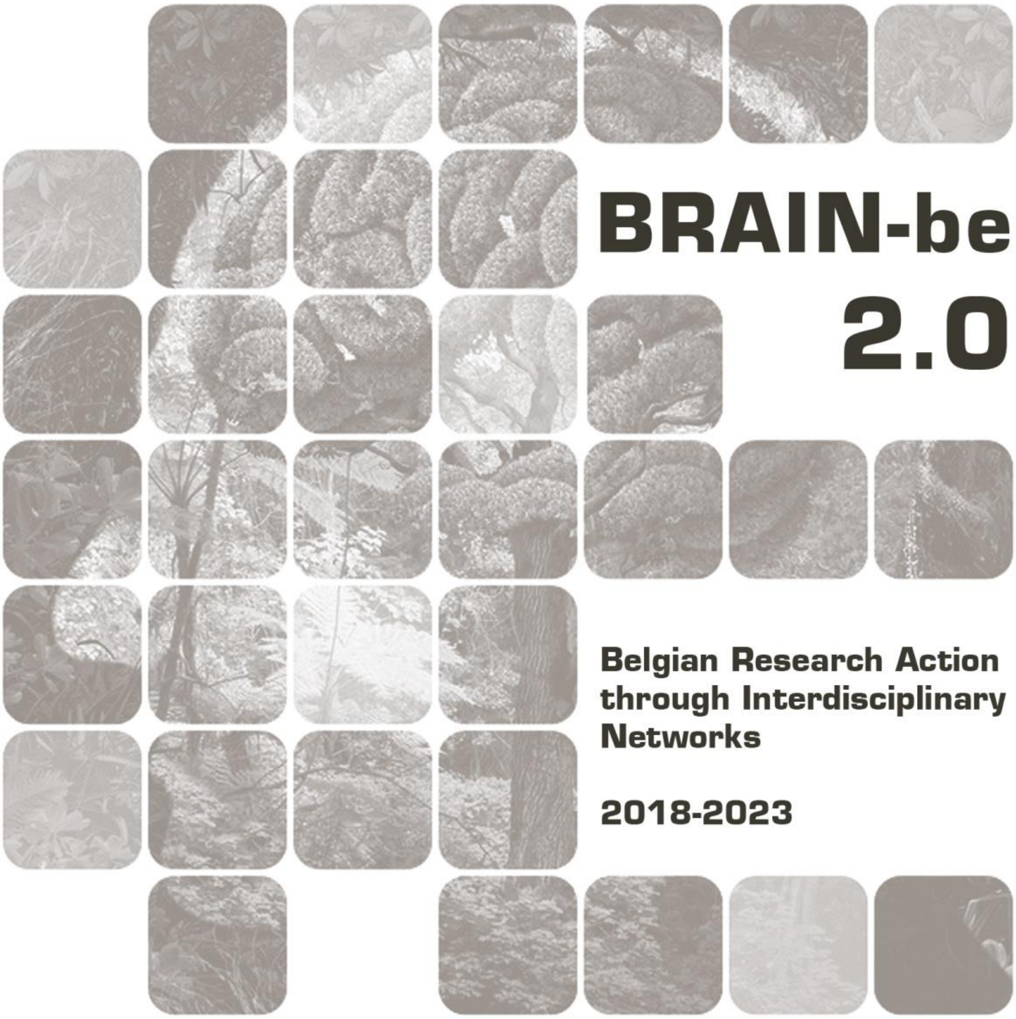

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Belgian Research Action through Interdisciplinary Networks

2018-2023

ROADMAP

The Role of ocean dynamics and Ocean-Atmosphere interactions in Driving cliMAte variations and future Projections of impact-relevant extreme events

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Pillar 1: Challenges and knowledge of the living and non-living world

NETWORK PROJECT

ROADMAP

The Role of ocean dynamics and Ocean-Atmosphere interactions in Driving cliMAte variations and future Projections of impact-relevant extreme events

Contract - B2/20E/P1/ROADMAP

FINAL REPORT

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TABLE OF CONTENTS

ABSTRACT

The goal of the JPI-Oceans / JPI-Climate ROADMAP project ("The Role of ocean dynamics and Ocean-Atmosphere interactions in Driving cliMAte variations and future Projections of impact-relevant extreme events") was to strengthen our understanding of the ocean role in shaping Northern Hemisphere climate and associated extreme events, on seasonal to climate change time scales. The Royal Meteorological Institute (RMI) has provided important input to the project, mainly through the application of a relatively novel causal method, called the Liang-Kleeman information flow (LKIF) method. This method allows to identify true causal relationships between variables, and thus goes beyond classical correlation analyses. Seven different peer-reviewed publications were produced in collaboration with partners from or outside the ROADMAP consortium. Our main recommendation is to systematically use a proper causal method as a complement to any correlation analysis in order to identify true causal links between variables, as successfully illustrated in the different applications which have been performed during the course of the project.

1. INTRODUCTION

Weather and climate at mid-latitudes display a variability on a wide range of time scales from minutes to centuries. At long time scales, the atmospheric variability is impacted by other components of the climate system, in particular by the underlying oceans that can exacerbate or reduce the impact of extreme events. These extreme events can affect millions of people in densely populated areas all over the world.

The main objective of the ROADMAP project ("The Role of ocean dynamics and Ocean-Atmosphere interactions in Driving cliMAte variations and future Projections of impact-relevant extreme events") was to strengthen our understanding of the ocean role in shaping Northern Hemisphere climate and associated extreme events, on seasonal to climate change time scales. ROADMAP, in particular, helped to address a key challenge in climate science, i.e. the understanding of interactions between the ocean and atmosphere, through the use of model simulations and satellite observations, as well as novel statistical techniques.

This JPI-Oceans / JPI-Climate project encompassed leading climate research institutions from seven European countries and was coordinated by the Max-Planch-Institute for Meteorology (MPI-M, Germany). It was funded in the framework of the "Next Generation Climate Science for Oceans" (https://jpi-oceans.eu/en/climate-science-oceans), which run from March 2020 to May 2024. More information on the ROADMAP project can be found at https://jpi-climate.eu/project/roadmap/.

At the Royal Meteorological Institute (RMI), the research was funded by BELSPO and the main goal was to provide statistical tools to be applied in the analysis of the interactions between the different climate components. The approach proposed was to use causal techniques going beyond correlation analyses in order to investigate the interactions and connections between the different components of the climate system at time scales from seasons to decades.

2. STATE OF THE ART AND OBJECTIVES

As mentioned, ROADMAP's main objective was to strengthen our understanding of the ocean role in shaping the Northern Hemisphere climate and associated extreme events, on seasonal to climate change time scales.

ROADMAP went beyond the state-of-the-art by analyzing climate model simulations and observations with advanced statistical-dynamical techniques, concepts from information theory, and by developing novel numerical modelling configurations. An interdisciplinary team of climate (oceanographers and meteorologists) scientists, mathematicians, and computer scientists brought together the competence required to perform this research.

Specifically, ROADMAP addressed:

- the impact of the ocean circulation, especially the Atlantic Meridional Overturning Circulation, on large-scale sea surface temperature (SST) patterns [WP1]

- the changing modes of variability of the Northern Hemisphere western boundary current extensions and what novel ocean-eddy resolving climate models can say about their future evolution [WP1]

- how and on which time scales extratropical ocean-atmosphere interactions control the tropospheric eddy-driven jets, cyclone variability (storm track), blocking events and the associated dynamical link to extreme conditions; and how such controls can be modified by global warming [WP2]

- the impact of tropical El Niño Southern Oscillation and Madden Julian Oscillation SST anomalies on the mid-latitude and polar atmospheric circulation [WP3]

- the multidecadal links between tropical and subtropical North Atlantic, and inter-basin connections between the Atlantic and the Pacific Oceans, as well as modifications of linkages under climate change conditions [WP3]

- the role of the Northern Hemisphere ocean surface state (SST and sea ice) for driving impact-relevant atmospheric extremes, such as atmospheric and marine heat waves and droughts, including compound weather extremes and Mediterranean mesoscale cyclones; both large-scale natural variability modes and climate-change induced anomalies were considered [WP4]

- the identification of key spatial-temporal variability patterns as well as cross-scale causal coupling between different variability modes of ocean and atmosphere [WP5 jointly with WP2 and WP3].

The ROADMAP consortium encompassed leading climate research institutions from seven European countries, including universities as well as institutions providing (national) meteorological and climate services. ROADMAP continued a long-standing history of international collaboration between its partners within the framework of previous joint projects, making significant contributions to climate variability, predictability and response, as well as climate extremes, particularly in the North Atlantic/European sector.

RMI was co-leading WP5, whose aim was to develop and provide methodological tools to be applied in the analysis of the interaction between the different components of the climate system. RMI was also involved in WP2 and WP3.

Most climate studies use correlation analyses, but correlation does not imply causation. Thus, the main goal of the different studies carried out at RMI was to identify true causal relationships between different climate variables. This was done by applying the newly developed causal method named "Liang-Kleeman information flow" (LKIF; Liang & Kleeman, 2005; Liang, 2014; Liang, 2021) in various fields of interest of the consortium.

The work carried out by RMI culminated with the publication of seven different studies:

1) a study of the causal links between Arctic sea ice and its potential oceanic and atmospheric drivers using LKIF, in collaboration with the Swedish Meteorological and Hydrological Institute (SMHI, Sweden) and Fudan University (China) (Docquier et al., 2022)

2) an analysis of the inter-dependence between different large-scale climate indices in the North Pacific and North Atlantic Oceans using LKIF, in collaboration with Fudan University (China) and the Division of Frontier Research, Southern Marine Laboratory (Zhuhai, China) (Vannitsem & Liang, 2022)

3) an investigation of ocean-atmosphere interactions based on LKIF, in collaboration with Consiglio Nazionale delle Ricerche (CNR, Italy), a member of the consortium (Docquier et al., 2023)

4) a comparison of LKIF with another causal method applied to different artifical models and a real world-case study, in collaboration with two other groups of the consortium: Potsdam Institute for Climate Impact Research (PIK, Germany) / Magdeburg-Stendal University of Applied Sciences (H2, Germany) and Instituto Dom Luiz (IDL, Portugal) (Docquier et al., 2024)

5) a study on the sources of low-frequency ™^{18}O variability in coastal ice cores from Dronning Maud Land (Antarctica), in collaboration with Université Libre de Bruxelles (ULB, Belgium) (Vannitsem et al., 2024b)

6) a collaboration with IDL (Portugal) on the development of a nonlinear extension of LKIF (Pires et al., 2024)

7) an application of the newly developed nonlinear extension of LKIF to a reduced-order atmospheric model, also in collaboration with IDL (Vannitsem et al., 2024).

All these fruitful collaborations using new causal methods helped understanding the dynamics of the climate system, as it will be illustrated in the next sections.

3. METHODOLOGY

RMI has applied a relatively recent causal method, the Liang-Kleeman information flow (LKIF) method (Liang & Kleeman, 2005; Liang, 2014; Liang, 2021), to different climate studies in the context of the ROADMAP project. This causal method directly comes from the first principles of information theory and is relatively simple to apply, although the interpretation of results may be challenging. It allows to identify the direction and magnitude of cause-effect relationships between variables. Compared to classical correlation analyses, it has the advantage to remove spurious dependencies, i.e. causal relationships that could appear by chance or due to the presence of a common driver.

LKIF provides the rate of information transfer (RIT) from one variable X to another variable Y based on the covariance matrix in a multivariate framework. If the RIT is statistically different from 0, it means that X has an influence on Y, while the reverse means that X does not have any influence on Y. The sign of the RIT has an additional meaning, with a positive (negative) value meaning that the variability in X increases (decreases) the variability in Y. The statistical significance is computed via bootstrap resampling with replacement. More information about the methodology can be found in the different publications of the project in Section 6 and the codes are freely available online on Github and Zenodo.

This method has been applied with its linear assumption in five different climate studies. First, we computed the causal links between Arctic sea ice and its potential drivers using monthly model outputs from the EC-Earth3 climate model (Docquier et al., 2022). Second, we computed the causal relationships between a set of observed indices characterizing different climate modes, such as El Niño Southern Oscillation (ENSO) and Arctic Oscillation (AO) (Vannitsem & Liang, 2022). Third, we used LKIF to better understand ocean-atmosphere interactions at the surface of the globe based on satellite observations (Docquier et al., 2023). Fourth, we realized a comparison of LKIF with the Peter & Clark momentary conditional independence (PCMCI; Runge et al., 2019b) algorithm, applied to four different artifical models and a real-world case study (Docquier et al., 2024). Fifth, we used LKIF to clarify the sources of low-frequency ™^{18}O variability in coastal Antarctic ice cores (Vannitsem et al., 2024b).

However, LKIF in its original formulation assumes linearity and may fail in highly nonlinear cases. That is why we participated to an effort with IDL (Portugal) to extend the method to nonlinear cases, which had not been done before. This culminated in an important study that successfully demonstrated the usefulness of the nonlinear LKIF approach in artificial models (Pires et al., 2024). Finally, Vannitsem et al. (2024) applied this nonlinear extension of LKIF to a reduced-order atmospheric model.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4.1. Causal links between Arctic sea ice and its potential drivers

Arctic sea ice has substantially changed over the past four decades, with a large decrease in sea-ice area and volume. The exact causes of these changes are not entirely known. In our study, we made use of the Swedish Meteorological and Hydrological Institute (SMHI) Large Ensemble (Wyser et al., 2021). This ensemble consists of 50 members realized with the EC-Earth3 global climate model and covers the period 1970-2100.

In this study, we quantified the contribution of both ocean and atmospheric drivers in the recent and future loss of Arctic sea ice using LKIF for the first time. We found that there is a two-way influence between changes in Arctic sea ice on the one hand and air temperature, sea-surface temperature and ocean heat transport on the other hand (Figure 1). We also found a progressive decrease in the influence of sea-ice area and volume on air temperature and ocean heat transport through the twenty-first century. These results have been published in *Geophysical Research Letters* (Docquier et al., 2022).

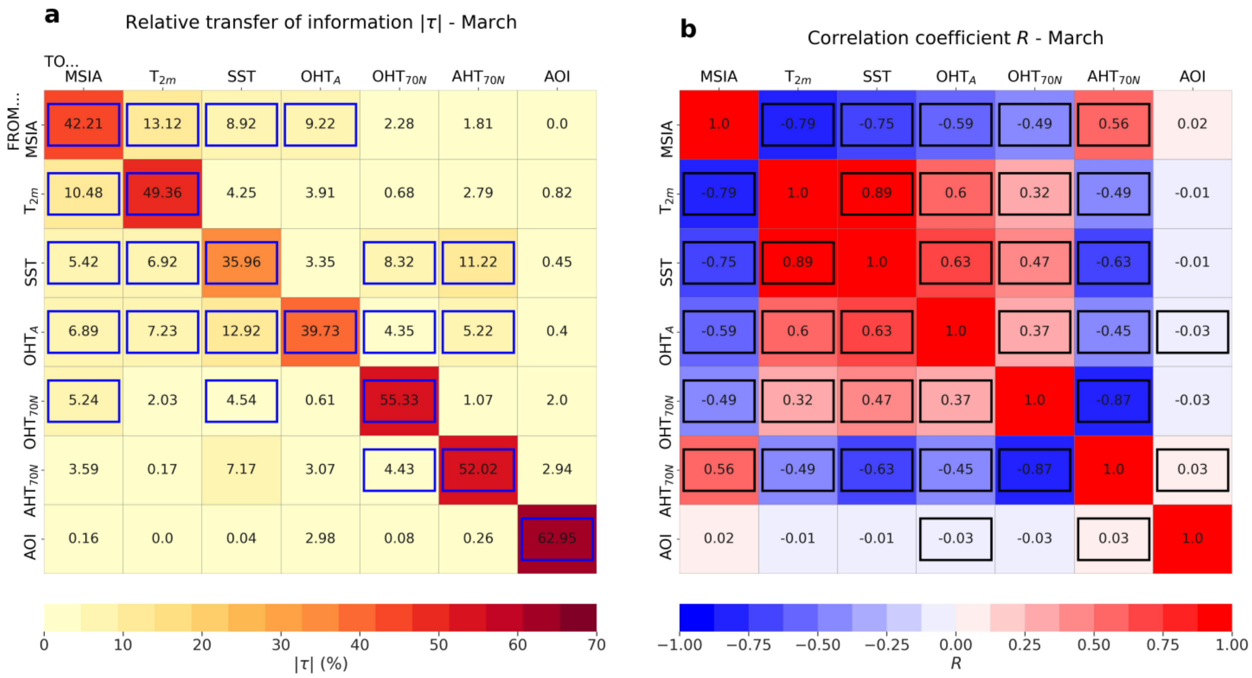


Figure 1: (a) Rate of information transfer and (b) correlation coefficient between March sea-ice area (MSIA) and six potential drivers (surface air temperature [T_{2m}], sea-surface temperature [SST], Arctic ocean heat transport [OHT_A], ocean heat transport at 70°N [OHT_{70N}], atmospheric heat transport at 70°N [AHT_{70N}], and Arctic Oscillation Index [AOI]) over 1970-2100 for the EC-Earth3 model (ensemble mean over 50 members; combination of historical and SSP5-8.5 simulations). The highlighted elements are significant at the 5% level [Credit: Figure 2a,b from Docquier et al., 2022]

4.2. Teleconnections between large-scale climate modes

Usually, the analysis of the influence of a region in the climate system on another region is done through either teleconnection analysis based on correlation, e.g. Philander (1990), or by investigating the sensitivity of the climatology of a region in a climate model by forcing another key region, e.g. Johnson et al. (2020). These approaches, although useful, do not allow to disentangle the one-way or two-way interactions between remote regions. During the last decades, there were considerable efforts devoted to the development of approaches allowing to clarify the causality between different observables, see the recent reviews of Palus et al. (2018) and Runge et al. (2019).

The directional dependencies of different large-scale climate indices were explored using LKIF. Seven key indices (Niño3.4, Atlantic Multidecadal Oscillation [AMO], North Atlantic Oscillation [NAO], Pacific-North American [PNA] pattern, Arctic Oscillation [AO], Pacific Decadal Oscillation [PDO], Tropical North Atlantic [TNA] pattern), collected from the NOAA website, together with three local time series located in Belgium, were selected. The analysis was performed on time scales from a month to 5 years by using a sliding window as a filtering procedure. Beside a very complex network of dependencies, the approach allowed to isolate a few key new results: (i) the AO plays a key role at short time (monthly) scales on the dynamics of the North Pacific and North Atlantic; (ii) the NAO plays a global role at long time scales (several years); (iii) the PDO is slaved to other influences; (iv) the local observables over Western Europe influence the variability on the ocean basins on long time scales (Figure 2). These results were published in *Tellus A* (Vannitsem and Liang, 2022). Additionally, a comparison of LKIF with PCMCI on these climate indices showed that, while there were similarities between the two causal methods, the AO is the largest driver at monthly time scales according to the former method, while ENSO is the main influencing variable according to PCMCI (Docquier et al., 2024).

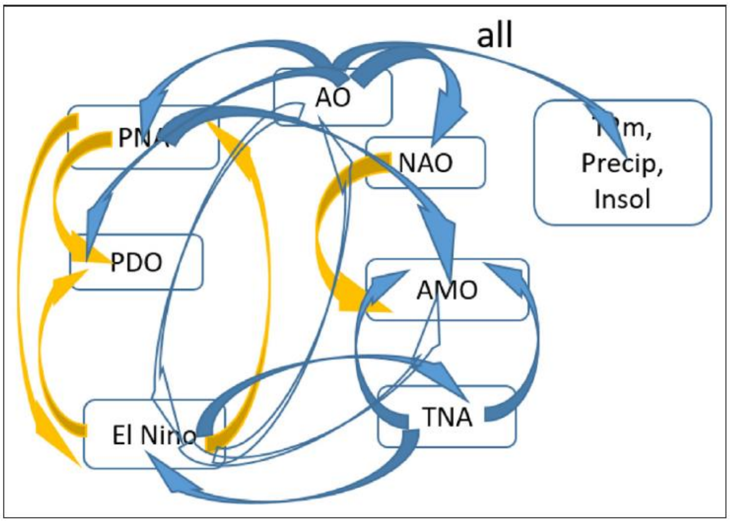


Figure 2: Causal influences between the different observables at short (blue arrows) and all time scales (yellow arrows). The open blue arrows indicate weak dependencies as compared to the other ones. The label “all” indicates that all local variables are influenced by AO. Acronyms: Arctic Oscillation (AO), Pacific-North American pattern (PNA), Pacific Decacadal Oscillation (PDO), North Atlantic Oscillation

(NAO), Atlantic Multidecadal Oscillation (AMO), Tropical North Atlantic pattern (TNA) [Credit: Figure 8 from Vannitsem & Liang, 2022].

4.3. Ocean-atmosphere interactions

The climate on Earth is strongly affected by exchanges of mass, momentum and energy between the ocean and atmosphere. The ocean absorbs a large amount of solar energy and releases part of this energy to the atmosphere. In turn, the atmosphere modifies the ocean state through changes in wind, humidity and temperature. The classical view is that the slowly changing upper ocean is modulated by the high-frequency atmospheric variability (Frankignoul and Hasselmann, 1977). While this paradigm has been successful in explaining the variability in sea surface temperature (SST) and surface heat flux over large parts of the ocean, it has been challenged over ocean regions characterized by intense mesoscale activity, such as western boundary currents and the Antarctic Circumpolar Current (e.g. Bellucci et al., 2021).

In this study, we quantified interactions between the ocean and atmosphere at the global scale over the period 1988-2017. We looked at influences between SST, SST tendency and turbulent heat flux (THF) in satellite observations. We found a strong two-way influence between SST and/or SST tendency and THF in many regions of the world, with the largest values in the eastern tropical Pacific and Atlantic Oceans, as well as in western boundary currents. Overall, we found that the influence of SST and SST tendency on THF was larger than the reverse, suggesting a stronger influence of the ocean compared to the atmosphere (Figure 3). These results have been published in *Earth System Dynamics* (Docquier et al., 2023).

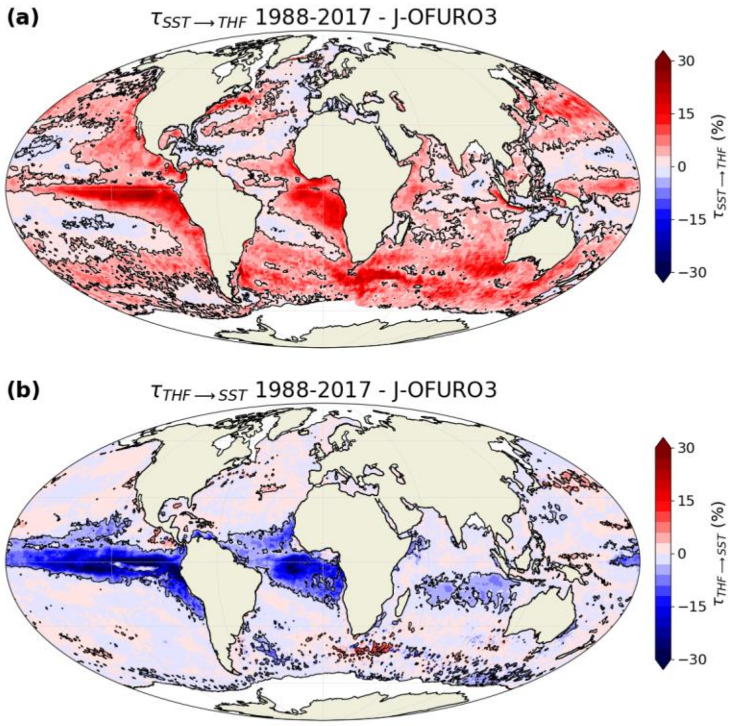


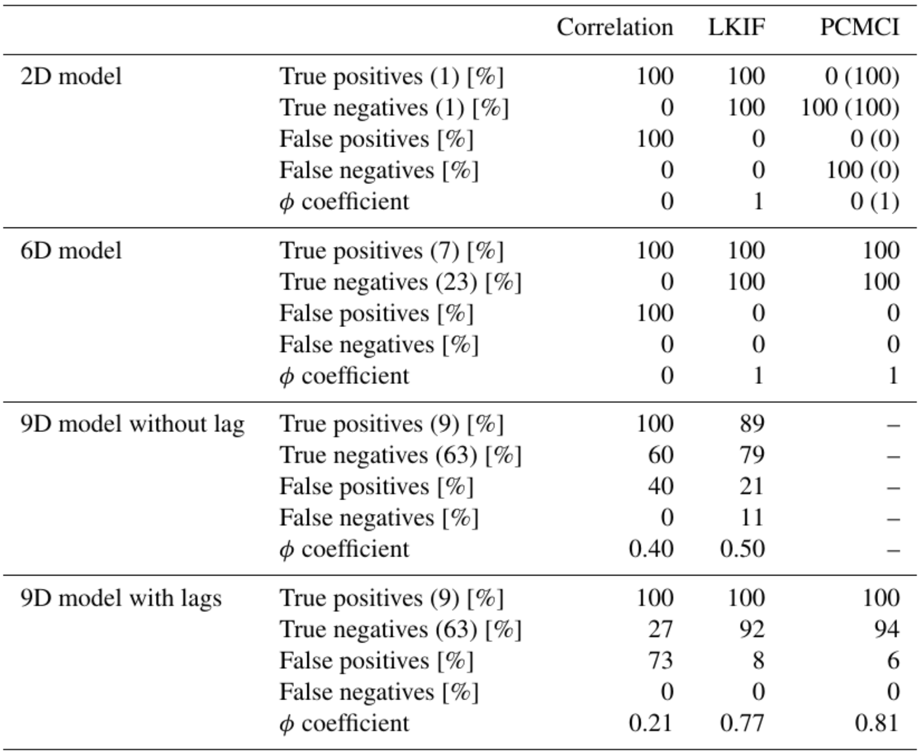
Figure 3: Rate of information transfer (a) from sea-surface temperature (SST) to turbulent heat flux (THF) and (b) from THF to SST, based on J-OFURO3 satellite observations. Black contours are drawn

around regions with a statistically significant information transfer [Credit: Figure 4 from Docquier et al., 2023].

4.4. Comparison of two causal methods

Correlation does not necessarily imply causation, and this is why causal methods have been developed to try to disentangle true causal links from spurious relationships. In this study, we used two causal methods, namely LKIF and PCMCI, and we applied them to four different artificial models of increasing complexity - three different stochastic models (including two linear models and one nonlinear model), and one deterministic nonlinear model (Lorenz, 1963) - as well as one real-world case study involving climate indices.

We showed that both methods are superior to the classical correlation analysis, especially in removing spurious links (Figure 4). LKIF and PCMCI displayed some strengths and weaknesses for the three simplest models, with LKIF performing better with a smaller number of variables and with PCMCI being best with a larger number of variables. Detecting causal links from the fourth model (Lorenz, 1963) was more challenging as the system is nonlinear and chaotic. Results from the real-world case study with climate indices was already discussed in Section 4.2. The results of this comparison have been published in *Nonlinear Processes in Geophysics* (Docquier et al., 2024).



		Correlation	LKIF	PCMCI
2D model	True positives (1) [%]	100	100	0 (100)
	True negatives (1) [%]	0	100	100 (100)
	False positives [%]	100	0	0 (0)
	False negatives [%]	0	0	100 (0)
	ϕ coefficient	0	1	0 (1)
6D model	True positives (7) [%]	100	100	100
	True negatives (23) [%]	0	100	100
	False positives [%]	100	0	0
	False negatives [%]	0	0	0
	ϕ coefficient	0	1	1
9D model without lag	True positives (9) [%]	100	89	–
	True negatives (63) [%]	60	79	–
	False positives [%]	40	21	–
	False negatives [%]	0	11	–
	ϕ coefficient	0.40	0.50	–
9D model with lags	True positives (9) [%]	100	100	100
	True negatives (63) [%]	27	92	94
	False positives [%]	73	8	6
	False negatives [%]	0	0	0
	ϕ coefficient	0.21	0.77	0.81

Figure 4: True-positive, true-negative, false-positive, and false-negative rates (in %), as well as phi coefficient, for the correlation and the two causal methods (LKIF and PCMCI) for the first three artificial models (2D, 6D, and 9D models, the latter without and with lags), excluding self-influences. The number of ground truth correct (incorrect) links is indicated in parentheses after "True positives" ("True negatives") for each model. For the 2D model and PCMCI, numbers are also provided in parentheses for the case with larger sampling time step [Credit: Table 2 from Docquier et al., 2024].

4.5. Application of LKIF to Antarctic ice cores

The low-frequency variability of the $\delta^{18}O$ recorded in ice cores (named FK17 and TIR18) recently drilled at two different locations in Dronning Maud Land (Antarctica) was investigated using multi-taper spectral method, singular spectrum analysis, and the LKIF method. The spectral analysis showed that multiple dominant peaks emerged in these records with periods between 3 and 20 years. The two sites show distinct spectral signatures, despite their relative proximity in space (about 100 km apart; Figure 5), suggesting that different processes are involved in generating the variability at these two sites. In order to clarify which processes are acting on $\delta^{18}O$ at these two locations, the impact of several climate indices as well as sea ice area was investigated using LKIF. The analysis of the origin of this low-frequency variability from external sources revealed that ENSO, PDO, the Southern Annular Mode (SAM), the Dipole Mode Index (DMI) and sea ice area displayed important causal influences on $\delta^{18}O$ at FK17. For TIR18, the main influences are from ENSO, PDO, DMI, sea ice area, and AMO, revealing the complexity of the interactions in Dronning Maud Land. The two locations share several drivers, but also show local specificity potentially linked to ocean proximity and differences in air mass trajectories. The manuscript is currently published on arxiv (Vannitsem et al, 2024b) and in review for *Climate Dynamics*.

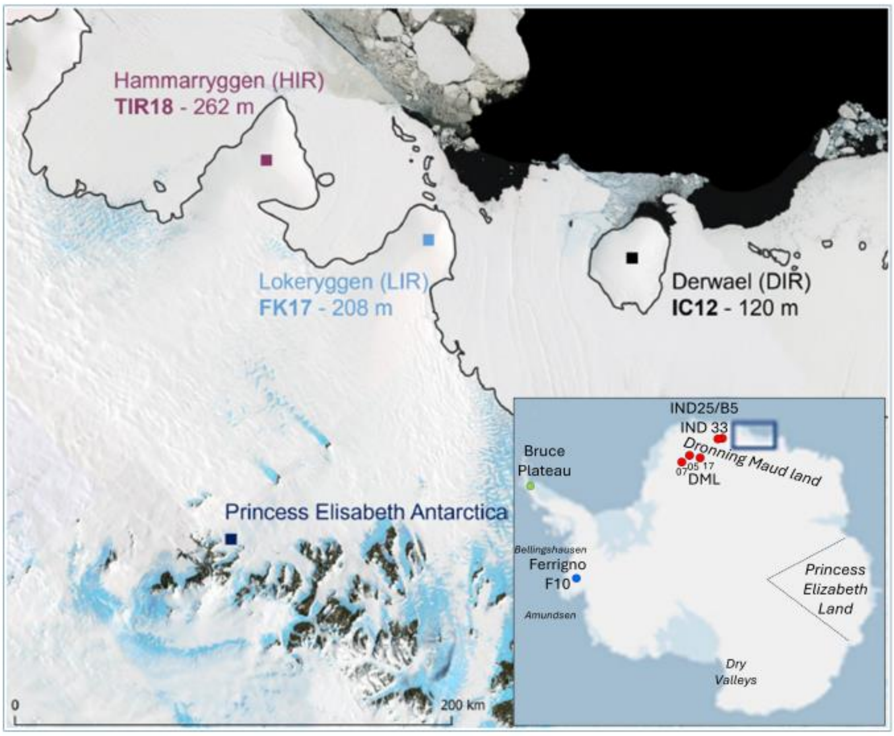


Figure 5: Map of the study area with location of FK17 and TIR18 ice cores in Dronning Maud Land (Antarctica) [Credit: Figure 1 from Vannitsem et al., 2024b].

4.6. Extension of LKIF to nonlinear problems

The theory of Liang and Kleeman (2005) was considerably expanded in a series of papers by Liang, culminating in expressions of the rate of information transfer in multivariate systems that can be used when dealing pragmatically with time series (Liang, 2014; 2021). The latter developments were done by assuming that the system underlying the dynamics of the observed data could be approximated by a multivariate linear stochastic system with additive noise, i.e. a multivariate Ornstein-Uhlenbeck process. This assumption is somehow restrictive and could miss some important nonlinear connections between variables.

A nonlinear estimate of the LKIF method has been developed by Pires et al. (2024), to which RMI collaborated. This is an effective method for computing the rates of Shannon entropy transfer (RETs) between selected causal and target variables, called the “Causal Sensitivity Method” (CSM), which relies on the estimation of conditional expectations of the system forcings and their derivatives. Those expectations are approximated by nonlinear differentiable regressions, leading to a much easier and more robust way of computing RETs than the “brute-force” (AN) approach, which calls for the computation of numerical integrals over the state-space and the knowledge of the multivariate probability density function of the system. This study shows the better performance of the nonlinear estimate of LKIF (CSM) compared to the linear estimate (ML), with reference to the “brute-force” (AN) approach, for both a potential model displaying nonlinearities (Figure 6) and the Lorenz (1963) model, both forced by additive and/or multiplicative noises.

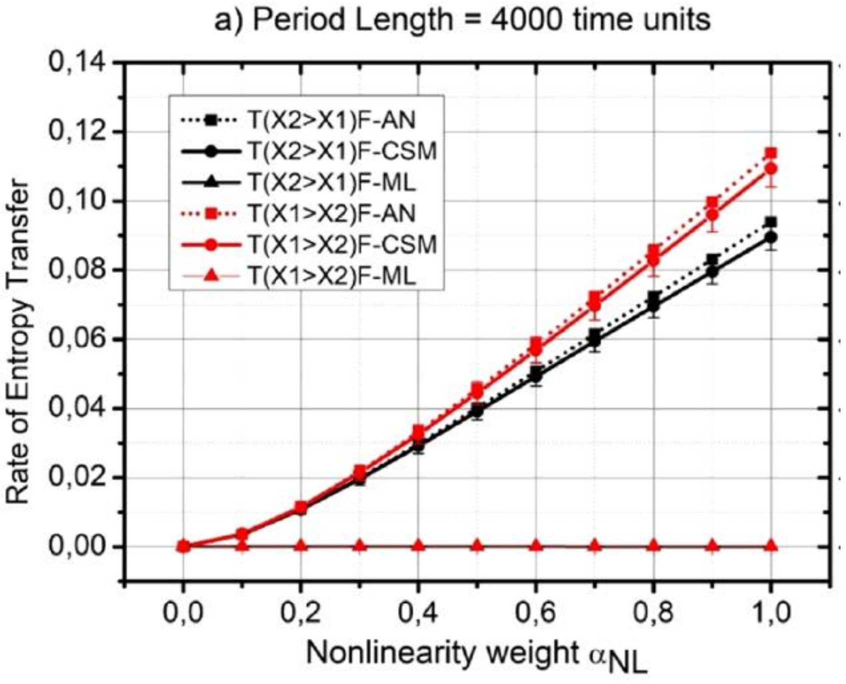


Figure 6: Rates of entropy transfer for the potential model. Mean over 30 noise seeds of T(X1→X2) (red curves) and T(X2→X1) (black curves) by the AN (dotted line, squares), CSM (solid line, circles) and ML (solid line, triangles) methods. Standard deviations over the ensemble of seeds are marked by the

error bar length. Note that curves for T(X1→X2) and T(X2→X1) for the ML approach superpose to each other [Credit: Figure 1a from Pires et al., 2024].

4.7. Application of nonlinear LKIF to a reduced-order atmospheric model

In this study, we applied the nonlinear version of LKIF developed by Pires et al. (2024) to the reduced-order Charney-Straus atmospheric model. The detailed information entropy budget analysis of this system reveals that the linear rotation terms plays a minor role in the generation of uncertainties as compared to the orography and the surface friction (Figure 7). Additionally, the dominant contribution comes from the nonlinear advection terms, and their decomposition in synergetic (co-variability) and single (impact of each single variable on the target one) components reveals that for some variables the co-variability dominates the information transfer.

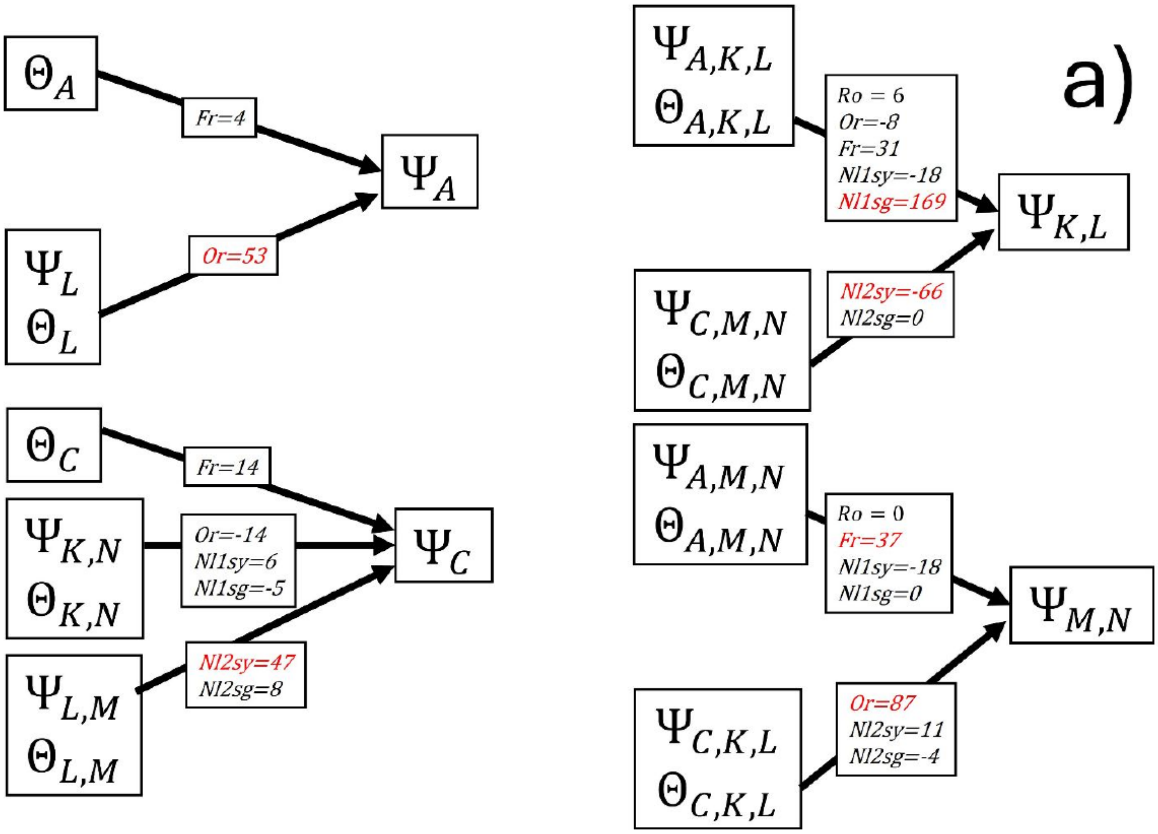


Figure 7: Drivers of the entropy changes for each target barotropic variable of the Charney-Straus model. The influencing and target groups are on the left and right sides, respectively. These are connected in the middle by arrows labeled with the budget amplitudes (in 10^{-4} nats/time unit) and the nature of the processes acting on the target variable. The leading terms appear in red [Credit: Figure 3a from Vannitsem et al., 2024].

4.8. Training and networking

In the context of the ROADMAP project, a postdoc researcher (D. Docquier) was employed at RMI. S. Vannitsem trained D. Docquier on the use of causal methods, in particular the LKIF method. D. Docquier also brought to RMI his expertise on sea ice – ocean – atmosphere interactions using global climate models. The new knowledge on causal methods allowed D. Docquier to obtain a 3-year BELSPO project at RMI in 2023 as a Principal Investigator (RESIST project together with F. Massonnet at UCLouvain) to quantify the causes and consequences of Arctic and Antarctic sea-ice lows.

During the ROADMAP project, strong collaborations were established with IDL (Portugal; C. Pires and A. Simon), PIK-H2 (Germany; G. Di Capua and R. Donner), CNR (Italy; A. Bellucci), Fudan University (China; X. S. Liang) and Sorbonne University (France; C. Frankignoul). These collaborations will allow to develop new projects in the future.

4.9. Recommendations

The main recommendation arising from results found at RMI in the context of the ROADMAP project is to systematically use a proper causal method as a complement to any correlation analysis in order to identify true causal links between variables. If there exists a causal influence from one variable to another, the two variables are necessarily correlated (Liang, 2014), but the reverse is not true. As such, a correlation analysis can be performed *a priori* in order to identify statistically significant correlations between variables. Then, a causal method can be applied to test the presence of a causal link or not. We recommend the use of the Liang-Kleeman information flow (LKIF; Liang, 2021) method as it directly comes from the first principles of information theory and is relatively simple to implement. Ideally, results from this causal method should be compared to another causal method, e.g. PCMCI, in order to check the robustness of results. Additionally, in the case of a highly nonlinear problem, such as the Lorenz (1963) model, we recommend the use of the nonlinear extension of LKIF (Pires et al., 2024). The latter should be tested on real-world case studies in the near future.

5. DISSEMINATION AND VALORISATION

As already mentioned in the previous sections, RMI has produced **seven peer-reviewed publications** directly related to ROADMAP, six of which have been published in international journals and one is under review (see Section 6). The LKIF Python scripts are available on Github and Zenodo.

These studies have been presented at multiple international conferences, including:

- 09/2021: Workshop on multi-annual to decadal climate predictability in the North Atlantic sector, Online poster by D. Docquier et al. “Causes of recent and future Arctic sea-ice changes”.
- 12/2021: AGU Fall Meeting 2021, Online poster by D. Docquier et al. “The rate of information transfer as a measure of rapid changes in Arctic sea ice”.
- 04/2022: EGU General Assembly 2022, Vienna, Oral presentation by S. Vannitsem and X. S. Liang. “Dynamical dependencies at monthly and interannual time scales in the Climate system: Study of the North Pacific and Atlantic regions”.
- 05/2022: Climate Coffees, Online seminar by D. Docquier et al. “Ocean – Sea Ice – Atmosphere interactions measured by the rate of information transfer”.
- 09/2022: Symposium on Ocean, Sea Ice and Northern Hemisphere Climate in memory of Y. Gao, Bergen (Norway), Oral presentation by D. Docquier et al. “Causal links between Arctic sea ice and its potential drivers based on the rate of information transfer”.
- 04/2023: EGU General Assebly 2023, Vienna, Oral presentation by D. Docquier et al. “The rate of information transfer as a measure of ocean-atmosphere interactions”.
- 04/2024: EGU General Assembly 2024, Vienna, Poster by D. Docquier et al. “A comparison of two causal methods in the context of climate analyses”.
- 04/2024: EGU General Assembly 2024, Vienna, Oral presentation by C. Pires, S. Vannitsem and D. Docquier. “Evaluation of Shannon Entropy-based Information transfer in nonlinear systems”.

These works have also been presented at different ROADMAP meetings, including:

- 04/2022: ROADMAP virtual meeting, Oral presentation by D. Docquier et al. “The rate of information transfer as a measure of ocean-ice-atmosphere interactions”.
- 09/2022: ROADMAP annual meeting, Lisbon, Oral presentation by D. Docquier et al. “Ocean-atmosphere interactions based on the rate of information transfer”.
- 06/2023: ROADMAP annual meeting, Brussels, Oral presentation by D. Docquier et al. “ The rate of information transfer as a measure of ocean-atmosphere interactions”.

Seminar under invitation:

- 06/2024: Marine Laboratory, Sun-Yat Sen University Campus (Zhuhai, China), Seminar given by S. Vannitsem. "Causal dependencies and Information entropy budget: Analysis of a reduced order atmospheric model".

D. Docquier and S. Vannitsem have also organized the ROADMAP annual meeting at RMI from 13 to 15 June 2023, including the physical presence of 25 researchers and online attendance of 14 other researchers.

D. Docquier has regularly written blog posts for the EGU Cryosphere Blog for a larger audience, some of them directly relevant to ROADMAP:

- 05/2022: C. Burgard, D. Docquier, M. Scheel, L. van der Laan, "Ice-hot news: A cryo-summary of the new IPCC assessment report".
- 09/2022: D. Docquier, "For Dummies: How Arctic sea ice and the AMOC ineract".
- 06/2023: D. Docquier, "How over-consumption leads to reduced sea ice: Visualization through artwork". This blog post followed an intense collaboration with the artist Zacharie Bodson, which culminated with the exposition of an artwork at the Seas & Oceans exhibition in May 2023 in Brussels organized by Talk CEC.

D. Docquier has also given an online seminar on "Sea ice – Ocean interactions in the Arctic" in the framework of the European Marine Board Science Webinars in February 2023.

6. PUBLICATIONS

Here is a list of peer-reviewed publications directly linked to the project:

- Docquier, D., S. Vannitsem, F. Ragone, K. Wyser, X. S. Liang (2022). Causal links between Arctic sea ice and its potential drivers based on the rate of information transfer. *Geophysical Research Letters*, https://doi.org/10.1029/2021GL095892.
- Docquier, D., S. Vannitsem, A. Bellucci (2023). The rate of information transfer as a measure of ocean-atmosphere interactions. *Earth System Dynamics*, https://doi.org/10.5194/esd-14-577-2023.
- Docquier, D., G. Di Capua, R. V. Donner, C. A. L. Pires, A. Simon, S. Vannitsem (2024). A comparison of two causal methods in the context of climate analyses. *Nonlinear Processes in Geophysics*, https://doi.org/10.5194/npg-31-115-2024.
- Pires, C., D. Docquier, S. Vannitsem (2024). A general theory to estimate Information transfer in nonlinear systems. *Physica D: Nonlinear Phenomena*, https://doi.org/10.1016/j.physd.2023.133988.
- Vannitsem, S., X. S. Liang (2022). Dynamical dependencies at monthly and interannual time scales in the climate system: Study of the North Pacific and Atlantic regions. *Tellus A: Dynamic Meteorology and Oceanography*, https://doi.org/10.16993/tellusa.44.
- Vannitsem, S., C. A. Pires, D. Docquier (2024). Causal dependencies and Shannon entropy budget: Analysis of a reduced-order atmospheric model. *Quarterly Journal of the Royal Meteorological Society*, https://doi.org/10.1002/qj.4805.
- Vannitsem, S., D. Docquier, S. Wauthy, M. Corkill, J.-L. Tison (2024b). Sources of low-frequency $^{\mathrm{TM}18}$O variability in coastal ice cores from Dronning Maud Land. Under review for *Climate Dynamics,* https://doi.org/10.48550/arXiv.2405.02471.

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