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

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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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1 INTRODUCTION AND MOTIVATION

1.1 MOTIVATION

Since the discovery (and further confirmation) of the greenhouse effect in the years from 1824 to 1900 [12, 13] humans came a long way of fighting the consequences of the increased greenhouse gas concentration in earth's atmosphere. In 1972 Sawyer summarized the knowledge and predicted quite accurately the warming at the end of the century [39]. 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 (IPCC) in 1988).

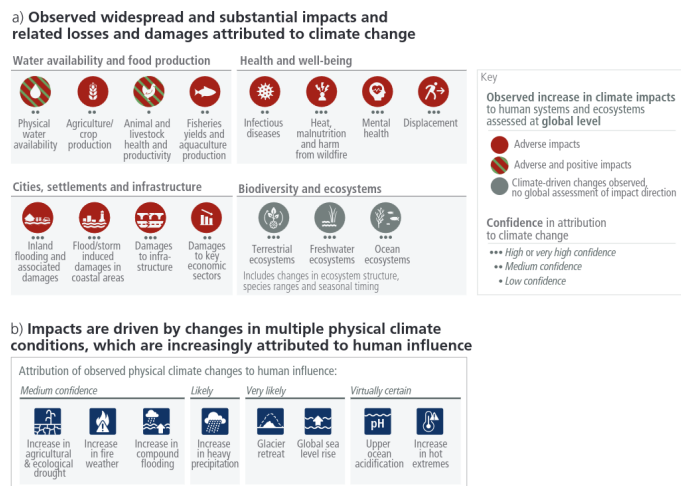


Figure 1.1: Impact of Climate Change for Humans, taken from [22]

In 2019 more than 11,000 scientists from around the world released a declaration [35], calling governments from around the world to action. The consequences for the environment and humans are prevalent and are, in part, already visible today. Figure 1.1 shows likely consequences for humans from the latest IPCC report for policymakers [22]: Flooding, malnutrition, displacement, and damages to all kinds of ecosystems can be attributed with high confidence to climate change. The sources of such consequences are manyfold,

but recent research shows that big circulation systems like the North Atlantic Oscillation[47] or the Atlantic Meridional Overturning Circulation [24] change as well.

Although the water vapor in the air accounts for only 0.001 % of the water on the earth, it is the most active part of that cycle [55]. Also, research shows that the precipitation on land does not match the evaporation, meaning the water was transported (from the oceans) to land, providing water for the ecosystems there. Analyzing the structural change of this moisture transport could help predict consequences. Motivated by the research of Vietinghoff et al., this thesis aims to evaluate similarly the systemic changes of moisture transport patterns in Europe and the northern Atlantic.

CITE!!! Where the fuck did I read this?

1.2 CLIMATE AND CLIMATE RESEARCH

1.2.1 QUICK OVERVIEW OVER CLIMATE SYSTEMS AND CLIMATE CHANGE

In difference to weather, which is the momentary state of the atmosphere at a time, climate is the average of weather patterns over a larger period of time, usually 30 years or more [29]. So the term climate change does not refer to any unexpected weather changes, but to the structural changes of said patterns over a large period of time (e.g. the warming of the global average temperature). Earth's climate system can be seen as complex interactions of its major components: atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere [19, 46]. Changes in this system can have (roughly) two reasons: Either "internal variations in form of redistributions of energy" [46], which can happen on arbitrary scales (see the discussion on the change of AMOC in [24]) or in the form of external forcings. Such forcings could be volcanic activity, differences in solar radiation, and of course the emission of greenhouse gases (GHGs).

Figure 1.2 gives an example what effect such external forcing can have: It shows the change in effective radiative forcing (ERF) and its contributing components. ERF (in Wm^{-2}) is a way of measuring how much energy from the sun is "trapped" instead of reflected back to space (greenhouse effect). A positive value means warming, while a negative value is associated with cooling. In can be seen in Figure 1.2 that neither volcanic activity or solar radiotian changed that much, the main drivers of change in ERF are the man-made GHGs and cooling aerosols. [19]

Regarding the internal variations: Most of it is part of some oscillation, with the oscillations of the atmosphere with the hydrosphere (i.e. all liquid forms of water on earth) being responsible for large parts of climate's internal variations on decadal and interannual time frames [46]. Prominent examples for such oscillations are the El Niño Southern

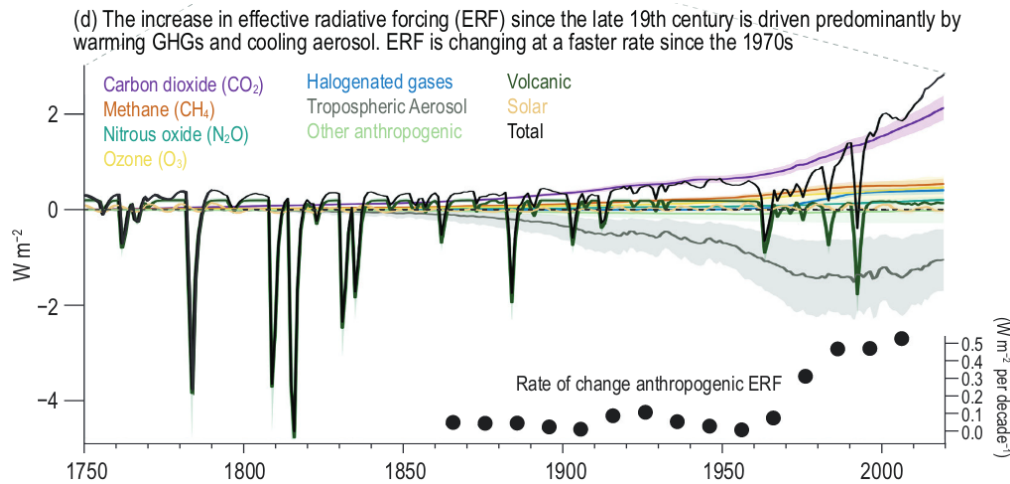


Figure 1.2: The evolution of the effective radiative forcing and contributing components, taken from [19]

Oscillation (ENSO) or the North Atlantic Oscillation (NAO), which is especially relevant for this thesis.

1.2.2 THE NORTH ATLANTIC OSCILLATION

The aforementioned NAO is “... one of the most recurrent and prominent patterns of atmospheric circulation variability” [18]. It is also one of the oldest known weather patterns, since some descriptions of Scandinavians exist from a few centuries back. It dictates the climate variability for a large area: From the East Coast of the USA to Siberia and from the Arctic to the subtropical Atlantic. Especially in the boreal winter (usually from December to February), the variations of the NAO influences a wide range of variability areas: From the mean wind speed and direction to the heat and moisture transport as well as the intensity and amount of storms and their path.

The NAO is a redistribution of atmospheric mass from the Arctic to the subtropical Atlantic, producing the aforementioned effects while swinging from one phase to another. Its basis is a characteristic dipole in the Sea Level Pressure Field (SLP) of the Atlantic (see Figure 1.3). Due to the Coriolis Force, air flows clockwise around high pressure and counterclockwise around low pressure in the Northern Hemisphere, leading to the transport of the maritime air from the Atlantic towards Europe (see Figure 1.3) [18, 46]. Depending on the pressure differences, the effect varies: High pressure differences lead to higher transport of mild, humid air to Europe, which in turn results in milder European winters. In contrast, a low difference leads to a less pronounced effect and therefore to colder winters.

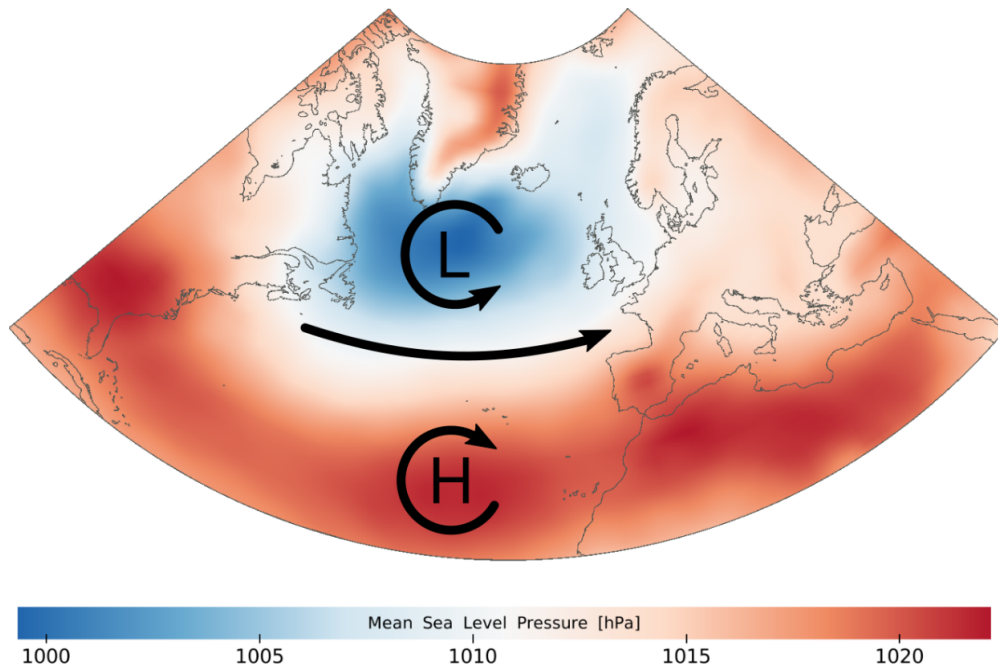


Figure 1.3: Characteristic mean SLP field of a boreal winter season, taken from [46]. It shows a high (H)/low (L) pressure pattern, directing air from the Atlantic westwards towards Europe.

This varies on an interannual scale, and this effect is called the North Atlantic Oscillation. The difference per year is called the NAO index and can be seen in Figure 1.4.

A large fraction of the recent warming in Europe can be linked to the behavior of the NAO in the last decades: it shifted from large amplitude anomalies in the negative to similar anomalies in the opposite direction in the later years. Therefore, Hurrell et al. points out the need to study the relationship of anthropogenic climate change and the NAO. Following this, the motivation of thesis [47] by Vietinghoff et al. tried to track the shift of the centers of the dipoles in different climate scenarios.

1.2.3 CLIMATE RESEARCH: THE IPCC AND THE COUPLED MODEL INTERCOMPARISON PROJECT (CMIP)

The reason for the endorsement of the IPCC by the UN General Assembly 1988 was to prepare comprehensive reviews and report about the current state of scientific knowledge and research. Since then there were six assessment cycles and six reports were published, condensing the research of the scientific community. Figure 1.1 is a graphic from the latest

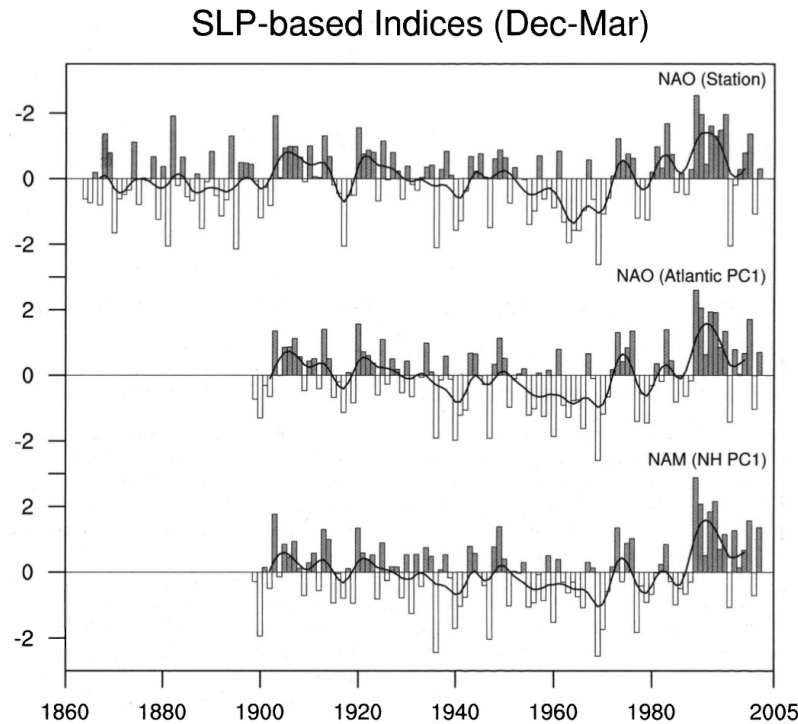


Figure 1.4: Comparison of the NAO index from [18]: The top panel are differences of SLP from weather stations in Portugal and Iceland, the middle panel is the first principal component of corresponding to the first EOF of the northern Atlantic SLP field, and the bottom panel is the same as the middle panel but for the whole Northern Hemisphere. See [18] for a more detailed description

report for policymakers from 2023 [22], displaying the probable consequences for humans in climate change.

A main source for such figures in the reports are so-called Global Coupled Models (GCMs)¹, trying to model the state and evolution of certain fields of earth data. They consist of multiple Models, each representing a major part of Earth's complex climate system (like atmosphere, hydrosphere, etc.), also allowing to model the dynamic interactions between these parts [46]. In the mid 90s the Coupled Model Intercomparison Project (CMIP) was brought to life, with the aim of streamlining results of GCMs and making them comparable. CMIP provides the outer structure, amongst others what kind of simulations to produce (e.g. preindustrial control simulations, future scenarios etc.), what kinds of fields should be generated, what kind of resolutions to provide and also how these results should be serialized. Since then the results of CMIP played an increasingly major part in

¹Unfortunately, Global Coupled Models share their acronym with General Circulation Models, which are quite similar

the reports of the IPCC [45], and are now even called “... one of the foundational elements of climate science” [9]. CMIP is currently in its 6th phase, corresponding to the recently finished 6th Assessment Report of the IPCC [22]. The 6th phase describes an inner core (DECK + historical simulations), required for participating in CMIP, and some endorsed Model intercomparison Projects (MIPs). The latter are optional and consist of e.g. ScenarioMIP (future scenario simulations), HighResMIP (for exploring Models with higher resolutions), and GeoMIP (exploring effects of geoengineering).

1.3 RESEARCH QUESTIONS AND THESIS STRUCTURE

Following up the previous sections, the research question for this thesis is:

“How do the Patterns of Moisture Transport change in the face of various climate scenarios in the North-East Atlantic?”

The remaining thesis is structured as follows: Chapter 2 gives the theoretical background on fields and pattern analysis. The following Chapter 3 gives a detailed overview about the used CMIP6 based dataset. Chapter 4 provides an overview of related work, the motivation for this thesis and the placement of this thesis in the academic context. While the results are discussed and presented in Chapter 6, Chapter 5 gives a detailed description how these results came about. The thesis is concluded with Chapter 7 and gives an outlook for future research.

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 dataset chosen for this project is the *Max Planck Institute Grand Ensemble CMIP6* (from now on MPI-GE CMIP6), presented by Olonscheck et al. It is a Single-model initial-condition large ensemble (in short: SMILE) consisting of multiple coupled models: ECHAM6 for the atmosphere directly coupled to JSBACH for land and MPIOM for sea and sea-ice. The models are coupled once a day, meaning that the simulation results serve as inputs for the other models. This means that a single model was run with different initial conditions but the same external forcings (e.g. greenhous gasses) mutiple times. Every sepearate intial condition is a member of the simulation, and all members together are the whole ensemble. [32]

Following this, every variable/field of the dataset can be interpreted as a uncertain field (see Section 2.1). Combining the members into an ensemble makes it possible to sepearate 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 [26].

Since MPI GE CMIP6 follows the CMIP6 protocol (see Section 1.2 and [9]), it implements the DECK core with (amongst others) a quasi-stationary preindustrial control simulation and the historical simulations. Futhermore it also uses the forcings defined by CMIP6 (like volcanic eruptions, solar circle etc.) for the historical and future simulations (see Section 3.1).

The historical simulations are split from 1000 year preindustrial control simulation circa 25 years apart for each member, and the results of them in the year 2015 serve as the initial state for each corresponding member in the future scenarios.

1. It uses the latest (6th) phase of the Coupled Model Intercomparison Project (CMIP6)
2. Compared to its predecessor (MPI-GE [27]) 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

3.1 SCENARIO MIP: FUTURE SCENARIOS AND SHARED SOCIOECONOMIC PATHWAYS

Since the goal of this thesis is to evaluate the future patterns of climate change, simulations of the future are necessary. Fortunately, CMIP (Phase 3) introduced a project of future climate scenarios (ScenarioMIP) in the 2000s, which define and simulate developments of different anthropogenic drivers of climate change [31]. They play an important role in climate research and are since then the source for many figures and assessments in IPCC reports [45]. The different scenarios can be used to assess “...possible changes in the climate system, impacts on society and ecosystems, and the effectiveness of response options such as adaptation and mitigation under a wide range of future outcomes” [31]. Basically, the differences between them are the forcings introduced by multiple variables, including change of land use, climate change mitigation policies, energy usage, population, economic growth and emissions [34]. For CMIP6 they extended the old model of RCPs (Representative Concentration Pathways), which were used for CMIP5, by adding so called Shared Socioeconomic Pathways (SSPs). These SSPs add socioeconomic reasons for the assumed changes in land use and emissions.

SSPs are derived from five broad, abstract narratives, which are then quantified in different ways. So for example the narrative for SSP1 is:

“Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation) The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries.

Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.” [34]

while the narrative for SSP5 is:

“Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation) This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and

institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world.

All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.” [34]

These narratives are then quantified in multiple dimensions (resource availability, technical development, lifestyle changes, population, economic activity etc.). These quantifications then serve as an input for a range of integrated assessment models (IAMs), which turn them into the actual forcings needed (e.g. land and energy use, emissions) [34].

In the actual scenarios these pathways are combined with the additional radiative forcing (RCP, the earlier version of scenarios in CMIP5), resulting in a matrix which can be seen in Figure 3.1. RCP describes the level of radiative forcing (in Wm^{-2}) reached in the year 2100 (see Section 1.2). Although there are now 35 possible scenarios, O’Neill et al. defined two different tiers of scenarios ranked by their importance. Figure 3.1 lists Tier 1, which are scenarios mostly comparable to the old RCP scenarios. These scenarios are available in the MPI GE CMIP6, amongst some of Tier 2. [4, 31, 34]

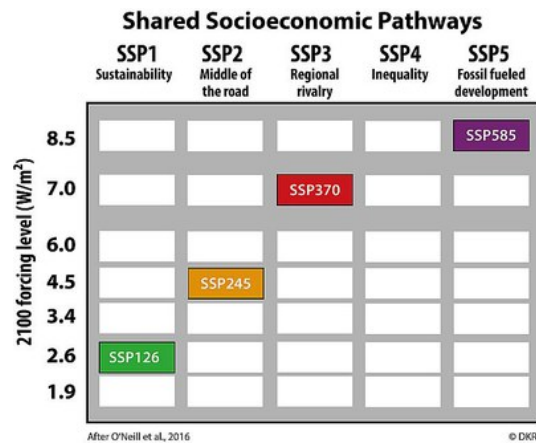


Figure 3.1: Combinations of SSPs and RCPs leading to scenarios comparable to the old RCPs [4]

3.2 DATASET DESCRIPTION

3.2.1 RESOLUTIONS AND DIMENSIONS

In terms of spatial resolution, MPI GE CMIP6 comes in three variants: The low resolution variant MPI-ESM1.2-LR with a horizontal resolution of roughly 1.8° longitude/latitude resolution in the atmospheric part and 0.4° lon/lat for the ocean, the high resolution variant MPI-ESM1.2-HR with a horizontal resolution of $1.0^\circ/0.4^\circ$ for atmosphere/ocean and the extreme high resolution MPI-ESM1.2-XR with $0.5^\circ/0.4^\circ$ for atmosphere/ocean. Each variant has a vertical resolution of 47 levels for the atmosphere and 40 for ocean. With increasing spatial resolution comes decreased availability of other variables like simulation members, covered time period, and implemented scenarios. Although [32] reports 30 members for each simulation (for the LR variant), in the actual dataset available for this work 50 member were simulated.

In terms of time resolution, MPI GE CMIP6 provides very few, limited variables in 3 hour intervals and most variables in a 6 hour interval. A full list of the variables can be seen in [32, Table 3], the variables necessary for this thesis are listed in Table 3.1.

Table 3.1: Variables necessary for this thesis, derived from [32]

Name	Parameter Long Name	Unit	Vertical Levels
<i>hus</i>	Specific Humidity	1	47
<i>ua</i>	Eastward (Zonal) Wind	ms^{-1}	47
<i>va</i>	Westward (Meridional) Wind	ms^{-1}	47
<i>ps</i>	Surface Air Pressure	<i>Pa</i>	1
<i>pr</i>	Precipitation	$kg\ m^{-2}s^{-1}$	1

3.2.2 VERTICAL HYBRID SIGMA PRESSURE LAYERS

Regarding the vertical levels, all variables were not available in fixed pressure layers but in so called *hybrid sigma pressure coordinates*. In comparison to fixed pressure layers (like 1000 *hPa*, 750 *hPa*...), hybrid sigma pressure coordinates follow the terrain (mountains, valleys etc.). Essentially, sigma vertical levels are given as fractions of the surface pressure P_S at any point, following the equations in [7]:

$$\sigma = h(p, P_S) = \frac{p - P_{top}}{P_S - P_{top}} \quad (3.1)$$

Here $p \in [P_S, P_{top}]$ is a pressure level. It was proposed that instead giving it at pure fractional levels, it would be better to smoothly converge from terrain following fractions

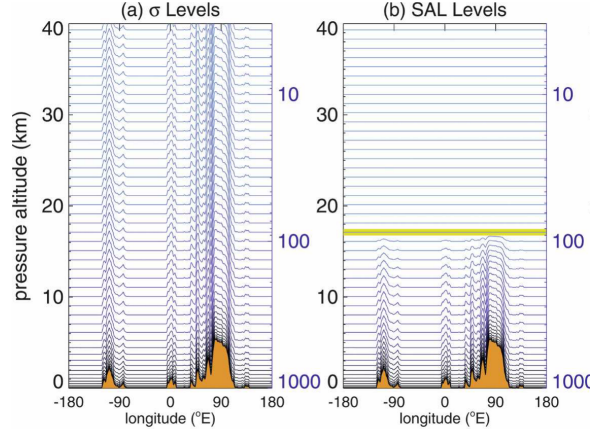


Figure 3.2: Examples of (hybrid) sigma pressure layers. a) shows sigma layers like in Equation 3.1, while b) shows a hybrid approach in the form of Equation 3.2 [7]

(sigma levels) at lower (meaning near the earth surface) levels to isobaric (= same pressure) levels in higher altitudes. This gives numerical as well as practical advantages. So there were alternative functions tested for $h(p, P_S)$, but a final form¹ for calculating pressure levels at any discrete sigma level $\tilde{\eta}$ is

$$p(\tilde{\eta}, P_S) = A(\tilde{\eta}) + B(\tilde{\eta})(P_S - P_{top}) \quad (3.2)$$

with $A(\tilde{\eta})$ being a vertical shift, which is close to 0 at low levels, and $B(\tilde{\eta})$ being a fraction of the pressure range $(P_S - P_{top})$.

This results in levels of equal pressure thickness, converging to isobaric layers at higher altitudes. Which exact form $A(\tilde{\eta})$ and $B(\tilde{\eta})$ took in the MPI GE CMIP6 could not be found in [32], but every dataset using hybrid sigma pressure levels contains the variables $ap(lev)$, $b(lev)$ and the field of pressure levels $ps(lon, lat, time)$, from which the pressure at any grid-point and level can be calculated with

$$p(lev, lon, lat, time) = ap(lev) + b(lev)ps(lon, lat, time) \quad (3.3)$$

The top pressure can be ignored in this dataset since the upper border is zero.

¹The equations that lead to to that can be seen in [7]

3.2.3 STRUCTURE OF THE DATA

The data is available in the HPC cluster of the DKRZ², the structure can be seen in if Figure 3.3.

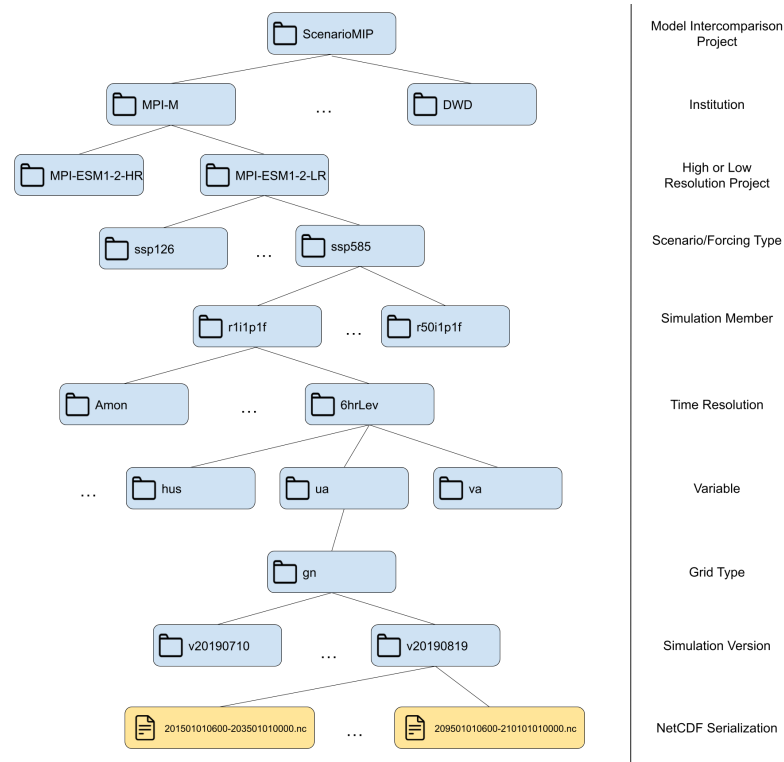


Figure 3.3: Structure the data is available on the DKRZ cluster. Example is given for ScenarioMIP, but applies aswell for CMIP DECK for historical and piControl.

It starts in a root folder for one MIP, being ScenarioMIP or the CMIP core, followed by the institution and the resolution category (see Section 3.2.1). After a hierarchy of Forcing Types (e.g. SSP, historical, piControl), member IDs, and time resolutions, the variable (e.g. *hus* for specific humidity) can be selected. After the grid type (only *gn* is available) the version directory contains the actual data, serialized in the NetCDF4 format (which in turn is based on HDF5 [11]) and split up in timescopes of up to 20 years. The version is named after the date of the simulation, and since a later version indicates a problem fix in the older version, it is generally advisable to pick the latest version for each variable.

Explain NetCDF datasets, chunking etc.

²Deutsches Klimarechenzentrum (en.: German Center for Climate Calculation)

4 RELATED WORK

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

4.1 MOTIVATION

As explained in Chapter 1, the approach of this thesis is motivated by the approach of Vietinghoff et al. in [47] and the affiliated dissertation [46], which tackles the issue of detecting critical points in unstable scalar fields. Hereby [47] analyzes the MPI GE [27] from the 5th phase of CMIP, an ensemble simulation with 50 members. The goal was to find the probable centers of pressure high/low in the NAO pattern (see Section 1.2) and to track their shift over time. They employed a sliding window approach, computing the dominant pattern (see Section 2.2) for each window and member, and determine the likely areas of critical points by merging the results of different members per time step. The centers of mass of these critical areas are then tracked over time to visualize the shift of the pressure high and low. The results show that the patterns do change, and this change is more pronounced if climate change is stronger. Also, there is no significant change if the climate remains stable.

4.2 MOISTURE TRANSPORT

To computationally extract any spatio-temporal patterns of moisture (transport), it first needs to be quantified in any way. The variable from the MPI GE CMIP6 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 grid point. The vast majority of literature regarding moisture transport use some form of vertically integrated humidity and the variants will be explained in the following section. A popular usage of these

quantifications was to find a filamentary weather structure called “Atmospheric Rivers”¹, a prominent way of water vapor transportation in the extratropic regions [15].

The most straightforward way of quantifying moisture is **Vertically Integrated Water Vapor (IWV)** [2, 15, 28, 40, 52], which is essentially the vertical integral of the specific humidity q over the pressure levels p from earth’s surface P_s to some upper limit in the atmosphere:

$$IWV = \frac{1}{g} \int_0^{P_s} q \, dp \quad (4.1)$$

Similar to Equation 4.1, Zhu and Newell proposed in [54] to use **Vertical Integrated Moisture Transport (IVT)** for Atmospheric River detection. It is calculated by vertically integrating over the different pressure levels the zonal (along latitude lines) and meridional (along longitude lines) fluxes. It became a popular metric for finding atmospheric rivers [15], sometimes alongside IWV [8]. IVT has the unit $\frac{kg}{ms}$ and is usually defined with

$$\overrightarrow{IVT} = \frac{1}{g} \int_0^{P_s} q \begin{pmatrix} u \\ v \end{pmatrix} dp \quad (4.2)$$

or in a mathematically equivalent form [10]. Here u and v stand for the zonal and meridional components of the horizontal wind vector. An equivalent way is to calculate the zonal and meridional component separately with

$$IVT_z = \frac{1}{g} \int_0^{P_s} q u \, dp \quad (4.3)$$

$$IVT_m = \frac{1}{g} \int_0^{P_s} q v \, dp \quad (4.4)$$

While Equation 4.2 yields a vector field, the Euclidean norm of said vector field

$$\|IVT\| = \sqrt{(IVT_z)^2 + (IVT_m)^2} \quad (4.5)$$

is also a popular choice in detecting atmospheric rivers [33, 43] and other use cases [1].

The IVT is also part of the atmospheric moisture budget [50] (and similar in [42]) given by

$$\frac{1}{g} \frac{\partial}{\partial t} \int_0^{P_s} q \, dp = -\nabla \cdot \frac{1}{g} \int_0^{P_s} q \begin{pmatrix} u \\ v \end{pmatrix} dp + E - P \quad (4.6)$$

¹Earlier or alternative name: “Tropospheric Rivers”

With E being the total evaporation and P the precipitation. Yang et al. showed in their report [50] the directions of moisture flux and its evolution in the last three decades. The analysis was done for all continental borders based on the big ERA5 reanalysis. The metrics used for this analysis were mostly the evaporation E , precipitation P and the moisture transport convergence $VIMC = \frac{1}{g} \int_0^{P_s} \nabla \cdot q \left(\frac{u}{v} \right) dp$ from Equation 4.6.

While the integration in the previous equations integrates from the surface to the outer border of the atmosphere (0 Pa), it is quite common to integrate up until the limit of 300 hPa [1, 16, 21, 54], since the amount of moisture in the regions from 300 hPa to 0 Pa is quite negligible and amounts in total to about 2-3 cm/year in terms of freshwater flux [53].

There are also some other notable other algorithms, namely stable oxygen isotope investigation [25] and langragian backwards trajectories [52], but both rather look for the origin of the water vapor instead of its destination and are therefor out of scope for this thesis.

4.3 PATTERN ANALYSIS REGARDING IVT

While there are many areas of interest for the application of EOF, this Section will give an overview what kind of pattern analysis has been performed in relation with moisture transport data. This is not just limited to patterns of moisture (transport), but also work calculating patterns of other variables (mainly precipitation) and linking/comparing those to the moisture (transport). An overview of datasets, timescopes and other metadata is given in Table 4.1.

Although most found related work uses EOF analysis, Teale and Robinson employ an approach using Self Organizing Maps (SOMs) to detect patterns of moisture transport in the eastern United States. SOMs are a machine learning approach to reduce data dimensionality, producing a 2D map of higher dimensional data. While they acknowledge the efficiency of EOF to extract dominant patterns, they emphasize the problem of required orthogonality of modes, which is not given for SOMs. The results show that fluxes with the highest moisture content occur less frequently than those with less moisture. But despite the higher moisture content, fluxes with lower moisture transport dominate water vapor movement due to their prevalence. Many of these fluxes meet typical criteria for atmospheric rivers, with varying trajectories and sources suggesting diverse mechanisms of formation. The temporal variability in monthly flux frequencies correlates with regional precipitation patterns, indicating that this approach is a valuable framework for studying precipitation changes [44].

CITE?

4 Related Work

Ayantobo et al. analysed the primary six modes of EOF in China, which was grouped in different regions for comparison. While the variances of IVT in eastern to southern China were quite high, the variances in northern China were quite low. It was shown by comparing the temporal patterns of the primary mode of EOF with the ENSO, that these patterns were related. The cross-wavelet coherence revealed that IVT and ENSO time-series were coherent, which implies that increased IVT was prevalent linked to increased ENSO activities [1].

Wypych et al. compares the patterns of precipitable water (IWV) in Europe for different seasons/months for the last ≈ 50 years. Similar to [1], Europe was grouped into different regions with different moisture conditions. This revealed significantly different moisture patterns for the regions, for example Northern Continental vs. Northern Atlantic. The results confirmed the expected important role of atmospheric circulation for the moisture in the winter by measuring the correlation, while relationships were substantially weaker for transitional months like April or October. Noticeable was also the lack of correlation between the atmospheric circulation and the moisture patterns in summer.

Published in 1982, Salstein et al. provided the first example of calculating EOF on IVT. Based on data from 91 weather stations, they computed the IVT of the whole northern hemisphere. Statistical significance was determined by employing a Monte Carlo testing method. EOF was computed on the IWV, the zonal and meridional IVT fields respectively, but they also evaluated an approach of combining both IVT components in one data vector. They reported the significance of the primary mode of IWV, encoding nearly half (44 %) of variance of the data.

Fernández et al. analyzed the precipitation modes in the mediterranean sea and linking them to the moisture transport in the same area. A goal of this analysis was to contribute to the understanding of the reduction of precipitation which happened in the area as well as to the low-frequency precipitation variability, leading to multiyear drought periods. They employed multiple methods of validating their data: The precipitation data as well as the wind/moisture data for IVT were validated with data from actual weather stations. The stability of the eigenvectors was tested with a Monte Carlo simulation, comparing the variability of actual data with random test data, while degeneracy of the EOF modes was tested using the method of North et al. [30]. Results of the analysis identify the interpretation of the three main precipitation modes: The first mode (22 % variance) seems to be linked to the NAO and Atlantic Storm tracks and associated moisture transports, while the second mode (16 %) represents the internal redistribution of moisture in the mediterranean basin between the eastern and western parts. The third mode (11 %) explains increased precipitation in the northern part of the domain. Additionally, moisture transport during positive

and negative phases of leading mode showed increased inflow of moisture from the west [10].

Similar to [10], Zhou and Yu analyzed the anomalous summer rainfall patterns over China and link them to water vapor transport. They confirmed their results by using a second dataset for IVT calculation. They showed that the primary mode of anomalous rainfall is associated with heavier rainfall in the Yangtze river region, while the same applies to the second mode and the Huaihe river. Connecting these patterns to moisture transport, they identified the different ways how these heavier rain areas are coming about by certain convergences of water vapor transports. Furthermore they compared the supply of anomalous rainfall patterns to the one of normal monsoon rainfall, revealing that those differ significantly [53].

In [16], the authors calculate rotated EOF on IVT data and try to analyze the relation between the 15 most dominant modes and the occurrence of atmospheric rivers (AR) on the USA west coast. For this they divided the coast into different regions and linked the activity (positive and negative) of the corresponding temporal pattern of each mode to the occurrence of atmospheric rivers. It was found that a few modes seem very influential for certain regions' AR activity, while others seem to play no role at all. They also identified favorable and unfavorable circulation states (e.g. amongst others a low pressure anomaly in a certain region) for AR occurrence [16].

Kim and Alexander showed in their analysis the connection of the IVT patterns in the western USA to three different ENSO events (eastern pacific El Niño (EPEN), central pacific El Niño (CPEN) and La Niña (NINA)). While EPEN events are associated with large positive IVT anomalies from the subtropical Pacific to the north-western USA, CPEN events lead to enhanced moisture transport to the southern USA. During NINA events the mean IVT anomaly is flipped in comparison to EPEN and CPEN. Furthermore it was shown that IVT patterns computed for these events differ significantly from the ones computed for neutral years. Furthermore the results were connected to precipitation anomalies on the USA west coast, showing huge differences (especially for the northern part of the coast) for EPEN and CPEN events. But the authors also emphasize that while the suggestions are strong, exceptions occur (e.g. one El Niño leading to a dry winter, another to the opposite) and need to be studied in greater detail.

Similar to [47] and the approach of this thesis, Zou et al. applied a sliding window approach to IVT patterns in the tropical Indian Ocean–western Pacific to analyze the evolution over time. For the studied period from 1961 to 2015, they studied every 20 year period with a 5 year sliding window, computing Multivariate EOFs for each window, resulting in vector fields of patterns. The results show that the two most significant modes show

significant changes in the mid 80s: The primary mode is characterized by a anti-cyclonic pattern in the north-western Pacific, which shifts significantly to the south. An analysis of the relation to sea surface temperature (SST) revealed that the correlation between the mode and SST rose in the mid 80s, from weakly correlated to significant positive correlation between IVT and SST anomalies. Furthermore, the primary mode seems to be regulated significantly by ENSO. The second most significant mode is related to the variability of the tropical Indian Ocean dipole (defined by the differences in average SST) [56].

A different approach was employed by [55], evaluating the EOF patterns of vertically integrated apparent moisture sink. Results indicate that the primary mode is a southwest-northeast oriented dipole, while the secondary mode is a southwest-northeast oriented tripole. The primary mode seems to be heavily regulated by the ENSO in the previous winter season, while the second mode seems to originate from internal atmospheric variability. Based on the much higher standard deviations in ENSO years, it seems that water vapor source and sink tend to be dominated by the primary mode in ENSO years, while the secondary mode is prevalent in non-ENSO years.

While the main focus of [51] is to evaluate and compare a regional air-sea coupled model, they also performed EOF analysis on the zonal and meridional components of IVT, respectively. They used the results to evaluate the connection to SST, revealing that the results from the regional coupled model aligns better with results from other datasets and reality than the regional uncoupled model.

Li and Zhou evaluated the connection of the IVT-EOF patterns to ENSO in the Asian western northern Pacific. They used a different approach than most in applying EOF to IVT, by concatenating the meridional and zonal components in one matrix and calculating EOF on it. To confirm their results, they compared the results with another reanalysis from the same (and a larger) region. Furthermore, these IVT patterns were linked to the SST. They revealed the characteristics of the two most significant modes, but most prominently they showed the quasi-4-year coupling of the two most prominent modes with ENSO [23].

4.4 UNCERTAINTY VISUALISATION

Since the used dataset (see Chapter 3) is an ensemble simulation consisting of 50 members, most of the figures and other visual representations in this thesis need to display the uncertainty stemming from them. This section summarizes advances fitting for this topic, giving a frame of references of current possibilities of visualizing uncertainty.

Kamal et al. give a recent overview over the whole topic of uncertainty visualization: From the introduction to the whole concept of uncertainty, to the differentiation between

Table 4.1: Overview table of patterns with moisture transport

Release Year	Pattern extraction	Area of Interest	Timescope	Time Resolution	Studied Season	Variable used for EOF
2020 [44]	SOMs	USA east	1979 to 2017	daily	all year	IVT norm
2022 [1]	EOF	China	1979 to 2010	daily	all year	IVT norm
1982 [37]	EOF	Northern hemishpere	1958 to 1973	monthly/yearly	all year	IWV, IVT_u IVT_v, combined
2003 [10]	EOF	mediterranean sea	1948 to 1996	6hr	DJF	P
2005 [53]	EOF	China	1951 to 1999	monthly	JJA	P
2018 [16]	EOF	USA (west coast)	1948 to 2017	daily	NDJF	IVT norm (assumed)
2015 [21]	EOF	western USA	1979 to 2010	6hr	DJF	IVT norm (assumed)
2018 [56]	EOF	TEIOWP	1961 to 2015	monthly	JJA	IVT
2020 [55]	EOF	TEIOWP	1958 to 2018	6hr/monthly	JJA	Integrated Water Vapor Sink
2013 [51]	EOF	East Asia	1997 to 2002		JJA	IVT_u IVT_v
2012 [23]	EOF	East Asia	1979 to 2009	monthly	summer	IVT
2018 [49]	EOF	Europe	1981 to 2015	daily	all year	IWV, SLP

different kinds of uncertainty in the visualisation process. They grouped all kinds of representing uncertainty in two categories: quatification, consisting of mostly mathematical approaches of handling uncertain data, and visualisation, displaying the uncertain data in a way directly. An overview of the different kinds of uncertainty visualization were given: Manipulation of attributes (like shading), animation, visual variables (like color, hue, brightness), graphical techniques like box/scatter plots and glyphs. Furthermore, recent advances in uncertainty visualization are given, with a special emphasis on ensemble (simulation) data, big data and machine learning, listing the most prominent areas where the presentation of uncertainty is crucial. In the end, a framework for evaluating uncertainty visualization is presented, followed by an overview of possible future research directions [20].

A way of using animation to display uncertainty in scalar fields was shown by Coninx et al. Their goal was to enrich the usual display of scalar fields with colormaps with additional uncertainty information. The tool of choice here was animated Perlin noise, and the uncertainty was presented by modifying the noise mask with the uncertainty information at each point. The results were tested using a psychophysical evaluation of contrast sensitivity thresholds [6], evaluating effective parameters for proper presentation of the uncertain area [6].

Sanyal et al. proposed Noodles, a tool for displaying uncertainty in weather ensemble simulations. It employs three different ways of displaying uncertain isocontours: ribbon, glyphs and spaghetti plots. Additionally, they added tools for exploring the uncertainty of datasets, like an colormap of the whole dataset uncertainty. Uncertainty in spaghetti plots is clear (one line per member), but gets confusing and chaotic quickly. The glyphs display the uncertainty by different sizes, and can be displayed on the whole map or alogside means of isocontours. Ribbons condense the information of multiple lines by adapting the

ribbon width to the uncertainty of isolines at a specific gridpoint. The resulting tool was tested by two meteorologists, and classified the results as beneficial [38].

Another way of visualizing groups of isocontours are contour boxplots proposed in [48], grouping isocontours together in a similar way like conventional boxplots. This means that the easiest default presentation (spaghetti plots) is replaced by popular boxplot stats: The median, the mean, the quartiles around that mean, the whole range and the outliers (not part of the whole range). But the implementation is not as straight forward as in conventional boxplots. To quantify the aforementioned statistics, Whitaker et al. propose a data depth based approach, which encodes how much a particular sample is centrally located in its function (or in this case: How central is a isocontour to a whole set of isocontours). While the results look very promising, it lacks a publicly available implementation, making it hard to use the approach.

4.5 POSITION OF THIS THESIS

As shown in Section 4.3, Empirical Orthogonal Functions are a relatively popular tool for analysing spatiotemporal patterns in moisture transport. While mostly applied to water vapor transport in South East Asia and the Chinese Sea, there is not much coverage of the European Area, and especially the larger scope of the north east Atlantic. Additionally, there has been no EOF IVT analysis for ensemble-scale data, just for reanalysis data (see Table 4.1) or actual weather station data. To analyse the evolution of spatio-temporal patterns is also quite underrepresented, since most approaches apply the pattern analysis on the whole available dataset (in most cases around 50 years), exeptions are the motivational work for this theses from Vietinghoff et al. and [56]. Additionally, to my knowledge no future scenario pattern analysis has been performed with IVT, especially not with data from CMIP datasets.

In terms of uncertainty visualization, most of the presented approaches could be quite useful in this thesis: The animated Perlin noise from [6] could be used to show the uncertainty in the scalar fields, while the ribbons and contour boxplots can be used to represent contours in the patterns (see Section for the descision of the feature extraction). Unfortunately, none of these algorithms is available as a library , which hinders applicance to a great extent.

ref to feature
selection section

double check if
this is true

5 METHODOLOGY

5.1 OVERVIEW

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

5.2 PREPROCESSING

The purpose of this step is to prepare the datasets for generating the patterns via EOF and generating visualizations. For this the datasets need to be reduced to the area of interest (northern Atlantic and Europe), the directory structure shown in Figure 3.3 needs to be simplified, the necessary moisture transport (see Section 4.2) needs to be calculated and data needs to be reduced to different time resolutions (daily, monthly).

The calculations were performed on the high performance computing cluster¹ 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 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 occurred in.

Still need to write somewhere why

5.2.1 CHOSEN FRAMEWORK

The goal of this step is to prepare the data for further usage. After a few failed attempts with other languages/tools (CDO and Julia, see Section 5.2.3), the Python libraries xarray [17] and dask [36] were chosen as the fitting tools for this step. Xarray is a library

¹<https://docs.dkrz.de/doc/levante/>

for handling n-dimensional, labeled arrays. It supports multiple input and output options (amongst others the required NetCDF format) and is compatible with the most popular scientific Python libraries (e.g. Pandas, NumPy). It comes with a great variety of features, making it easy to index and transform data and dimensions, joining different datasets (either along a dimension like time or multiple different variables having the same dimensions) and many more. But most important, it leverages the Dask library, which enables xarray to actually use the infrastructure of the DKRZ HPC cluster. Dask is enabling parallel and out-of-the-core² computing for the Scientific Python stack. Its goal is to be a NumPy clone leveraging the full potential of modern hardware, which usually utilizes multiple computing cores, without the need for rewriting the already existing scientific Python stack. It uses an acyclic task graph, which distributes tasks efficiently over multiple workers, which can be either different threads or processes. [36]

5.2.2 PROCESS

The following the process for handling one timescope of member of one scenario is described. For one member the different timescope files are handled iteratively. Scaling it up for all the members is trivial by either running them in parallel on multiple nodes of the cluster (for the relatively computation-heavy IVT calculation) or by running different members iteratively (for simple variables). The high resolution of 6 hourly data is used at first for all the variables since it can be trivially reduced to daily/monthly means later.

1. Loading the Dataset

In the first step the process is to load the required dataset(s) into xarray. This means not actually loading the grids into RAM but rather loading the metadata. The actual loading and computation is only performed when required (e.g. when writing the result), every step in between only returns another xarray dataset. Xarray offers different methods for either loading one dataset file or multiple, the latter is needed for the IVT calculation since multiple different variables need to be used. Important choices are here setting the `compat` parameter and choosing the chunking for Dask. The first one needs to be set to `override`, which prevents xarray to check variables with the same label for compatibility (in this case here dimension like *lon*, *lat*, *time* and the pressure fields *ps*), which is useful e.g. when using dataset of different sources, but since all datasets conform to the same resolutions it is unnecessary.

The latter choice is far more important: In NetCDF datasets data is often grouped into chunks of a certain, useful size and these chunks can then be compressed to reduce disk

²This usually means handling datasets larger than RAM, using disks (usually SSDs) as extension for RAM.



Figure 5.1: Example of the general overview of the dask dashboard used for analyzing the efficiency of the process.

memory usage. If the chunks are compressed reading anything smaller than a chunk is useless, since the whole chunk needs to be loaded anyway to decompress it. Also reading too small chunks reduces the efficiency of dask, since the introduced scheduling overhead per task is too large and becomes overwhelming. Furthermore, reading too small chunks result in too much worker-to-worker communication, which also results in significantly decreased execution time. On the other hand, reading too large chunks results in memory spills³ or workers crashing, which both significantly reduce execution time. To find the sweet spot of dask chunk size, dask offers a handy dashboard which visualizes the process of the dask task graph execution (see Figure 5.1). Grey areas in the *Bytes stored per worker* section in Figure 5.1 show memory spilled to disk, which is an indicator for too large chunk sizes. Red sections in the *Task Stream* section refer to worker-to-worker communication, which may be an indicator for too small chunk sizes if they dominate the *Task Stream*. So the Task overview given in Figure 5.1 indicates a slightly too large chunk size, since too much is spilled to disk. [5]

The chunk size in the available datasets is $(192, 96, 47, 1)$ ⁴, which means one chunk corresponds to one time snapshot of the whole atmosphere. Following the previous argumentation, the only useful way of changing the chunks are different amounts of time snapshots per chunk. Using the dask dashboard to evaluate different chunk sizes, the optimal chunk

³This refers to a function in dask where overloaded workers save data on disk to prevent the worker from crashing

⁴Referring to $(lon, lat, lev, time)$

size with minimal spilled memory, worker communication and no crashing workers⁵ was (192, 96, 47, 128)⁴.

2. Reduction to Area of Interest

The next step is to cut out the geographical area of interest, which is the northern Atlantic and Europe. Following [47] and [18], it was defined as $90^\circ W - 40^\circ E$, $20^\circ - 80^\circ N$. Unfortunately for this case, the longitude coordinate is saved in the range of $[0, 360]^\circ$, so it can't be loaded as one slice. Therefor, the longitude coordinates are first transformed to the form $[-180, 180]^\circ$, with negative values being $^\circ W$ and positive values being $^\circ E$. Then the area of interest can be cut out without problems and the result can either be used for further calculations (Step 3) or directly saved as a NetCDF file (Step 4).

3. Calculating IVT Field

The first step to calculate the IVT field is to convert the hybrid sigma pressure levels (see Section 3.2.2) to actual pressure values. For this Equation 3.3 is used for calculating a new variable `plev` containing the pressure values at each gridpoint in each timestep. Then NumPy's trapezoidal integration function is used to calculate the zonal (Equation 4.3) and meridional (Equation 4.4) components of the IVT. Similar to related literature [1], a constant value for the gravitational acceleration $g = 9.806 \text{ ms}^{-2}$ is used in the calculation. Using the result of the zonal and meridional components, the norm field $\|IVT\|$ can be calculated using Equation 4.5.

4. Saving Results to NetCDF dataset

The results of these calculations (or the geographical box cutout) are then again saved as NetCDF files, in the far less complex directory structure `time_resolution`, `variable`, `member` and then the actual file `timescope.nc`. In case of the IVT, both (zonal and meridional) components are saved alongside the Euclidean norm.

5. Generating daily/monthly means

Since the related literature does not entirely agree regarding the timely resolution of IVT in EOFs (see Table 4.1), the six hourly data is reduced to monthly and daily means using CDO. Monthly IVT is also called stationary moisture transport and dominates the total water vapor transport [53], while the anomalies (departures from monthly mean per daily/subdaily timestep) are transient components. Both are important parts of total moisture transport, but since a comparison of stationary and transient components is beyond the scope of this thesis, only monthly data will be used for the further analysis. The higher resolutions are still saved and can be used in future work.

⁵For one of the DKRZ HPC cluster's nodes with 100 GB RAM

5.2.3 PROBLEMS WITH PREPROCESSING

The steps described in the section before were just the final attempt. The first idea was using Climate Data Operators [41], a command line tool containing multiple operators for processing climate and similar data. The operators consist of common statistical and mathematical functions (mean, add, sum), sampling and data selection tools (select geographical or time limits) and other helpful operators like interpolations and even EOF calculation. Although this sounded very promising, it quickly turned out to be very complicated to implement the desired vertical integration in CDO. The following idea was to implement the IVT calculation in Julia [14], using just a NetCDF library [] while the rest was coded from scratch. The algorithm was very simple:

1. Load all datasets into the RAM (as recommended by the NetCDF library itself) and cut out the used geographical limits. This should be feasible since all in all one dataset for one timescope-file accounts for $\sim 12\text{ GB}$ ⁶, so the maximum is around 36 GB , since the surface pressure data is not that large ($\sim 260\text{ MB}$)
2. Calculate the IVT with trapezoidal integration multithreaded by handling one time-step by one thread
3. Write the results (Euclidean norm and the meridional/zonal component)

Although Julia promises high performance, it performed quite poorly on the HPC. The reason for this is the slow IO on the cluster: While the calculation itself took only $\sim 235\text{ s}$ ($\approx 4\text{ min}$)⁷, the loading of the required datasets took around $\sim 3350\text{ s}$ ($\approx 55\text{ min}$). This results in roughly $5h$ (including saving the data to disk) for one member of ScenarioMIP, which leads to 250 h node hours for one scenario. Taking into account that it needs to run for historical simulations as well as other scenarios, this was not feasible according to the limited node hours provided⁸.

To reduce the loading time of the data multiple optimizations were evaluated. First, the amount of moved data in memory was minimized by preallocating the needed RAM and writing directly to the preallocated space. Furthermore, other NetCDF libraries were tested, but simple loading times were very similar. Although this significantly reduced the amount of allocations, the effect on loading time was negligible. To actually archive a significant boost in loading time it was tried to load the required datasets (located in different files) in parallel. Unfortunately, the used library [3] encountered a segmentation fault

⁶ $70\text{ lon} * 32\text{ lat} * 47\text{ levels} * 29220\text{ timesteps} * 4\text{ byte} \approx 12\text{ GB}$

⁷Referring here and in the following to one timescope of 20 years in one member

⁸Also taking into account that the processes may need to run multiple times due to errors

used in multiple threads, so the alternative libraries NetCDF.jl and HDF5.jl were explored, since the HDF5 standard allows parallel access to files [11]. Although the parallel access to files using multiple threads (with HDF5.jl) lead to increased speeds in tests, the results did not yield any significant increased efficiency on the cluster itself. Even splitting up the loading according to the chunking in the files (all data from one timestep is one chunk) and loading each timestep separately in one thread even increased the data loading time quite far. The next approach was to split the task up into different processes, each one loading data from one variable. This actually reduced time spent to one third in tests, but testing it on the actual data sizes revealed that the 12 GB are too much to be returned from the child processes loading the file to the mother process.

From here on some other approaches could have been explored, like splitting up different time steps amongst different processes, but the far more suitable method of using xarray and dask has been found and implemented.

5.3 EOF CALCULATION

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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