On Time Lag Detection Between Time Series Sampled by Eddy Covariance Systems

Domenico Vitale and ICOS-ETC Teams

MEMOTEF Department, Sapienza Università di Roma

domenico.vitale@uniroma1.it

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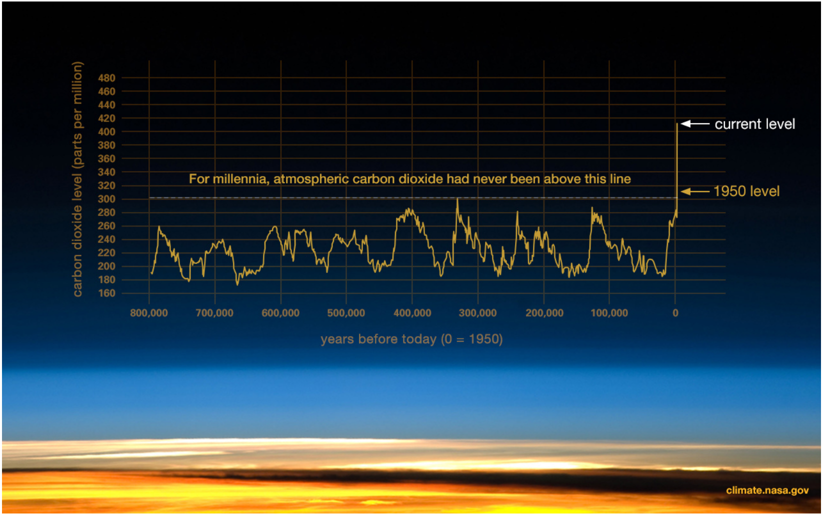
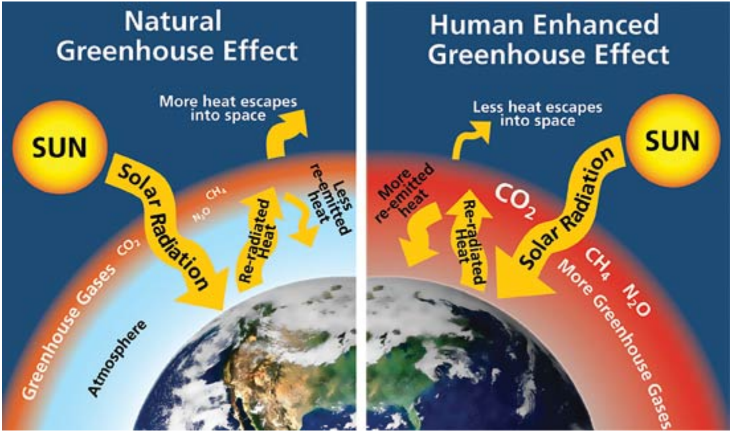
Overview

The Climate Change Context



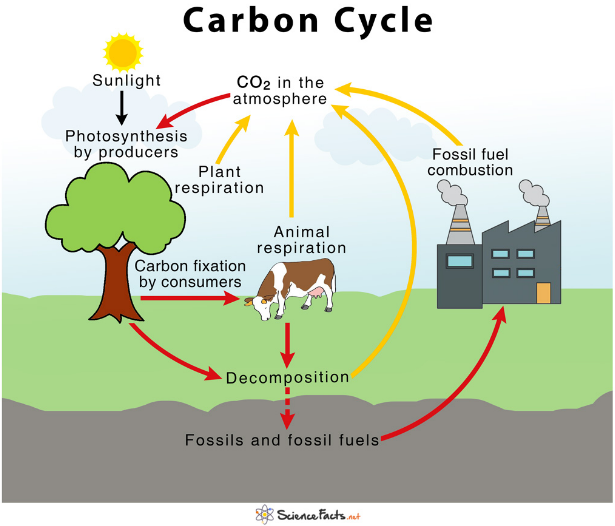
Carbon dioxide over the last 800000 years measured from the EPICA Dome C ice core in Antarctica. Recent measurements are from NOAA Mauna Loa site.
Source: `https://climate.nasa.gov/evidence/`

The Climate Change Context



Idealized models of the natural and human enhanced greenhouse effect.
Source: `https://www.nps.gov/goga/learn/nature/climate-change-causes.htm`

The Climate Change Context



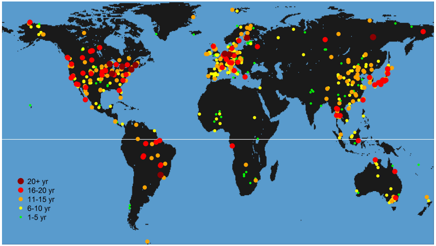
The Eddy Covariance Data

- The eddy covariance (EC, Aubinet et al, 2012) is a modern scientific method used to monitoring the rate of exchanges of GHGs between ecosystems and the atmosphere
- The basic setup of an EC system requires a sonic anemometer for the wind velocity components and a gas analyzer for scalar atmospheric concentrations

- EC variables are sampled at *ultra* high-frequency (e.g. 10 obs per sec) and collected in raw data files of 30 min length (this means sampling 1800 obs for each variable every 30 mins; storing and processing 48 raw data files per day, 17520 raw data files per year, and so on)
- Half-hourly EC fluxes are derived from the covariance between vertical wind speed (w) and the atmospheric concentration of the gas, like CO_2

The Eddy Covariance Networks

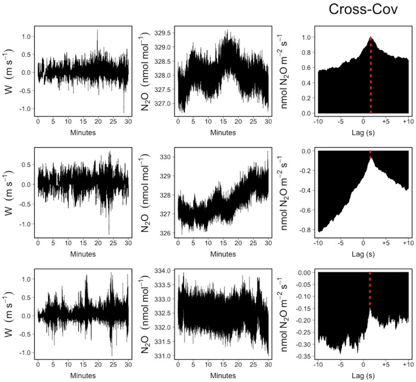
The ICOS station network (https://www.icos-cp.eu)



The FLUXNET network (https://fluxnet.org)

The Time Lag Issue

- The calculation of EC fluxes requires the instantaneous quantities of vertical wind velocity (w) and atmospheric concentration of the scalar of interest (c) be simultaneously measured
- Such a condition is not perfectly fulfilled during field measurements because in general there is no perfect co-location of the anemometer and the gas analyzer
- The most used procedure consists of identifying the time lag in correspondence of the timestep that maximizes (in absolute terms) the covariance between c and w (MaxCov)



The Pre-Whitening with Bootstrap (PWB) Procedure

The proposed procedure for time lag detection consists of the following steps:

1. Select the X and Y variables, where the X-variable is the atmospheric scalar concentration of interest (e.g. CO_2, H_2O, N_2O, CH_4) and the Y-variable is one of vertical wind speed or sonic temperature

2. Pre-Whitening

   Filter the X variable via an AR filter to retrieve *iid* residuals (X_R)
   Filter the Y variable via the same AR filter to retrieve residuals (Y_R)

3. Bootstrapping

   Compute n block-bootstrapped versions of X_R^i and Y_R^i, for $i = 1, \ldots, n$

4. Cross-Correlation Function (CCF) Assessment

   Compute n CCFs between X_R^i and Y_R^i
   For each CCF, select the plausible time lag in correspondence of the maximum (in abs terms)

5. Optimal Time Lag Detection and Uncertainty Quantification

   Given the distribution of the n plausible time lags
   1. select the optimal time lag in correspondence of the modal value
   2. estimate the 50% Highest Density Interval (HDI) as a measure of uncertainty

The proposed procedure is implemented in the RFlux R package available at https://github.com/icos-etc/RFlux

Pre-whitening

$$r_k(X,Y) = \frac{\sum(X_t - \overline{X})(Y_{t-k} - \overline{Y})}{\sqrt{\sum(X_t - \overline{X})^2}\sqrt{\sum(Y_t - \overline{Y})^2}}$$

If X and Y are *iid*, $E(r_k) = 0$ and Var$(r_k) \approx \frac{1}{n}$ which leads to the conventional confidence intervals (CIs)

When X and Y are not *iid*

$$\text{Var}(r_k) \approx \frac{1}{n}\left[1 + 2\sum_{k=1}^{n} \rho_k(X)\rho_k(Y)\right]$$

where $\rho_k(X)$ and $\rho_k(Y)$ are the autocorrelation estimates at lag k of X and Y, respectively.

For example, for two AR(1) processes, independent of each other,

$$\text{Var}(r_k) \approx \frac{1 + \phi_X\phi_Y}{n(1 - \phi_X\phi_Y)} \quad \rightarrow \quad +\infty \quad \text{when } \phi_X\phi_Y \text{ is close to 1!}$$

Prewhitening aims at avoiding the risk of spurious correlations and consists of

1. removing the contribution of autocorrelations from at least one of the variables involved in the CCF:

$$\tilde{X}_t = (1 - \pi_1 B - \pi_2 B^2 - \ldots - \pi_p B^p)X_t = \pi(B)X_t$$

2. transforming the Y in $\tilde{Y}$ by means of the same (linear) filter $\pi(B)$
3. evaluating the CCF between $\tilde{X}$, $\tilde{Y}$ using conventional CIs

Block-Bootstrapping

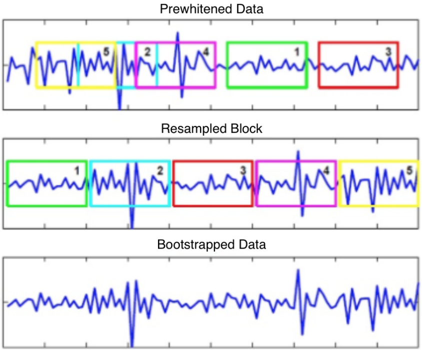
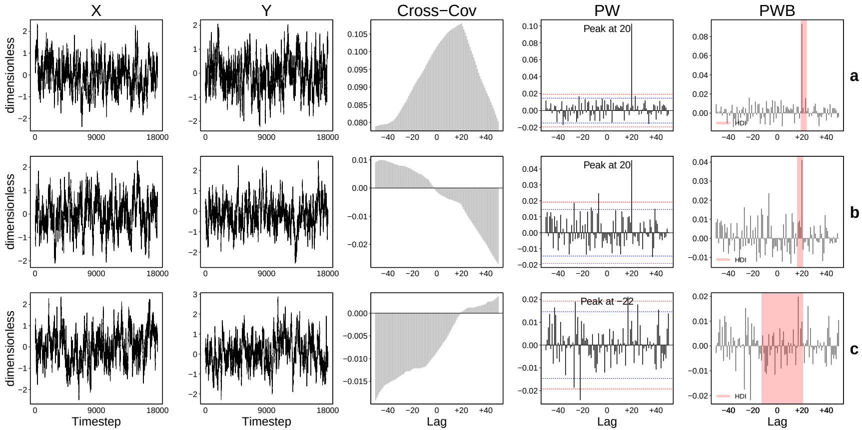


Illustration courtesy of El Anbari, Abeer, and Ptitsyn (2015) https://doi.org/10.1371/journal.pone.0131111

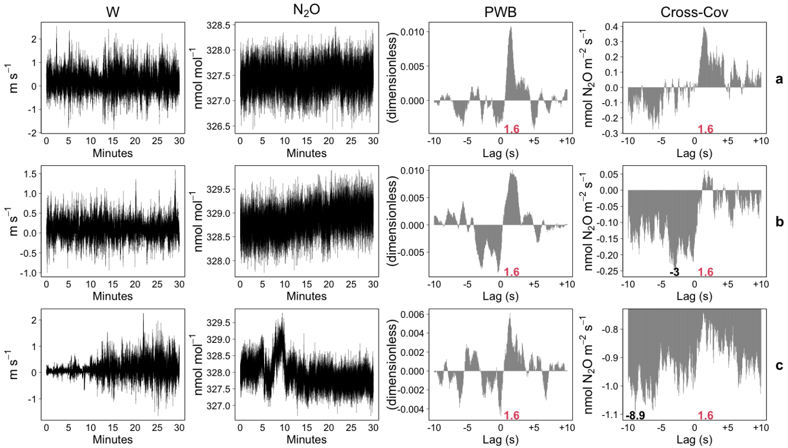
- Block-bootstrap is performed on pre-whitened variables
- aims to mimic measurements from repeated sampling
- enhances the accuracy of time lag detection by reducing the effect of noise
- allows an estimation of the uncertainty

Illustrative examples on simulated data



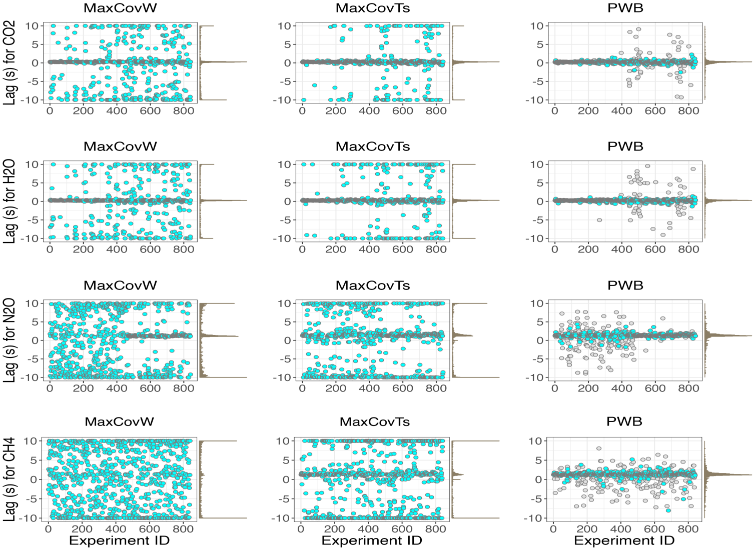
Time lag detection between simulated bivariate VAR(1) processes characterized by:
panel a: $\rho(X,Y) = 0.1$
panel b: $\rho(X,Y) = 0.05$
panel c: $\rho(X,Y) = 0.005$
simulated misalignment: 20 steps

Illustrative examples on EC raw data



Time lag detection between EC raw data characterized by:
panel a: high signal-to-noise ratio
panel b: low signal-to-noise ratio
panel c: non-stationary conditions
(time lags detected by PWB and MaxCov are denoted in red and black, respectively)

Methods Comparison



Grey points indicate time lags highly uncertainty, 50% HDI >0.5 sec

Deciles of the distribution of time lags (in sec)

	Method	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
CO_2	$MaxCov_W$	-10.00	-9.65	-5.21	0.10	0.20	0.25	0.30	0.30	0.40	5.81	10.00
	$MaxCov_{TS}$	-10.00	-0.30	0.00	0.15	0.20	0.25	0.30	0.35	0.40	0.60	10.00
	PWB	-9.30	-0.20	-0.05	0.10	0.20	0.25	0.30	0.35	0.40	0.50	9.10

	Method	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
H_2O	$MaxCov_W$	-10.00	-8.25	-0.16	0.15	0.20	0.25	0.30	0.30	0.40	7.45	10.00
	$MaxCov_{TS}$	-10.00	-4.19	0.00	0.15	0.25	0.25	0.30	0.35	0.40	6.51	10.00
	PWB	-9.05	-0.25	0.00	0.15	0.20	0.25	0.30	0.30	0.35	0.45	9.55

	Method	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
N_2O	$MaxCov_W$	-10.00	-9.70	-8.35	-5.03	1.00	1.15	1.30	1.70	7.35	9.46	10.00
	$MaxCov_{TS}$	-10.00	-10.00	-8.97	0.00	1.20	1.35	1.47	1.75	4.61	9.90	10.00
	PWB	-8.95	-0.10	1.05	1.20	1.25	1.30	1.40	1.50	1.65	1.96	7.75

	Method	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
CH_4	$MaxCov_W$	-10.00	-10.00	-8.26	-5.13	-1.62	0.97	2.22	5.77	8.41	9.90	10.00
	$MaxCov_{TS}$	-10.00	-10.00	-9.12	-0.71	1.10	1.25	1.45	1.90	8.67	10.00	10.00
	PWB	-9.05	-0.45	1.00	1.15	1.20	1.30	1.35	1.45	1.60	1.90	8.20

(in gray the plausible range)

Concluding Remarks

1. The proposed procedure is completely data-driven
2. Pre-Whitening avoids the risk of spurious correlations
3. Block-Bootstrapping enhances the accuracy of time lag detection and allows to quantify uncertainty
4. Compared with MaxCov approach, time lags detected by PWB are more stable, in particular for fluxes with low signal-to-noise ratio

References

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Thanks for your attention!