FINAL REPORT PROGRAM LEFE

Program LEFE/ IMAGO	VADEMECUM	Years 2017 – 2019

PI: Didier Swingedouw (EPOC) Participating Laboratories: LOCEAN, EPOC, BSC	Contribution to*: PAGES2K* Other funding sources: PAGES2K, U Bordeaux.

Decadal to centennial variations of the climate over the last few millennia is still poorly understood. In particular, over the most recent millennium, the causes of the variations from the Medieval Climatic Optimum towards the Little Ice Age are still poorly known. This is notably related with considerable difficulties in gathering together the different existing proxy records in an efficient way through integration in climate model simulations for instance.

This project proposed new approaches to gain insight on the decadal to multi-centennial variability of the climate system over the last 2000 years as well as its potential role on the recently observed climatic variability. It was proposing to first explore the potential gain from advanced statistical methods to reconstruct key modes of large-scale climate variability and then to try to use them to restore, through nudging techniques, a climate model towards this reconstruction, in order to assess the associated dynamical variations of the climate.

Several up-to-date statistical methods have been used, related with machine learning technics. They have been applied to paleoclimate data coming from natural archives (tree rings, ice cores...). This has led to the development of a freely available code named *ClimIndRec*, described in *Geoscientific Model Development* (Michel et al. 2019). The recently released PAGES 2k database, gathering more than 700 proxy records covering the last 2000 years, have been used for training the proposed statistical models. Objective mathematical metrics show that a non-linear technique, namely the Random Forest, generally produces more robust results than the usual linear technics such as Principal Component Regression. We thus used the Random Forest method to reconstruct variations of the preferential modes over the North Atlantic, as well as over the Pacific and Southern Oceans.
We first reconstruct the main mode of variability of sea surface temperatures (SST) of the North Atlantic, namely the Atlantic Multidecadal Variability (AMV), which is notably related to the Atlantic Meridional overturning circulation (AMOC) in climate models. Our reconstruction suggests that abrupt changes in this circulation occurred at the end of the 12th century caused by internal dynamics and not external forcing, and this has probably been the catalyzer of the early onset of the Little Ice Age, a relatively cold period of the last millennium (Figure 1a). The strong volcanic activities from the 13th, 15th, and 19th centuries have nevertheless been identified as the main causes of the little ice age extension, which reached its climax during the 19th century. Moreover, our results have shown, using dynamical systems theory, that recent changes in the AMV constitute an early warning signal of a potential incoming tipping point in the AMOC (Figure 1b). Finally, the reconstructed AMV exhibit a range of preferential frequencies going from 20 to 80 years depending on time, highlighting a non-stationarity in the main time scale of variability (Figure 1c).
A gridded SST reconstruction over the last millennium has also been produced using the Random Forest method. This reconstruction constitutes a unique opportunity to investigate decadal climate variablity over the globe. It shows in particular that positive phases of AMV are likely to drive, after about a decade, a negative phase of the preferential mode of Pacific SST, namely the Interdecadal Pacific Variability (IPV). Since observation show that the 1998-2012 hiatus period matches with a long term negative phase of the IPV, this result suggests that the AMV is one of the key drivers of such hiatus periods. In line with the assumption of an AMOC weakening deduced from spectral properties of the reconstructed AMV, this grid reconstruction also suggests that the AMOC has recently reached an unprecedentedly low level of intensity, since at least 850 C.E.
Finally, this gridded reconstruction has been assimilated using SST nudging method within the IPSL-CM5A2-LR general circulation model. While the obtained reanalysis fairly reproduces the observed temperatures and paleo-temperatures, the nudging method seems to be less efficient over land than more complex data assimilation technics, such as Kalman filtering (Figure 2). Moreover, the simulated AMOC in this reanalysis does not correspond to the one obtained from statistical reconstructions, which might be related to the fact that salinity also largely influences ocean surface layers densities, forcing oceanic convection and the AMOC. Assimilating surface salinity data thus appears to be essential to correctly reproduce the last millennium AMOC variability using a general circulation model and is under development using similar approaches.

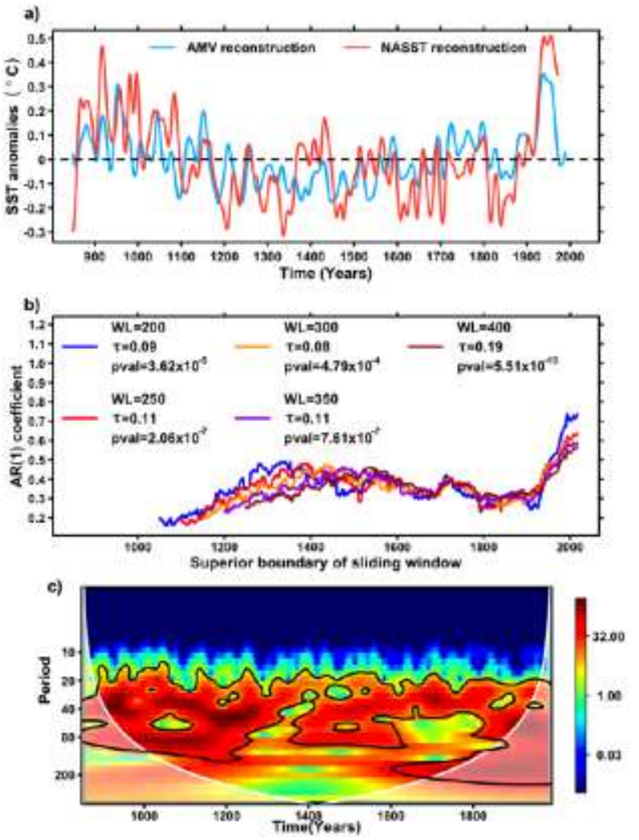

Figure 1 *: a) AMV reconstruction (in blue) and North Atlantic variation (in red). b) AR1 evolution of the AMV time series, used as an early warning indicator. C) wavelet analysis of AMV time series.*

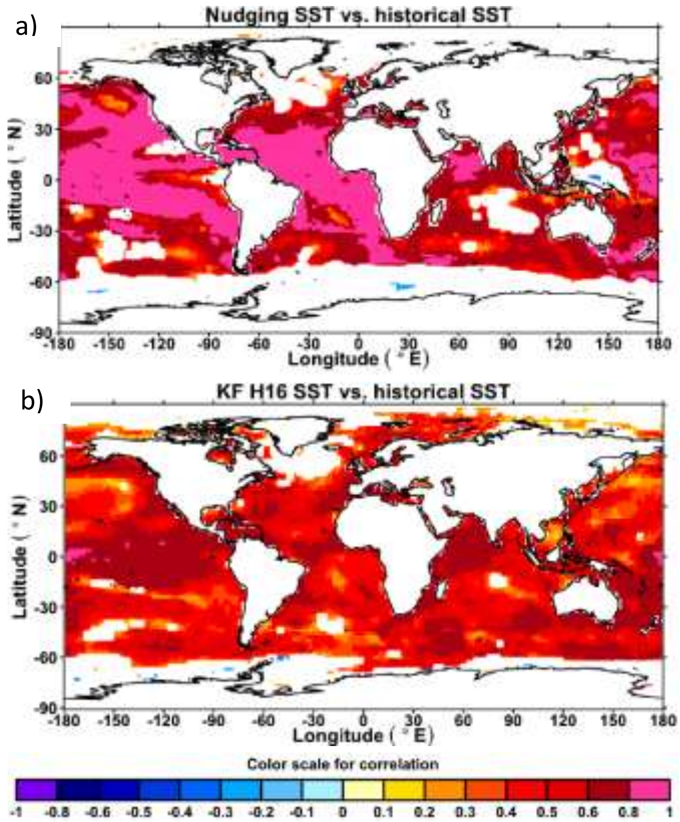

Figure 2 *: Correlation over the period 1870-1970 between HadISST data and a) paleoclimatic reanalysis obtained within the project and b) the reanalysis from Hakim et al. (2016) using a Kalman filter.*

Follow up of the project:

- Myriam Khodri has obtained an ERC synergy project within which she will pursue the development of particle filtering within IPSL model.
- Didier Swingedouw is part of the ClimoVar initiative which is under consideration for being a new PAGES group.

Valorisation *: 5 publications + 2 en révisions, 5 communications international et 1 thèse soutenue*

1. **Michel S., Swingedouw D., Chavent M., Ortega P., Mignot M., Kodri M**. (2020) Reconstructing climatic modes of variability from proxy records by using different statistical approaches. *Geophysical Model Development* 13, pp. 841-858.
2. **Michel S., Swingedouw D., Mignot J., Gastineau G., Ortega P., Khodri M., McCarthy G.** Internal abrupt change in the Atlantic Multidecadal Variability as the onset of the Little Ice Age , Nature Communications, in rev.
3. **Michel S., Swingedouw D., Mignot J.** Analysis of last millennium ocean variability through a gridded random forest-based SST reconstruction. *Climate Dynamics*, in rev..
4. Moffa-Sanchez, P., E. Moreno-Chamarro, D. J. Reynolds, **P. Ortega**, L. Cunningham , **D. Swingedouw**, D. E. Amrhein, J. Halfar, L. Jonkers, J. H. Jungclaus, K. Perner, A. Wanamaker and S. Yeager (2019) Variability in the northern North Atlantic and Arctic oceans across the last two millennia: A review. *Paleoceanography*, 34:1399-1436.
5. Hernandez A. ***et al***. (2020) Modes of climate variability: synthesis and review of proxy-based reconstructions through the Holocene. *Earth-Science Reviews* 2009, Art. No 103286.