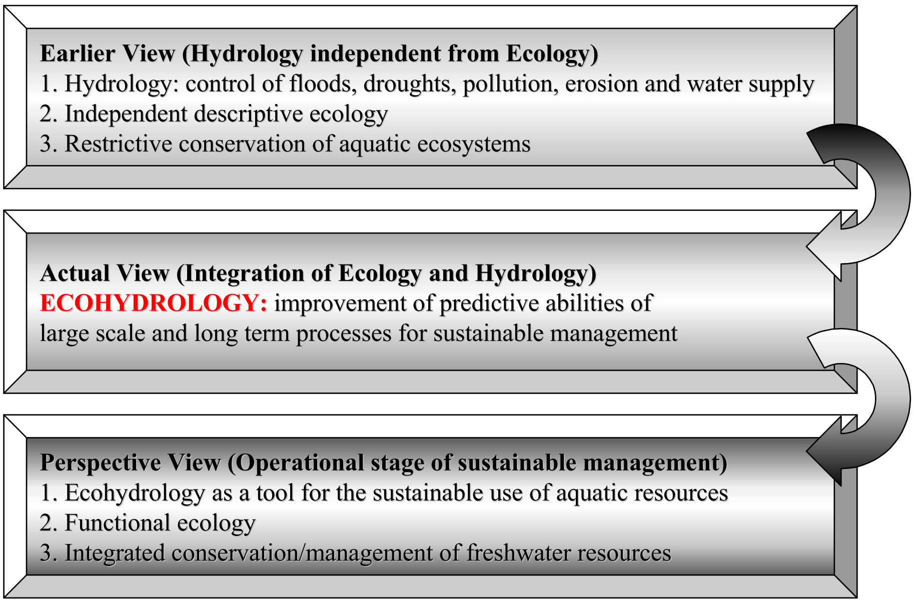


FIGURE 1.1 - Evolution of Zalewski´s concept on Ecohydrology.

Bringing greenhouse gas emissions from hydroreservoirs under the light of Ecohydrology it is imperative to increase dynamical knowledge on:

- Climatological effects on mass transfer through diffusive and turbulent processes under stratified and well-mixed conditions;
- Biogeochemical responses within the water body and sediments under stratified and well-mixed conditions;
- Process-based models integrating climate-hydro-biosphere; and
- The prediction of changes in emission patterns by modeling, contrasting different management policy scenarios to reduce greenhouse gas emissions.

Under this view, the HIDRO-NUSASC research group has implemented five telemetric data acquisition systems in Brazilian hydrosystems. Two systems were installed in the Central-East Amazon; a natural floodplain lake and a hydroreservoir (CT-HIDRO/Fapesp Project). The remaining systems were set up in hydroelectric reservoirs spread around the Central Savannah (Furnas Project) (Lima et al., 2004; Stech et al., 2005). The telemetric systems are able of acquiring quasi-hourly data as wind direction/velocity, water current direction/velocity, air/water temperature, atmospheric pressure and downward/upward radiation. Each system is also provided with a limnologic 6200 Yellow Spring Instrument sonde at the epilimnion (about 2 m depth) for underwater data acquisition of temperature, dissolved oxygen, pH, conductivity, turbidity and chlorophyll-*a*. The HIDRO-NUSASC group experience has shown that acquiring underwater data is somewhat difficult and subjected to data failure. Most of the difficulties arise from detection limits of a few probe variables and the requirement of periodic calibration.

The actual state of art does not permit to obtain flux data by telemetric monitoring systems as described above. The mounting of automatic gas systems in the vicinity of the telemetric system for a few days was the "alternative effort" for establishing relationships between climatic-hydrologic and greenhouse gas flux dynamics. Despite of methodological drawbacks, particularly the humidity interference in gas methane analysis (Lima et al., 2005), a climatic-gas flux linkage has hardly been achieved so far, simply because *long-term processes require long-term monitoring*. In the following section, a preliminary attempt to link climatic and greenhouse gas flux dynamics was recently made for Corumbá reservoir (Furnas Project), where a longer period of gas flux measurements were finally performed.

2. APPLICATION OF ECOHYDROLOGY ON GREENHOUSE GAS EMISSIONS: THE EFFECT OF RAINY FRONTS OR METHANE AND CARBON DIOXIDE FLUXES

Telemetric data has provided important information concerning changes in atmosphere and underwater dynamics of water bodies. For instance, it was realized that quasi-periodic cold fronts might be responsible for changes in the vertical thermal structure of the reservoirs during the dry season (Lorenzzetti et al, 2005). The great importance on these findings is that cold fronts are likely responsible for *a general change in all underwater processes*. Another complimentary find, openly stated by Prof. J.G. Tundisi is that "*in hydroelectric reservoirs hydraulic stratification due to dam turbines is indeed more significant than thermal stratification occasioned by solar heating*". As a result, there are concurrently natural and anthropogenic forces driving reservoir hydro-biogeochemical dynamics.

During gas flux measurements carried out in Corumbá reservoir, near Caldas Novas (GO), from 11th to 19th March 2005, it was fortunately possible to get a glimpse of the effects of weather changes, specifically a rainy front, on greenhouse gas flux dynamics. Using a similar approach purposed by Lorenzzetti et al. (2005), it was evaluated atmospheric and limnologic data telemetrically obtained (Figure 2.1). By 13th March, rainy fronts started to appear, becoming stronger by the night of 14th March. The weather change resulted in increased wind speeds and decreased water/air temperatures, dissolved oxygen concentrations and pH values. Atmospheric pressure was steadily declining up to the beginning of 15th March and had risen just after. Turbidity has increased about 100% by the ending of 15th March (Figure 2.1) and stabilized at elevated values.

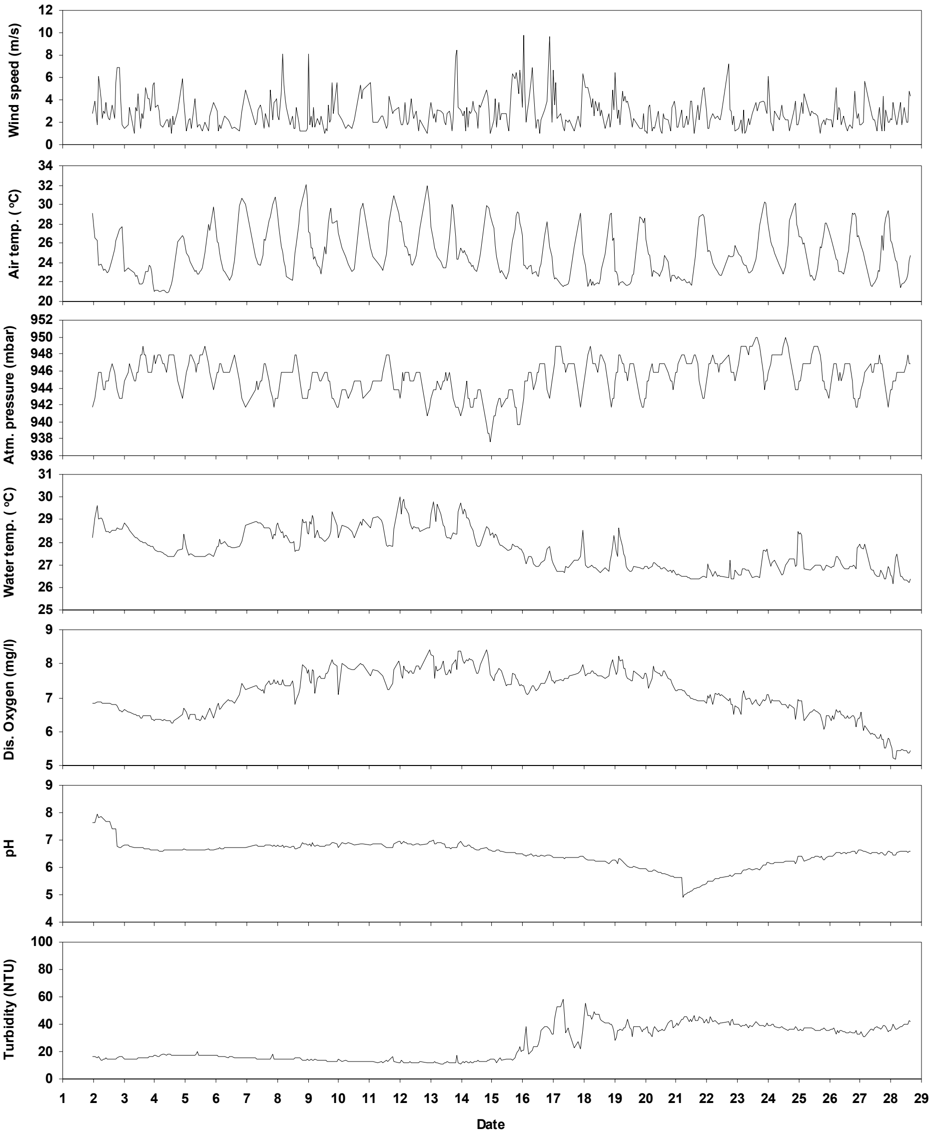


FIGURE 2.1 - Quasi-hourly time series of variables telemetrically gathered at Corumbá reservoir from 2nd to 28th March 2005. The last four curves were telemetrically acquired with a 6200 YSI sonde at 2 m depth. For a complete system description see Stech et al. (2005).

It was initiated in the night of 11th April, at about 1 km apart from the telemetric system, measurements close to the shoreline of methane and carbon dioxide concentrations using four floating open chambers. The gas flux system consisted of a photoacoustic detector measuring the concentration difference between air exiting the chamber and atmospheric air pumped into the chamber. Positive values indicate emissions to the atmosphere (Lima et al., 2005).

Figure 2.2 illustrates mean values of methane and carbon dioxide instantaneous flux dynamics, ϕ_t, monitored at 5-minute time interval, and calculated by $\phi_t = f\left(c_{out} - c_{in}\right)/A$, where *f* is the molar flow, *A* the chamber water-air exchange area, and c_{out} and c_{in} the concentration of the gas specie flowing out and into the chamber, respectively.

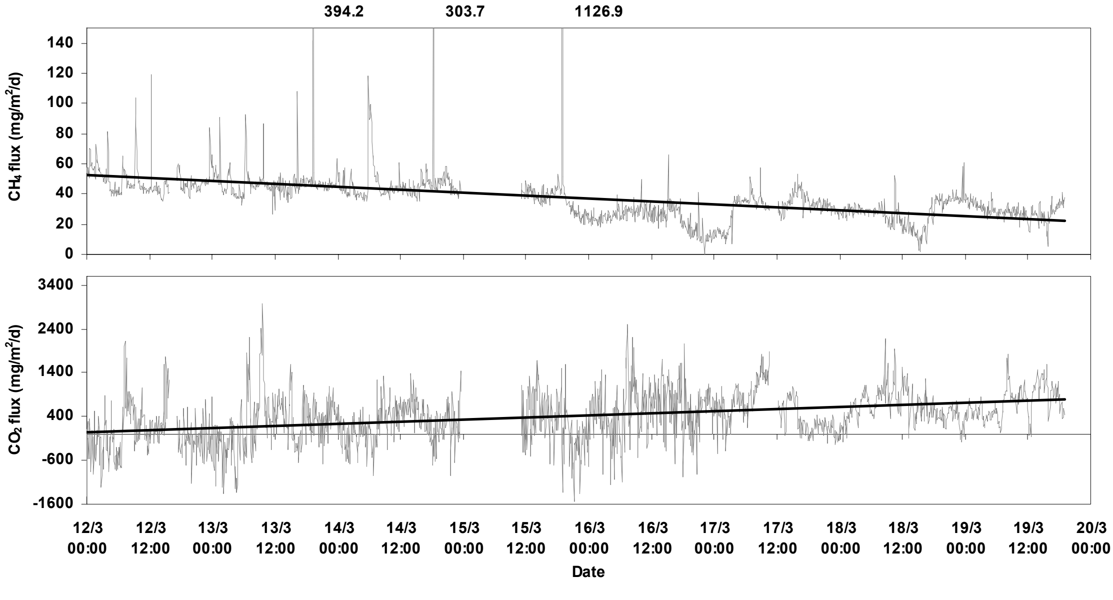


FIGURE 2.2 - Mean methane (top) and carbon dioxide (bottom) fluxes derived by four dynamic chambers simultaneously deployed in the shoreline of Corumbá reservoir (mean depth of three meters) about one kilometer distant from the telemetric system. Peaks in the methane flux time series characterize bubbling episodes, where out-of-scale peaks are labeled. The black lines are linear square fits for trend evaluation. For detailed information on dynamic chamber and photoacoustic gas detection method see Lima et al. (2005).

Note the lessening in size and frequency of methane bubbling after the rainy front, while carbon dioxide emissions increased (see also the linear trends). A pertinent cause for this biogeochemical phenomenon is the *thermal and chemical stratification disruption due to water circulation driven by weather changes*. Precipitation induces water mass circulation by adding cold water at the reservoir surface and water-land boundaries. The cold water tends to dropdown towards the hypolimnion owing to its higher density (lower buoyancy). Besides, wind-driven circulation is a common mass transfer mechanism in water bodies. A clear evidence of water stratification disruption is the doubling in the turbidity levels after the rainy front (Figure 2.1), resulted from both runoff and sediment re-suspension. On 16th March the oxygen levels in deep waters were comparable to the surface waters at about 5 mg/l (D.E. Cesar and F. Roland, unpublished results). The mixing of the water mass distributes uniformly the dissolved oxygen, making it possible methane oxidation in deep waters, and also in several centimeters into the sediments (D. Addams, personal communication). Therefore the lowering in bubble methane emissions and the increase in CO_2 emissions after the weather change might be an upshot of methane oxidation in the water column and in the sediments. The decrease in pH values at the telemetric system up to 21st March, due to an imbalance on the bicarbonate-carbonate buffer, also indicates an increase in dissolved CO_2 in water (Figure 2.1). Moreover, the decrease in water temperature may in some extent corroborate to attenuate sediment methanogenesis.

The automated quasi-continuous approach allows one to evaluate mechanisms leading to bubbling and also verify spatial variability on bubbling episodes. The underlying mechanisms of bubble releases assume sediment trigger by water wave motions, induced by wind energy and water currents (Keller and Stallard, 1994; Joyce and Jewell, 2003). It has been also argued that the decrease of the atmospheric pressure might also induce bubble releases by increasing bubble gas volume, making ruptures in the sediment structure (Lima and Novo, 1999). Due to disparity on the time step of data acquisition, simple correlation analysis does not provide useful information. Instead, it is more effective visually linking bubbling episodes (in minutes) to wind and pressure oscillation (in hours). In Figure 2.3 gray stripes identify the timing of bubbling episodes associated to wind and pressure. In most of the cases there is evidence that both wind and pressure acts concurrently over bubbling phenomena. Note in Figure 2.3 that wind/pressure-driven bubbling were commonplace solely before the rainy front. The lack of a clear link between methane bubbling and high wind speeds (lower atmospheric pressure) subsequent to the weather change can be explained by i) methanogenesis attenuation due to declining temperature and ii) methane oxidation amplification due to water column mixing.

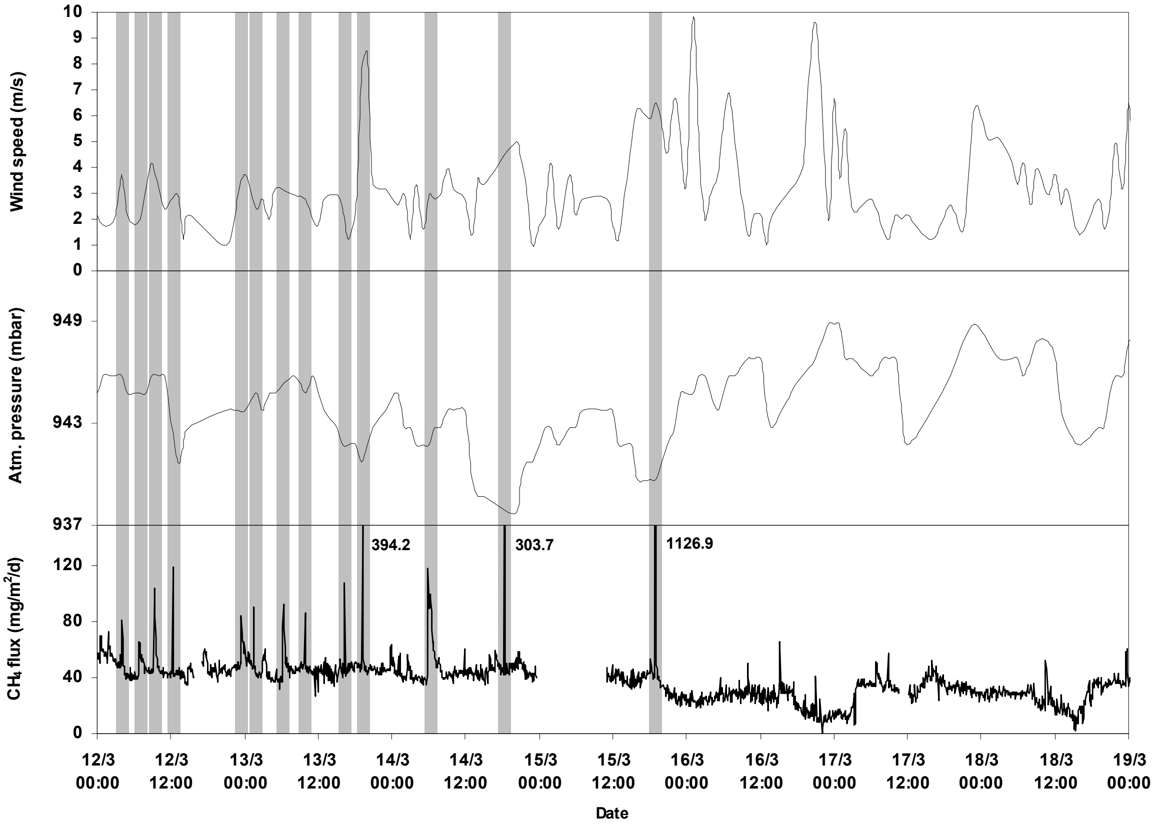


FIGURE 2.3 - Mean bubble methane episodes according to the wind and atmospheric pressure data obtained at the telemetric system. Out-of-scale peaks are labeled. The gray stripes indicate likely bubbling episodes wind/pressure-driven.

Recent studies have shown that the mechanism triggering bubbling episodes acts over tens of meters, evidencing strong spatial correlations (Joyce and Jewell, 2003). This is quite reasonable considering the nature of the variables acting upon methane bubbling. In Corumbá, the four open chambers were horizontally spaced every fifteen meters from the shore into the reservoir, varying from 0.4 m to 6.0 m water depths. Figure 2.4 present the time series of methane fluxes calculated for each chamber.

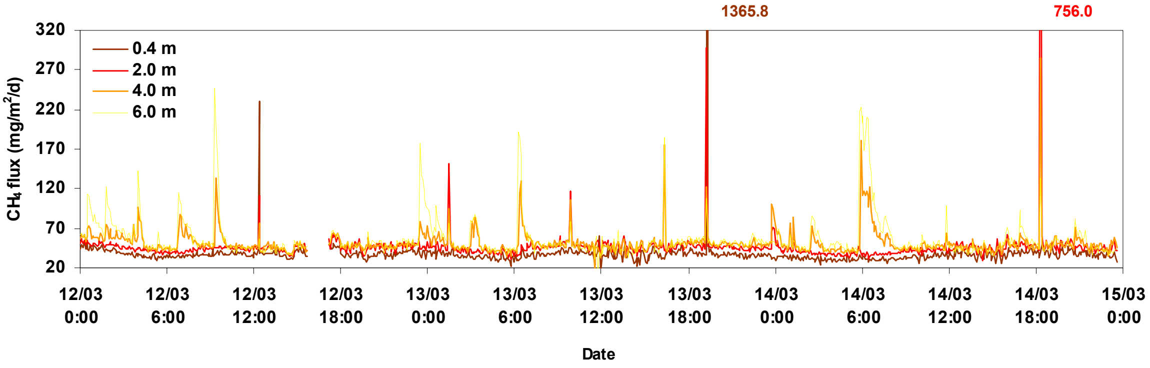


FIGURE 2.4 - Spatial variability of bubble methane fluxes according to the water depth of measurement (colored legend). Out-of-scale peaks are labeled and colored according to depth legend.

It is discernible two types of bubbling processes: a sudden big spike (bouncy release), common to all depths and usually greater for shallow sites, and a broadband bubbling only in deeper sites. Wind/pressure-driven mechanisms might cause both types of bubbling, but barely explain the broadband bubbling at deeper locations. *It is possible that in deep locations a sort of sediment-methane leaching (seepage) can be developed subsequent to some mechanical trigger; the methane seepage can result from higher hydrostatic pressure, creating resistance in the disturbed sediment for a complete gas methane bouncy release.* Despite of that, as can be seen in Figure 2.3, following a rainy front the two bubbling types are mutually suppressed, and from Figure 2.2 such suppression results in the enhancement of carbon dioxide emissions.

3. MULTIFRACTAL DETRENDED FLUCTUATION ANALYSIS OF GREENHOUSE GAS FLUXES AT THE WATER-AIR INTERFACE OF HYDRORESERVOIRS

From an ecohydrologic perspective, hydro-biogeochemical phenomena are usually dependent upon a consort of entities or variables that together produces fluctuations observed by manmade measuring systems. The capacity of simulation is thus conditioned on the ability of understanding variable linkages. Nevertheless, any attempt of fully describe the dynamical behavior will be lacking, given the impracticality of measuring all variables in infinite time and space resolutions. Even in the ideal case of infinite data accessibility, it would be necessary a countless number of high-efficient processors to run a process-based model with infinite inputs.

In the earlier section, it was show by using ecohydrologic principles that rainy fronts can result in shifting methane-to-carbon dioxide emissions due to water column mixing (oxygenation). Note, however, that the measurements were taken at finite positions, in a particular reservoir, and in a particular period of the year. Therefore, extrapolation to the whole reservoir, to other hydroreservoirs, or to a full year cycle is in any case defective. Otherwise, *due to the complex behavior of greenhouse gas emissions from water bodies, it can be helpful before any attempt of modeling, to investigate the time series (signal) nature according to Fractal concepts*. A fractal structure has the main characteristic of self-affinity (long range correlations) under several (with upper and lower cut-offs) scales in time and/or space. Several natural phenomena exhibit such property, especially in Hydrology (for an excellent review see the textbook "Scale dependence and scale invariance in Hydrology", edited by G. Sposito, Cambridge, 1998). If the same is valid to greenhouse gas flux data, thus process-based modeling can also account on the dynamical structure of the signal data for simulation improvements.

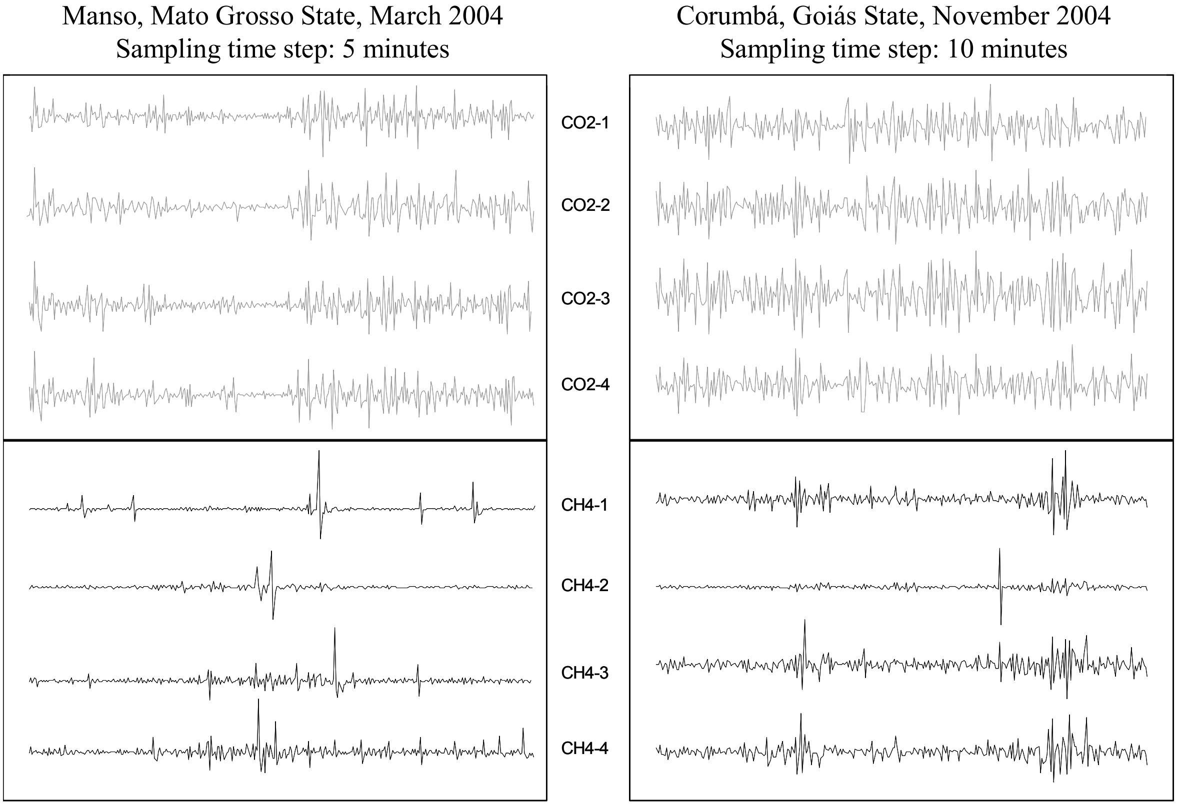
In recent years the Detrended Fluctuation Analysis (DFA) method has become a widely used technique for the determination of monofractal scaling properties and the detection of long range correlations in nonstationary signals. It has been show by DFA analysis that actual climate models do not include long range correlations observed in real climate signals (Bunde et al., 2001; Govindan et al., 2001). Besides, several signals do not exhibit a simple monofractal scaling behavior, which assign a single scaling exponent. In some cases, there exist crossover time scales s_t, separating regimes with different scaling exponents. For instance a signal may present long range correlations on small scales $s \ll s_t$ and another type of correlations or uncorrelated behavior on larger scales $s \gg s_t$. In this case a myriad of scaling exponents is required for a full description of the scaling behavior, where multifractal analysis must be applied. The Multifractal Detrended Fluctuation Analysis (MFDFA) technique, extensively discussed and applied to synthetic signals in Kantelhardt et al. (2002), allows one to define the nature of the fractal behavior. Accordingly to Kantelhardt et al. (2002), multifractality can be due to a broad probability density function (PDF) or due to different long range correlations for small and large scales of fluctuation. In terms of modeling, a multifractal signal fluctuation due to different long range correlations is considerably difficult to simulate. On the other hand, a monofractal signal due to long range correlation on small scales, but exhibiting multifractal exponents due to a broad PDF is, in theory, potentially reproducible, as discussed in the following.

The test for the fractal nature is a random shuffling of the signal values. After shuffling any long range (anti-) correlation in the signal is destroyed, and the signal becomes uncorrelated as white noise. After shuffling the hypotheses are:

H_o: the signal is multifractal due to several long range correlations on differing scale s_t, then shuffling will destroy all the correlations and multifractality disappears.

H_a: the signal is monofractal and its unique long range correlation is destroyed, but show multifractal nature due to a broad PDF, then shuffling will not alter the PDF and multifractality persists.

Usually, the properties of complex signals, despite the nature of the underlying dynamics, are studied from the fluctuating quantities (flux differences, in this case) at different time scales. Figure 3.1 presents the fluctuation signals of carbon dioxide and methane fluxes obtained in Manso and Corumbá reservoirs by the photoacoustic monitoring of four simultaneous open dynamic chambers.


Manso, Mato Grosso State, March 2004
Sampling time step: 5 minutes

Corumbá, Goiás State, November 2004
Sampling time step: 10 minutes

FIGURE 3.1 - Fluctuation signals, $\phi_{t+1} - \phi_t$, of carbon dioxide (in gray) and methane (in black) fluxes, in Manso and Corumbá reservoirs. Each signal corresponds to one of the four independent chambers.

The fingerprint of multifractality is the singularity spectrum $F(\alpha)$, where α is the singularity strength or Holder exponent. $F(\alpha)$ denotes the exponent dimension of the subset of the series that is characterized by α. The singularity spectrum based on the MFDFA method is shown in Figure 3.2 for original (open symbols) and shuffled (empty symbols) signals. The multifractal behavior is evident for all gas flux signals, independently of the gas specie. Differences in the singularity spectra between chambers are most likely due to spatial (depth) variability of the measurements. In contrast, a similar shape was obtained comparing spectra acquired in Corumbá and Manso reservoirs.

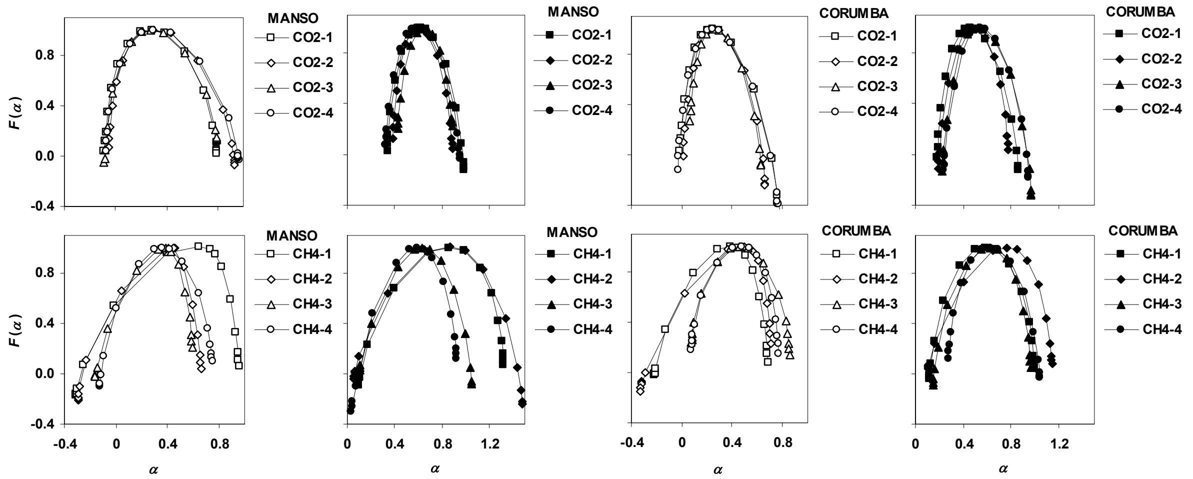


FIGURE 3.2 - Singularity spectra for original (open symbols) and shuffled (filled symbols) flux fluctuation signals.

The shuffling of the signal values have neither significantly changed the multifractality nor even annihilated (flattened) it (Figure 7). The multifractal behavior of gas flux fluctuation is most likely due to a broad PDF, being actually a monofractal process (refuse Ho). All shuffled signals are uncorrelated broad PDF multifractal signals. PDFs are shown for carbon dioxide and methane flux fluctuations in Figure 8. Both original and shuffled series present PDFs away from regular Gaussian distributions.

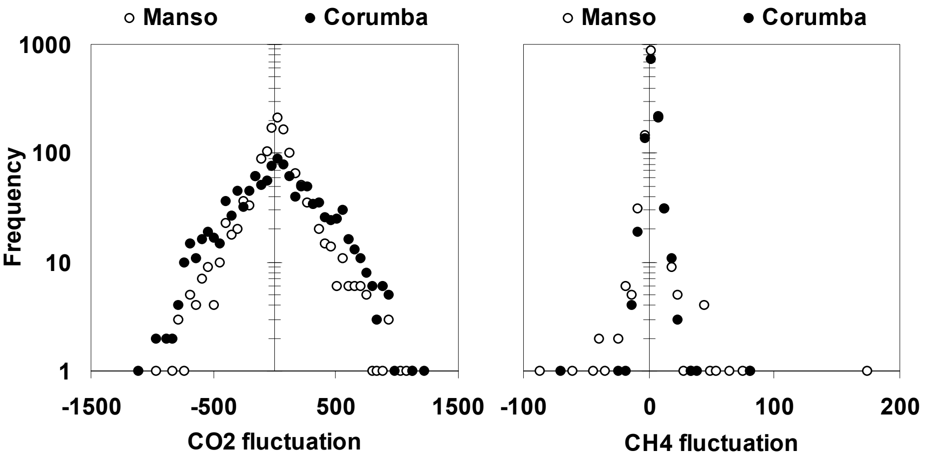


FIGURE 3.3 - Probability density functions of carbon dioxide and methane flux fluctuations measured with four open dynamic chambers in Corumbá and Manso reservoirs.

It is a well-known property of intermittent fluctuations that at large time scales the PDFs are normally distributed. However, at increasingly smaller scales they become strongly non-Gaussian and display flatter tails than those expected for a Gaussian process. This is understood as the mark of the intermittency, which can be linked by the entropic parameter q from generalized thermostatistics (Ramos et al, 2001a, 2001b; Ramos et al. 2004). The nonextensive parameter q represents a measurable quantity, robust to variations in the Reynolds number, and can be used to quantify the occurrence of intermittency in fluctuating signals. In short, the simulation of greenhouse gas flux dynamics at the water-air interface of hydroelectric reservoirs may aggregate long term data acquisition, long term process-based models and generalized thermostatistics models, issues that will be explored in the near future.

3. CONCLUDING REMARKS

In the context of a changing world, water resource researches must rely on ecohydrologic principles in order to comprehend and correctly manage aquatic ecosystems. The HIDRO-NUSASC research group is a pioneer Brazilian endeavor in ecohydrological studies. Despite of its early stage, it recognizes that exchanges of knowledge within a multidisciplinary group associated to task distributions are indispensable for the accomplishment of the ecohydrologic approach.

The first attempt to understand carbon dioxide and methane flux dynamics using ecohydrological concepts permitted verify that weather changes, such as rainy fronts are able of shifting methane to carbon dioxide emissions, due to the suppression of bubble emissions by both i) the intensification of methane oxidation and the attenuation of methanogenesis at lower temperatures. A generalization of this cause-effect process needs additional data in other periods, locations, as well as hydroreservoirs. In the case of truly generalization, an option for reducing hydroreservoir methane emissions, which is more than 20 times the carbon dioxide heating potential, is intensifying a regular rupture of water column stratification by any external force, inducing the oxygenation of the water column. For instance, varying the water depth of turbine intakes could shatter the hydraulic-anthropogenic stratification induced by turbines, which is assumed to be greater than the thermal-solar stratification.

The ecosystem impacts of lasting mixed water column are not know in general, but would definitely modify the reservoir trophic state, towards to an oligotrophic hydrosystem. This is because the nutrient cycling between the sediments and the water is intrinsically allied to oxygen dynamics; in the presences of high oxygen levels dissolved nutrients precipitates becoming unavailable for biological process. Paradoxically, a basic mechanism for releasing sediment nutrients to the water column is exactly the methane bubbling under anoxic conditions. As a result, more studies are desirable to verify i) the methane oxidation efficiency by destroying water column stratification, and ii) the effects of mixing water column on nutrients dynamics and biodiversity. Process-based models coupled to hydrodynamic models may help to provide answers to this matter.

Moreover, it has been shown that both wind and atmospheric pressure may synergistically control the triggering of methane bubbling, and these atmospheric variables should be taken into account for future process-based models. Surely bubbling process will vary with depth, as was illustrated by distinguishing a sudden big spike, usually greater for shallow sites, and a seepage broadband bubbling stirring only in deeper sites. Nonetheless, as the volume increases (pressure decreases) while bubbles travel upwards, they might collapse for extended water column depths before reaching the atmosphere, thus producing dissolved methane-enriched plumes.

The signals obtained by automated photoacoustic dynamic chamber method allowed applying signal processing analysis to study the dynamical behavior of carbon dioxide and methane fluxes at the water-air interface. Using the MFDFA analysis, it was noted that the signals presented monofractal long range correlations, which is destroyed after shuffling signal values. However, the multifractality observed in the signals have not change after shuffling, indicating that the multifractal behavior is exclusively due to a broad probability density function, alike for other process modeled by generalized thermostatistics. Consequently, future research on simulating carbon dioxide and methane fluxes must consider not only process-based models but also the generalized thermostatistical theory.

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