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

Masterarbeit

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vorgelegt von

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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 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 [11], 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). The mid and long-term consequences are manyfold and go far beyond the general rising of the worlds' average temperature, e.g. shifts in circulation systems like the North Atlantic Oscillation (NAO) [14], which in turn also have varying consequences.

Include sources!!!

1.2 Climate

This section should give an introduction to the current state of climate research. Therefor 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 involed in what and what the backroud 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.

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 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

The Max Planck Institute Grand Ensemble CMIP6 (MPI GE CMIP6) is a Single-model initial-condition large ensemble (in short: SMILE) [9]. This means that a single model was run with different initial condiditions but the same external forcings (e.g. greenhous gasses) mutiple times (⇒ ensemble). This makes it possible to seperate the internal variability from the responses to the external forcing, enabling researchers to better quantify the consequences of climate change (for example) . Additionally it makes the research of extreme weather phenomena (e.g. droughts, floods etc.) more robust in spite of their rare occurences [6]. As described in Section 1.2, Coupled models

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. [9]. 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 [7]) it provides high frequency output (6 hour intervals vs. monthly means), which enables taking short-lived weather events and structures (e.g. atmospheric rivers) into account which would be lost in the calculation of the mean
3.

This section should explain what datasets are available and why I chose the MPI-GE CMIP6 [9]

Maybe but the comparison table from [9] here and expand it a bit.

4 Related Work

This section outlies the current state-of-the-art in the main parts of this thesis explained in Section 1.3: Qantifying Moisture (Transport), extracting spatio-temporal patterns, tracking their change over time and visualizing the uncertain results in the end.

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 extract any spatio-temporal patterns of moisture (transport), it first needs to be quantified in any way. The variable usually used for this task is the *specific humidity*, which has no unit and is a float value between 0.0 and 1.0, denoting the percentage of water in the air at a specific gridpoint. The vast majority of literature use some form of vertically integrated humidity and the variants will be explained in the following section. The main usage of these algorithms was to find a filamentary weather structure called "Atmospheric Rivers", a prominent way of water vapor transportation in the extratropic regions [3].

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

The most straightforward way of quantifying moisture is **Vertically Integrated Water Vapor (IWV)** [2, 3, 8, 12, 16], which is essentailly the vertical integral of the specific humidity q from earth's surface to some upper limit in the atmosphere:

$$\int_0^{P_s} q\,dp$$

Insert some examples of usages with references to the papers, indicating the usefulness

There are also some notable other algorithms, namely stable oxygen isotope investigation [5] and langragian backwards trajectories [16], 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 [17], 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

Usages of IVT and differences

In [10] they used a vector field of the IVT: $\int_{p_{low}}^{p_{max}} qV dp$, where p is the pressure level, q is the humidity and V the horizontal vector.

In [13] they used a scalar field based on the euclidian norm of the vector field used by [10].

In [1] they also used the euclidian norm on a similar field like [10] to measure the impact of ENSO on south-chinese weather.

Yang et al. showed in their report [15] 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:

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

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.

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

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

4.3 Pattern analysis

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

See [4] 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

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

5.2 Preprocessing

The goal of this step is to generate an IVT field (see Chapter 4) from the MPI GE CMIP6 (see Chapter 3). The steps to complete this task are quite straight forward:

1. Load four different fields for each time period in each member in each szenario: Specific humidity *hus*, eastward horizontal wind *ua*, northward horizontal wind *va* and surface pressure *ps*. Here the geographical box around the area of interest is cut out: Europe and the North Atlantic (Longitude: $-90^\circ \rightarrow 40^\circ$, Latitude: $20^\circ \rightarrow 80^\circ$, based on [14])
2. For each geographical gridpoint (*lon*, *lat*) and timestep: Calculate the integrals of hte product of wind components and specific humidity over the vertical pressure levels $\frac{1}{g}\int_{ps}^{0} hus * ua$ and $\frac{1}{g}\int_{ps}^{0} hus * va$, with g being the gravitational acceleration ($9.806\frac{m}{s}$)
3. Save the results for each time period in each member in each szenario in a NetCDF file for the further steps.

The calculations were performed on the high performance computing cluster[1] of the German Climate Calculations Center (DKRZ), due to the MPI GE CMIP6 is saved there and downloading the data would take a lot of time. This also result in the goal of this step

[1]https://docs.dkrz.de/doc/levante/

to minimize the hours on the HPC system since they get billed by the time using nodes. Although these steps seem easy, due to the large sizes of the datasets and other issues many challenges were met. In the following those will be explained with regard to the step they ocurred in.

1. **Data Loading**
   - cutting out geobox
   - slow IO → started using dask+xarray
2. **Vertical integration**
   - calculate hybrid sigma pressure levels for each gridpoint and timestep to get the x values for integration
   - describe my idea of testing the integration

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

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