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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.

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Climate Model Intercomparison Project (CMIP)

2.2 Mathematical Background

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4.1 Climate simulation datasets

General infos from [5]:

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4.1.1 RCP Scenarios

4.1.2 MPI-GE - The Max Planck Institute grand Ensemble

General information about the future scenarios (all based on the *rcp85* dataset available to me on the DKRZ cluster, I just assumed its the same for other scenarios. Maybe need to confirm this):

- **Time**: The time axis is compromised of 1128 values, which count the days since 01.01.2005. The first one is 380, so it actually starts somewhere in 2006, and all of those values are roughly 30 days apart. This axis is part of every dataset, all stored as floats.

- **Lat**: Vector of 96 Float Elements ranging from roughly -88 to 88. Results in a resolution of 1.875° in North-South direction.

- **Lon**: Vector of 192 Float Elements ranging from roughly 0 to 358. Results in a resolution of 1.875° in East-West direction.

- **Pressure Level** (plev): Is given for each dataset and consists of 26 Floats, ranging from 10 to 100,000. Unit is *Pa*.

- **Eastward/Northward Wind**: Given as Floats in the unit of ms^{-1} per *(lat, lon, time, plev)*. Each compromises the wind direction in one orthogonal direction. Eastward wind directory is named *ua*, northward *va*

- **Specific Humidity**: Specific humidity is given as a float without value. Reason is the unit is actually kg moisture per kilogramm air, which cancels out in the end. Is given for each *(lat, lon, time, plev)*. Directory name: *hus*
- **Surface Wind Speed**: Given as float per *(lat, lon, time, height)*, represents the wind speed in ms^{-1} (no Vector!!) near the surface level. Directory Name: $sfcWind$
- **Evaporation**: Given as a float and per *(lat, lon, time)*, represents the evaporation flux. Unit is $\frac{kg}{m^2 s}$, directory name *evspsbl*
- **Preciptation**: Given either as normal or convective flux ($\frac{kg}{m^2 s}$) per *(lat, lon, time)*. Directory name *pr, prc*.
- **Water Vapor Content**: Integrated over the colum, given per *(lat, lon, time)*, just the water vapor content, no wind(vector) involved. Directory name: *prw*.

In [5] there is much information available:

4.2 Moisture Transport

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].

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

See Section 4.3 for further explaination.

There are also some notable other algorithms, namely stable oxygen isotope investigation [4] and langragian backwards trajectories [9], but both rather look for the origin of the WV instead of its destination and are therefor out of scope for this thesis.

4.2.1 Vertically Integrated Water Vapor (IWV)

4.2.2 Vertically Integrated Water Vapor Transport (IVT)

As proposed by Zhu and Newell in [10], 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 [6] 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 [7] they used a scalar field based on the euclidian norm of the vector field used by [6].

In [1] they also used the euclidian norm on a similar field like [6] to measure the impact of ENSO on south-chinese weather.

4.2.3 Moisture Budget

Yang et al. showed in their report [8] 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 evaluateded the correlation between the moisture transport and the precipitation variability, which correlate to a significant extent.

4.3 Atmospheric Rivers

4.4 Pattern analysis

4.4.1 Empirical Orthogonal Functions

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

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

5 Design

6 Evaluation

7 Conclusions and Future Work

7.1 Conclusions

7.2 Future Work

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. URL: https://link.springer.com/10.1007/s00704-021-03864-x (visited on 11/13/2023).
2. L. Gimeno, R. Nieto, M. Vázquez, and D. Lavers. "Atmospheric rivers: a mini-review". *Frontiers in Earth Science* 2, 2014. ISSN: 2296-6463. URL: https://www.frontiersin.org/articles/10.3389/feart.2014.00002 (visited on 11/27/2023).
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. URL: https://onlinelibrary.wiley.com/doi/10.1002/joc.1499 (visited on 11/13/2023).
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. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019MS001639 (visited on 11/13/2023).
6. 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. URL: http://journals.ametsoc.org/doi/10.1175/JHM-D-17-0036.1 (visited on 11/13/2023).

7. 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. URL: https://journals.ametsoc.org/doi/10.1175/JCLI-D-19-0348.1 (visited on 11/13/2023).
8. 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. URL: https://www.mdpi.com/2073-4433/13/10/1694 (visited on 11/13/2023).
9. 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. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL091441 (visited on 12/01/2023).
10. 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. URL: http://journals.ametsoc.org/doi/10.1175/1520-0493(1998)126%3C0725:APAFMF%3E2.0.CO;2 (visited on 11/13/2023).