

To the Editor

Dear Editor, Dear Stefano,

Please find below my responses to the reviewers' comments. I took into account all their comments as you will see below. I have also modified the text accordingly. If you need more information, let me know.

Best regards

Stéphane

Response to the points raised by Reviewer 1

Thank you very much for your evaluation of the manuscript. Please find below the list of your points together with the answers (italicized).

General

This study considers the atmosphere as a nonequilibrium steady state system and applies methods published by Gaspard (2004) to determine predictability and irreversibility by the information entropy in observational and simulated data. The author uses block entropies for the forward and the time reversed block entropy in time series describing the North Atlantic/West European weather. The time evolution is described as a coarse-grained sequence of visited boxes. The predictability is assessed by the forward entropy and the entropy production by the irreversibility due to time reversal asymmetry.

The data are Großwetterlagen in the Eastern North Atlantic/Western Europe sector, which had been extracted in observations and scenario simulations. The daily time series are reduced by clustering of the patterns to 3, 6 and 8 time series. The observational time period is 1850-2019, and the simulated data is for 1900-2100. As the numerical effort for the joint probabilities is enormous, the 30 patterns had to be drastically reduced to 3, 6 and 8. Furthermore, the block lengths had to be reduced to two, to calculate the entropy S_2 . Thus, the present study is at the border of computational feasibility.

The study is insightful and relevant, although somehow preliminary, mostly due to computation restrictions. The agreement with previous studies hints at a reproducible core of results. The author should try to respond to the concerns, and if possible, less costly analyses might be added.

Thank you very much for the positive comments on the manuscript. Indeed, the approach proposed here has a very strong potential in the comparison between the properties of different models, providing clues on the properties of succession and occurrence of weather patterns. You will find below the answers to your specific points. The extension of the current analysis to other models and weather pattern projections are indeed worth performing. Here we focus on the weather

patterns that were developed by the MetOffice, hence allowing for the direct use of their projections. An extension to other models or weather pattern projections would need to develop the full chain that was done at the MetOffice. This would request considerable efforts, that to my opinion, are beyond the scope of the present work. The current work should therefore be pursued in the future on theoretical and practical aspects. On the theoretical side, it is crucial to be able to relate the properties of the information entropy production to its thermodynamic counterpart at the macroscopic level, and on a practical side, to extend the analysis to very long model runs (forced or not) and to various decompositions in weather patterns.

Specific Comments

I have several concerns, mostly on the use of Großwetterlagen and the nonstationarities in the data (mentioned in line 199).

- **Großwetterlagen:** Großwetterlagen are certainly useful and have their merits in synoptics, but do they form a complete basis in state space? Do they depend on the domain similar to EOFs? Is a comparison with other sets meaningful? A short list of the selected Großwetterlagen patterns and the clusters would be useful.

The weather patterns are defined based on pressure fields over a very specific region covering western Europe and the eastern part of the Atlantic. So the description is limited to this specific region for large scale patterns. This is obviously limited but these patterns are very useful in developing scenarios for the weather evolution over this limited region. Some display strong similarities with patterns already isolated in other studies. See Hannachi et al (2017) for a review of former investigations.

The 8 weather patterns are described in Table 1 of Neal et al (2016), and displayed in their figure 3. The first two patterns with the largest populations in their analysis are referred to as the NAO+ (21.2 %) and NAO- (17.8 %) with opposite positive and negative mean sea level pressure anomalies over Iceland. These two patterns are usually found in the investigation of weather patterns over the North Atlantic and its surroundings. The other patterns mostly related to the local weather fields over the British Islands and western Europe are defined in Neal et al (2016) as Northwesterly, Southwesterly, Scandinavian high, High pressure centered over UK, Low close to UK and Azores high, respectively.

We have introduced this description in Section 3 where the description of the data is done:

“The 8 weather patterns are described in Table 1 of Neal et al (2016), and displayed in their figure 3. The first two patterns with the largest populations in their analysis are referred to as the NAO+ (21.2 %) and NAO- (17.8 %) with opposite positive and negative mean sea level pressure anomalies over Iceland. These two patterns are usually found in the investigation of weather patterns over the North Atlantic and its surroundings. The other patterns mostly related to the local weather fields over the British Islands and western Europe are defined in Neal et al (2016) as Northwesterly, Southwesterly, Scandinavian high, High pressure centered over UK, Low close to UK and Azores high, respectively.”

- **S₂ in the 3-pattern (Fig. 2):** For the 3-pattern the forward and backward entropies are $S_2^R=S_2$, hence there is no information entropy production in this basis. What does that mean for the choice of patterns? Is it possible to determine the entropy production independent of the basis?

These two questions are indeed very interesting.

Concerning the first one, these values are close to equality suggesting a form of detailed balance (local equilibrium), for which the forward and backward time series structure seems statistically similar. This has also been found in Provata et al (2007) while analyzing very crude decomposition of symbols in the symbolic description of the human DNA. But one key aspect of coarse graining as done in the present work is the fact that the information entropy production is decreasing when the number of patterns decreases (see Figure 2d of the manuscript and Gomez-Marín et al (2008) for a theoretical explanation). This suggests that the almost equal values of S_2 and S_2^R is most probably related to the statistical significance of the computed quantities. In order to get a better estimate of these quantities and to properly infer the information entropy production for such a coarse graining, much longer time series is needed (or a set of realizations as obtained with the model runs). In order to better clarify this point, we have modified the last paragraph of Section 2 as:

“The process of coarse-graining has also an impact on the amplitude of d_k as shown in Gomez-Marín et al (2008), and also Gaspard (2022, personal communication): When reducing the number of symbols or patterns to characterize the evolution of the system, the amplitude of d_k decreases. This could lead to estimates for very coarse partitions of the dynamics that are not statistically very well defined for the information entropy production. This is most probably the case of the analyses that are done with the coarser partition for the observations below. This problem is however alleviated when investigating the set of model runs as better statistics can be obtained.”

For the second question, the information entropy production based on coarse-graining is indeed dependent on the partition made. This is clearly visible by increasing the number of clusters in our analysis. The only general statement that can be made is obtained when the number of clusters is tending to infinity. That would imply that the cells of the partition are infinitesimally small, hence converging toward the continuous set of equations. In this situation and for a large class of dissipative dynamical systems obeying a Fokker-Planck equation, the information entropy production converges toward minus the sum of the Lyapunov exponents (e.g. Nicolis and Nicolis, 2012). In the context of the atmospheric dynamics and the very short series available, this limit is far from reachable.

- **Anthropogenic climate change since 1860:** Global warming started early. Is it possible to find a similar behavior in the 21st century, hence a common imprint of global warming?

This is indeed a very good point, that could also be related to the question of the impact of low-frequency variability on the information entropy. Investigating what was happening before 1850 would be indeed very useful. As said earlier in this response, this can be achieved but the whole process of projection should be made using new model trajectories, in particular long runs on millennial time scales. This will not be addressed here, as we do not have access to such data yet.

- **Natural low-frequency variability:** Is the sea surface temperature relevant for the frequencies of the patterns in Fig. 2?

This is also a possible conjecture that should be clarified in the future by investigating long runs with fixed anthropogenic forcing, in such a way to isolate the internal dynamics of the model from the external forcing. We cannot address this aspect at this stage of the research.

- **Decrease of S_2 during 1850-1900:** Is the strong decrease of S_2 in Fig. 2 a hint for an overlooked nonstationarity?

This question is an important one that was also mentioned in our conclusions. Is this decrease related to the intrinsic low-frequency variability, or to natural fluctuations of the statistics, or to an increase of the quality of the measurement network? This remains to be discussed by analyzing, for instance, long model runs on millennial time scales.

Minor/Typos

Line 10: is?

Thank you very much.

Lines 149-154: the paragraph could be clearer, is $n=7$?

We have tried to make it more clear. Indeed $i=7$ days.

Figure 3 caption: length of words, n ?

Thank you very much for pointing this out. We have changed the 'n' in panel (d) into an 'i' in order to be consistent with the other panels.

Figures 4,5: a legend would be useful.

We keep the panels without legends in order to have less crowded panels. The details are provided in the caption.

Response to the points raised by Reviewer 2

Thank you very much for your evaluation of the manuscript. Please find below the list of your points together with the answers (italicized).

Review of “Weather pattern dynamics over Western Europe under climate change: Predictability, Information Entropy and Production” by S. Vannitsem (Nonlinear Processes in Geophysics)

In this manuscript, the author analyzed the entropy and its production in the information theory to study the impact of climate change on the weather patterns over Western Europe. In historical data for the period 1885-2000, the author found a decreasing trend of the block entropy except afterward of 1980, which suggests a less diverse set of pairs of events. In addition, an increasing trend of the entropy production for 6 and 8 weather patterns indicates a time-asymmetry related to the

irreversibility of the process. The analysis of the UK Met Office CMIP5 model showed a wide range of the block entropy evolution depending on the realization. These findings suggest that the degree of irreversibility is increasing under climate change.

The manuscript is well written with a clear structure. I believe this study would contribute to understand how climate change affects the weather pattern over Western Europe. In addition, the application of block entropy to climate model runs would be useful index to evaluate climate models. However, I have concerns due to the lack of the discussion that connects the obtained results and weather events.

Thank you very much for your positive evaluation of the manuscript and raising this important point on the link between the classical thermodynamic entropy and the information entropy production. We address your main point below.

Major comments:

Discussions that connect the (information) entropy production to atmospheric dynamics would be helpful to deepen our understanding of climate change impact on the weather regime. The authors wrote that the production of information entropy is related to irreversibility of the system, and its trend would be associated with the heat production/dissipation in the thermodynamic entropy. I wonder if the production of information entropy is associated with the irreversible processes in the large-scale atmospheric dynamics, like irreversible mixing of momentum that occurred at the Rossby wave breaking. Modulation of Rossby wave breaking is known to be associated with the transition of weather regime (Michel and Riviere, 2011).

The positive character of information entropy production is providing an important signature of a time asymmetry in the behavior of the system, in analogy with the thermodynamic entropy production (Gaspard, 2004; Nicolis and Nicolis, 2012). This time asymmetry is associated with an irreversible evolution, which again by analogy with the standard thermodynamic entropy, can be associated with the presence of dissipative processes and to global constrained driving the system out of equilibrium (Nicolis and Nicolis, 2012). The precise link between the information entropy production, thermodynamic entropy production, and dissipation is however a complicate question. It has already been successfully addressed at the microscopic level by a certain number of authors (e.g. Roldan and Parrondo, 2010, 2012), but the generalization to mesoscopic and macroscopic processes is still an open question.

For the atmosphere, we are indeed in a situation for which dissipation and global constraints - like the equator-pole temperature gradient - are placing the system out of equilibrium, and according to the current status of the information theory for dynamical systems, induces a time asymmetry reflected in a positive information entropy production. The precise link to the heat production in the atmosphere and to the amplitude of the global constraints is still to be addressed. This is also the case for specific processes like the wave breaking (Michel and Rivière, 2011) mentioned by the reviewer is also missing.

We have slightly modified the corresponding paragraph as:

“The novel approach of evaluating the (physical) entropy production based on coarse-grained time series at the microscopic level proposed by Gomez-Marin et al (2008) and Roldan and Parrondo, (2010, 2012) offers an important opportunity to estimate experimentally this quantity. Yet, when dealing with the dynamics of a macroscopic system like the atmosphere, the connection between the information entropy production, the physical entropy production, dissipation and global constraints, is still missing. The possibility offered by these advances however opens the way to improve our knowledge of the dynamics of the climate system, provided appropriate researches are done in that direction.”

Thank you very much for drawing our attention on the work of Michel and Rivière (2011), now mentioned in the Introduction.

Minor comments:

Line 12: A quantitative assessment of the change of the entropy production (10% in the RCP2.6 and 30-40% in the RCP8.5) is missing in the result and conclusion.

Thanks for pointing this out. Now mentioned in the conclusions.

Line 110-114: As the main finding using the 15 model runs shows the diverged block entropy evolution depending on the realization, it would be useful for readers to briefly describe the difference in the realizations between 15 runs. (The difference is only in parameterization? or also in boundary conditions?)

As discussed in Pope et al (2022) and references therein, the only differences between the model versions are the set of parameter chosen. We add the following sentence in the description of the data:

“The model versions differ only by the choice of parameters and not by the forcing (Pope et al, 2022; Sexton et al, 2021).”

Line 124: “A clear trend ... is visible, and χ^2 tests ... are highly significant”. Please provide the evidence (figure/table) of this sentence.

Thank you very much for pointing out this. I have now introduced the values of the χ^2 tests as:

“A clear evolution in the probabilities is visible. χ^2 tests of differences between the first and the last values have been computed. The χ^2 test of differences between the two distributions are 50, 176 and 214 for 3, 6 and 8 clusters, respectively. With the respective degrees of freedom of 2, 5 and 7, these values indicate that the two distributions are significantly different at a probability level much lower than 0.001. The Panel (d) shows the evolution of the Shannon entropy for the three partitions. Here however, the (static) information content does not change much as a function of time whatever the partition chosen.”

Figures: labels (e.g. (a), (b),...) are too small to see. Please consider put larger labels in the upper left of the figure.

Thanks for pointing this out. The font size has been increased.

Figures 4-5: Legend would be useful.

We keep the panels without legends in order to have less crowded panels. The different lines are explained in the caption.

References

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