FINAL REPORT PROGRAM LEFE

Program LEFE/ action(s) MANU	Project Title SOLSTYCE	Years 2020 – 2022

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Context : The three major steps in the analysis of observational time series are firstly to improve data quality and more specifically removing noise, then to determine the dimensionality of the observed dynamics and finally to build a model sufficiently representative of the dynamics underlying the data of observation.

Objectives / scientific questions: The scientific objective of SOLSTYCE is to analyze and characterize the evolution of physical systems through a set of observational data sequences. The methodology developed is based on the coupling between the decomposition of observation time series into independent components and the characterization of the dynamics underlying the observation data. The specific objectives concerning the decomposition of observational time series are to identify the components linked to noise in order to eliminate them, and to estimate the dimensionality of the observed dynamics. The specific objectives concerning the characterization of the underlying dynamics are to represent it in the spaces state so as to better visualize irregularities and to estimate the capacities of a global modeling approach to obtain a model characterizing the evolution of the observed physical system. Another very important objective was to develop a network of expertise bringing together skills in atmospheric physics, nonlinear systems dynamics and data processing to optimize and validate the techniques developed during SOLSTYCE.

***Main result*:** The Empirical Adaptive Wavelet Decomposition EAWD (published in 2022) has been used for removing noise and determine the dimensionality of the observed dynamic. To represent the observed dynamics in the states space, a singular spectrum analysis (SSA) has been developed and results obtained has been compared to those obtained with the method of delays (MOD) currently used in the literature. A global modelling approach was tested, in collaboration with Sylvain Mangiarotti CESBIO-Toulouse), on two time series representing respectively ozone concentration in the stratosphere and troposphere collected in the Natal region (Brazil) The results obtained are very promising (see illustrations 1, 2). However, their validation against observations requires further developments. A network of experts has been set up, with a remote workshop scheduled in December 2021. The main research organizations involved in this workshop are listed below.

Illustration1

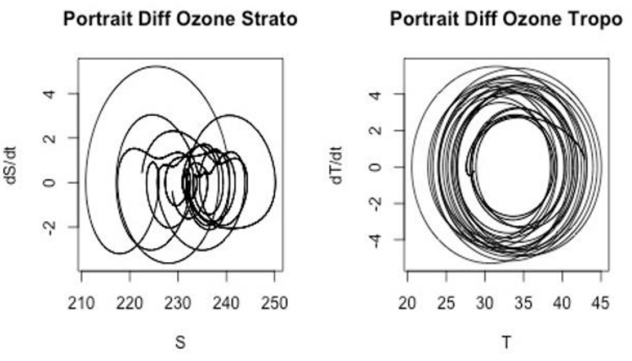
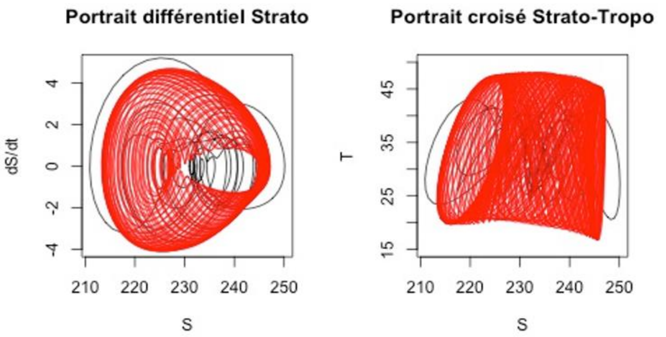


Illustration 2



Comments on illustration 1,2:

When the original variables of a system are not available, a reconstruction equivalent to the original phase space can be, in principle, obtained by using a single observed variable and its derivatives. A phase portrait is a two-dimensional projection of such a reconstruction. We start with two monthly time series representing respectively ozone concentrations in the stratosphere (S) and troposphere (T). The dimension of the dynamic in the S and T time series has been estimated to 3 by using EAWD (Empirical Adaptive Wavelet Decomposition) technic. Derivative coordinates used for S are $[S, dS/dt, d^2S/dt^2]$ and for T $[T, dT/dt, d^2T/dt^2]$. Phase portraits of Stratospheric ozone concentration (S,dS/dt) and Tropospheric ozone concentration (T,dT/dt) are respectively represented on the right hand side and the left hand side of the illustration 1. Ozone exchanges between troposphere and stratosphere are far non trivial. These exchanged are usually studied based on physical assumptions and modelling, but such an approach may be very costly. Our objective here is different. It is to investigate this coupling empirically, by reconstructing their coupling equations directly from the observed time series. Using the GPoM R package, the following set of equations was obtained: dT/dt = T2; dT2/dt = -38.4-0.24T+0.42S-0.00094S^2; dS/dt = S2; dS2/dt = 6.6-0.97T2-0.26T+0.71S2+0.021S+0.004ST2+0.00096ST-0.0031SS2-0.00019S^2. These equations reveal a bidirectional coupling of the ozone content between troposphere and stratosphere. Two projections of the model phase space are presented in illustration 2. The differential portrait (S,dS/dt) of the stratospheric ozone (illustration2-left) shows a relatively good consistency between the model (in red) and the data reconstruction (in black). It is also the case for the cross portrait (S,T) (illustration 2) which shows a good consistency between the model (in red) and the data reconstruction (in black).

Future of the project: The methodology described above was applied to data sequences of observation of ozone concentration respectively in the stratosphere and the troposphere. The results obtained by applying a global modelling approach give very encouraging results (see illustrations 1-2). However, concerning the methodology developed in the SOLSTYCE project, two points that require further developments need to be considered. The first point concerns the development of tools for validating models obtained from the global modelling technique in relation to observations. The development of a data assimilation technique for predictability analysis and model validation is envisaged. An extended Kalman filter-type data assimilation scheme could be used to analyze model-data errors and simulate their propagation. The development of such techniques will also enable to test the predictive capabilities of models. The second point concerns the development of dimensionality reduction techniques. The idea is to use tools from topological data analysis (TDA) for mapping data from its high dimensional space to a low dimensional space. One major reason to use such an approach is that topological data representation is known to be stable in the presence of noisy perturbations. The development of numerical methods relating to the two points addressed above can be carried out through the network of experts initiated in SOLSTYCE and could be the subject of a future LEFE-MANU project.

Number of publications, communications and thesis:

- **Publications (4)** : **1-** Critical Research: Selection of optimal embedding parameters applied to short and noisy time series from Rössler System: O.Delage, A. Bourdier, New Insights into Physical Science Vol.7, DOI: 10.9734/bpi/nips/v7 , 2020; **2-** The Empirical Adaptive Wavelet Decomposition (EAWD): An adaptive decomposition for the variability analysis of observation time series in atmospheric sciences, O.Delage, T. Portafaix, Hassan Bencherif, A. Bourdier, E. Lagracie, Non Linear Processes in Geophysics, https://doi.org/10.5194/npg-2021-37, 2022; **3-** Variability analysis of observational time series: An overview of the decomposition methods for non-stationary and noisy signals, O. Delage, H. Bencherif, T. Portafaix, R. Tato Loua, D. Ki. Pinheiro, Book: Time series analysis-recent advances, October 2023 ; **4-** Ozone Trend Analysis in Natal (Brasil) using Multi-Linear Regression and Empirical Decomposition Methods over 22 years of Observations, H. Bencherif, D.K. Pinheiro, O.Delage, T. Millet, L. Vaz Peres, N. Begue, G. Bittencourt, M.P.Pereira Martins, F.R Da Silva, L.A. Steffenel, K. Mbatha, V.Anabor, Remote Sens. 2024, 16, 208. https://doi.org/10.3390/;
- **Organization of a workshop** in 2021 to initiate a network of experts with expertise in atmospheric physics, non-linear system dynamics and data processing. The main laboratories participating involved in this workshop are: The Laboratory for the Atmosphere and Cyclone (LACy-UMR 8105-Reunion University), ESPACE-Dev (Reunion University), University of Kwazulu Natal (UKZN-South Africa), Laboratory of Dynamical Meteorology (LMD-Paris), Center for Biodiversity Spatial Studies (CESBIO-Toulouse), Laboratory of Aerology (UMR 5560-Toulouse), Paris-South University, University of Murcia (Spain).
- **Participation in the inaugural session of the GDR**: Theoretical challenges for climate science: Presentation of a poster on the EAWD method applied to ozone concentration total column collected on the Reunion Island.

Data availablility

https://filesender.renater.fr/?s=download&token=1baed9b7-39f9-4715-a219-d382cf57623c