

Universität Leipzig

Fakultät für Mathematik und Informatik
Institut für Informatik

Evolution of Moisture Transport Patterns in the North Atlantic in different Climate scenarios

Masterarbeit

Leipzig, Mai 2024

vorgelegt von

Denis Streitmatter
Studiengang Master Informatik

Betreuende Hochschullehrer:

Dr. Baldwin Nsonga

Universität Leipzig, Abteilung für Bild und Signalverarbeitung

Prof. Dr. Gerik Scheuermann

Universität Leipzig, Abteilung für Bild und Signalverarbeitung

ABSTRACT

The distribution and variability of precipitation in Europe are significantly influenced by moisture transport over the north(east)ern Atlantic. The objective of my master thesis is to analyze the evolution of moisture transport patterns in various future climate scenarios. The foundation of this research lies in the MPI-GE, the Max Planck Institute Grand Ensemble Dataset, comprising an ensemble of 100 members for different RCP (climate) scenarios up until 2100. Each member provides multiple fields of relevant climate data. A challenge will be the visualization of uncertainty stemming from 100 different simulations, which will not be straightforward.

To quantify moisture transport, an integrated water vapor transport (a combination of wind and specific moisture) scalar/vector field will be generated from the MPI-GE. Windowed Empirical Orthogonal Functions (EOFs) will be used to extract spatial-temporal patterns and simplify the data, making it easier to evaluate pattern evolution over time.

CONTENTS

1	INTRODUCTION AND MOTIVATION	1
1.1	Motivation	1
1.2	Climate	1
1.3	Research Questions and Thesis Structure	1
2	BASICS	3
2.1	(Uncertain) Fields	3
2.2	Empirical Orthogonal Functions	3
3	MPI GE CMIP6	5
4	RELATED WORK	7
4.1	Uncertainty Visualisation	7
4.2	Moisture Transport	7
4.3	Pattern analysis	9
5	METHODOLOGY	11
5.1	Overview	11
5.2	Preprocessing	11
6	RESULTS	13
7	CONCLUSIONS AND FUTURE WORK	15
7.1	Conclusions	15
7.2	Future Work	15
	ACRONYMS	17
	GLOSSARY	19
	BIBLIOGRAPHY	21

1 INTRODUCTION AND MOTIVATION

1.1 MOTIVATION

Since the discovery (and further confirmation) of the greenhouse effect in the years from 1824 to 1900 humans came a long way of fighting the consequences of the increased greenhouse gas concentration in earth's atmosphere. In 2019 more than 11,000 scientists from around the world released a declaration [8], calling governments from around the world to action. Especially the last decades the climate crisis gained more and more attention, leading to the creation of multiple international organizations and institutions (e.g. the International Panel on Climate Change in 1988).

Include
sources!!!

1.2 CLIMATE

This section should give an introduction to the current state of climate research. Therefore it should explain what the current way of future climate predictions is (Coupled Models), how they work, and it should explain some part of the politics, who is involved in what and what the background of the most important projects (CMIP, ScenarioMIP ...). It should be explained that the data used is the one that the highest council of fighting climate change uses for its report.

1.3 RESEARCH QUESTIONS AND THESIS STRUCTURE

Structure:

1. **Preliminaries:** explain what climate simulations are, what cmip(6) is and its relation to the IPCC reports and what that means for the global fight against the climate crisis. This chapter should prepare the reader to understand all the related work in Chapter 4.
2. **Problem Analysis:** explain what I want to do using the CMIP6 simulations: Describe what the general plan is: Visualization of the moisture transport in Europe

1 *Introduction and Motivation*

with the help. Also define what the goals of the visualizations are: Visualize different scenarios for comparison, visualize uncertainties of different members, visualize evolution over time, also try combining those. Here should be a graphic that explains the workflow that transforms a simulation into some nice pictures

3. **Related Work:** Show what efforts have already been done regarding analysis of moisture transport, future and past. Maybe preparing a comparison table would be good.
4. **Realization:** Describe in a step by step way what measures had been taken.
5. **Evaluation:** A little bit unsure how far I (as a CS person) can evaluate this, have to come up with a concept
6. **Conclusion:** Same as step before, but there will be something to write about after everything else is written

2 BASICS

This section should explain the basic math to understand the aforementioned topics, not that much needed but still needs to be there.

2.1 (UNCERTAIN) FIELDS

2.2 EMPIRICAL ORTHOGONAL FUNCTIONS

3 MPI GE CMIP6

Explain what I want to do using the CMIP6 simulations: Describe what the general plan is: Visualisation of the moisture transport in Europe with the help . Also define what the goals of the visualisations are: Visualize different scenarios for comparison, visualize uncertainties of different members, visualize evolution over time, also try combining those. Here should be a graphic that explains the workflow that transforms a simulation into some nice pictures

The dataset chosen for this project is the *Max Planck Institute Grand Ensemble CMIP6* (from now on MPI-GE CMIP6), presented by Olonscheck et al. [6]. The reasons for choosing this dataset are manifold:

1. It uses the latest (6th) phase of the Coupled Model Intercomparison Project (CMIP6)
2. Compared to its predecessor (MPI-GE [5]) it provides high frequency output (6 hour intervals vs. monthly means), which enables finding short-lived weather events and structures (e.g. atmospheric rivers)
- 3.

This section should explain what datasets are available and why I chose the MPI-GE CMIP6 [6]

Maybe but the comparison table from [6] here and expand it a bit.

4 RELATED WORK

This chapter builds on the foundation of Chapter 2, explaining what dataset is actually used, the reason for this and its properties. Furthermore, it summarizes the current state-of-science in quantifying and calculating (patterns of) moisture transport and the usage of it.

4.1 UNCERTAINTY VISUALISATION

4.2 MOISTURE TRANSPORT

This section should explain in what ways moisture transport can be quantified and used, give a few examples for each and maybe motivate why we do it like we want to.

To computationally study the change of moisture transport it first needs to be quantified. The vast majority of literature use some form of vertically integrated humidity, the variants will be explained in the following section. The main usage of these algorithms was to find a filamentary structure called “Atmospheric Rivers”, a prominent way of water vapor transportation in the extratropic regions [2].

There are also some notable other algorithms, namely stable oxygen isotope investigation [4] and langragian backwards trajectories [11], but both rather look for the origin of the WV instead of its destination and are therefor out of scope for this thesis.

As proposed by Zhu and Newell in [12], one way of measuring moisture (p) transport is by vertically integrating over the different pressure levels the zonal and meridional fluxes \overline{pu} and \overline{pv} .

An example of using this method can be found in [1] with many more references why this method is working well for these kinds of approaches.

Also, this paper lists some other methods of moisture transportation which are also used

1. integrated water vapor distributions
2. the lagrangian approach
3. stable oxygen isotope investigation

Create a table showing how different quantification were used in different algorithms

4 Related Work

USAGES OF IVT AND DIFFERENCES

In [7] they used a vector field of the IVT: $\int_{p_{low}}^{p_{max}} qVdp$, where p is the pressure level, q is the humidity and V the horizontal vector.

In [9] they used a scalar field based on the euclidian norm of the vector field used by [7].

In [1] they also used the euclidian norm on a similar field like [7] to measure the impact of ENSO on south-chinese weather.

Yang et al. showed in their report [10] the directions of moisture flux on the continent borders based on the big ERA5 reanalysis. They measure the moisture based on a equation called the *Moisture Budget*, which is based on multiple Faktors:

It seems related to the IVT the other authors used, but utilizes the gradient and some other differences. The complete formula is:

$$\frac{1}{g} \frac{\delta}{\delta t} \int_0^{P_s} qdp = -\nabla \cdot \frac{1}{g} \int_0^{P_s} (qv)dp + E - P$$

With:

1. p is the pressure, P_s is the surface pressure
2. q is the specific humidity
3. v is the horizontal wind vector
4. E is the evaporation
5. P is the Precipitation

In the actual analysis they used mostly other metrics:

1. Vertically integrated Moisture Convergence (*VIMC*): It is basically the gradient of the specific moisture in the air times the Wind vector
2. P is the precipitation
3. E is the evaporation

Furthermore, they evaluated the correlation between the moisture transport and the precipitation variability, which correlate to a significant extent.

This section should explain atmospheric rivers, but since we don't know if they are even relevant so i write it in the end.

I don't know where to put this, maybe it should go into the preliminaries

4.3 PATTERN ANALYSIS

Explain some usages of EOF in data, but extremely important: Explain what [1] did since its quite similar.

See [3] for a big overview of EOF in atmospheric science.

See [1] for a similar approach as we plan it, except it only focuses on the past. They

5 METHODOLOGY

5.1 OVERVIEW

5.2 PREPROCESSING

This should explain how you get a proper IVT field from a CMIP6 simulation, what the caveats are and what calculations are done.

6 RESULTS

7 CONCLUSIONS AND FUTURE WORK

7.1 CONCLUSIONS

7.2 FUTURE WORK

ACRONYMS

PCA	Principal component analysis
SNF	Smith normal form
TDA	Topological data analysis

GLOSSARY

\LaTeX	A document preparation system
\mathbb{R}	The set of real numbers

BIBLIOGRAPHY

1. O.O. Ayantobo, J. Wei, B. Kang, and G. Wang. “Integrated moisture transport variability over China: patterns, impacts, and relationship with El Nino–Southern Oscillation (ENSO)”. en. *Theoretical and Applied Climatology* 147:3-4, 2022, pp. 985–1002. ISSN: 0177-798X, 1434-4483. DOI: [10.1007/s00704-021-03864-x](https://doi.org/10.1007/s00704-021-03864-x).
2. L. Gimeno, R. Nieto, M. Vázquez, and D. Lavers. “Atmospheric rivers: a mini-review”. *Frontiers in Earth Science* 2, 2014. ISSN: 2296-6463.
3. A. Hannachi, I. T. Jolliffe, and D. B. Stephenson. “Empirical orthogonal functions and related techniques in atmospheric science: A review”. en. *International Journal of Climatology* 27:9, 2007, pp. 1119–1152. ISSN: 08998418, 10970088. DOI: [10.1002/joc.1499](https://doi.org/10.1002/joc.1499).
4. Y. Ma, M. Lu, H. Chen, M. Pan, and Y. Hong. “Atmospheric moisture transport versus precipitation across the Tibetan Plateau: a mini-review and current challenges”. en.
5. N. Maher, S. Milinski, L. Suarez-Gutierrez, M. Botzet, M. Dobrynin, L. Kornblueh, J. Kröger, Y. Takano, R. Ghosh, C. Hedemann, C. Li, H. Li, E. Manzini, D. Notz, D. Putrasahan, L. Boysen, M. Claussen, T. Ilyina, D. Olonscheck, T. Raddatz, B. Stevens, and J. Marotzke. “The Max Planck Institute Grand Ensemble: Enabling the Exploration of Climate System Variability”. en. *Journal of Advances in Modeling Earth Systems* 11:7, 2019, pp. 2050–2069. ISSN: 1942-2466, 1942-2466. DOI: [10.1029/2019MS001639](https://doi.org/10.1029/2019MS001639).
6. D. Olonscheck, L. Suarez-Gutierrez, S. Milinski, G. Beobide-Arsuaga, J. Baehr, F. Fröb, L. Hellmich, T. Ilyina, C. Kadow, D. Krieger, H. Li, J. Marotzke, É. Plésiat, M. Schupfner, F. Wachsmann, K.-H. Wieners, and S. Brune. *The new Max Planck Institute Grand Ensemble with CMIP6 forcing and high-frequency model output*. en. preprint. Preprints, 2023. DOI: [10.22541/essoar.168319746.64037439/v1](https://doi.org/10.22541/essoar.168319746.64037439/v1).
7. F. M. Ralph, S. F. Iacobellis, P. J. Neiman, J. M. Cordeira, J. R. Spackman, D. E. Waliser, G. A. Wick, A. B. White, and C. Fairall. “Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers”. en. *Journal of Hydrometeorology* 18:9, 2017, pp. 2577–2596. ISSN: 1525-755X, 1525-7541. DOI: [10.1175/JHM-D-17-0036.1](https://doi.org/10.1175/JHM-D-17-0036.1).

Bibliography

8. W.J. Ripple, C. Wolf, T.M. Newsome, P. Barnard, and W.R. Moomaw. “World Scientists’ Warning of a Climate Emergency”. en. *BioScience*, 2019, biz088. ISSN: 0006-3568, 1525-3244. DOI: [10.1093/biosci/biz088](https://doi.org/10.1093/biosci/biz088).
9. P. M. Sousa, A. M. Ramos, C. C. Raible, M. Messmer, R. Tomé, J. G. Pinto, and R. M. Trigo. “North Atlantic Integrated Water Vapor Transport—From 850 to 2100 CE: Impacts on Western European Rainfall”. en. *Journal of Climate* 33:1, 2020, pp. 263–279. ISSN: 0894-8755, 1520-0442. DOI: [10.1175/JCLI-D-19-0348.1](https://doi.org/10.1175/JCLI-D-19-0348.1).
10. Y. Yang, C. Liu, N. Ou, X. Liao, N. Cao, N. Chen, L. Jin, R. Zheng, K. Yang, and Q. Su. “Moisture Transport and Contribution to the Continental Precipitation”. en. *Atmosphere* 13:10, 2022, p. 1694. ISSN: 2073-4433. DOI: [10.3390/atmos13101694](https://doi.org/10.3390/atmos13101694).
11. N. Zhao, A. Manda, X. Guo, K. Kikuchi, T. Nasuno, M. Nakano, Y. Zhang, and B. Wang. “A Lagrangian View of Moisture Transport Related to the Heavy Rainfall of July 2020 in Japan: Importance of the Moistening Over the Subtropical Regions”. en. *Geophysical Research Letters* 48:5, 2021, e2020GL091441. ISSN: 0094-8276, 1944-8007. DOI: [10.1029/2020GL091441](https://doi.org/10.1029/2020GL091441).
12. Y. Zhu and R. E. Newell. “A Proposed Algorithm for Moisture Fluxes from Atmospheric Rivers”. en. *Monthly Weather Review* 126:3, 1998, pp. 725–735. ISSN: 0027-0644, 1520-0493. DOI: [10.1175/1520-0493\(1998\)126<0725:APAFMF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1998)126<0725:APAFMF>2.0.CO;2).