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Transboundary Storm Risk and Impact Assessment in Alpine Regions

REPORT ON STORM HAZARD AND CLIMATE CHANGE

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Table of Contents

[2] https://ajdawson.github.io/eofs/latest/

1. Introduction

In order to devise an improved operational framework for storm risk assessment, the basic relationship

EVENT -> HAZARD INTENSITY -> IMPACT (DAMAGE, LOSS)

has to be thoroughly investigated. Here, for the moment and for the sake of simplicity, we are omitting the exposure and vulnerability components that drive the relation between hazard and impact.

It is clear that the three concepts "EVENT", "INTENSITY" and "IMPACT", individually are clearly definable. Intuitively we can outline them in an abstract way as:

EVENT: temporary perturbation or the state (of a system) with a defined spatio-temporal footprint (i.e., a geographical boundary and a duration) and a set of measurable environmental conditions (parameters) which are defining and describing the event itself.

INTENSITY: level of measured or estimated intensity of one or more of the environmental parameters that contribute to characterize the event. Intensity is defined and possibly varying continuously over (geographical space) and time. In the case of storms intensity could refer to precipitation rate and cumulated amount, speed of wind gusts, etc.

IMPACT: set of (adverse) consequences of one event over people, assets, infrastructure, systems. More specifically in the context of TRANS-ALP we are interested in adverse direct and indirect consequences (fatalities, injuries and displaced people, physical damage to properties and infrastructure, interruption of services and businesses and other systemic disruptions). Impact can be defined in terms of individual items, each possibly identified by location and timestamp (or duration), type and severity.

In the course of deliverable 2.2, we laid the focus on the identification of extreme events affecting the cross-border region between Austria and Italy. Within this deliverable, gridded precipitation data for Austria and South Tyrol were used for the purpose of event identification.

The analyses of D2.2 identified 12 events between 1980 and 2020 whose dates of occurrence as well as the local maximum in South Tyrol (ST) and Austria (AT) are depicted in the following table:

Event date	Local max (AT)	Local max (ST)
18.07.1981	157,7	128,5
31.01.1986	166,6	162,9
25.11.1990	93,60	173,4
02.10.1993	151,0	144,3
20.09.1999	157,2	144,6
01.11.2003	158,7	127,3

[2] https://ajdawson.github.io/eofs/latest/

29.10.2008	92,0	148,0
27.05.2011	91,5	150,6
05.11.2014	248,1	195,7
25.08.2018	72,7	119,7
29.10.2018	212,0	184,6
01.02.2019	103,2	240,5
15.11.2019	118,6	166,3
29.08.2020	115,30	107,4
05.12.2020	251,5	274,4

Tab. 1 – events selected as significant according to the 99th percentile methodology

Extreme events like the above mentioned are expected to alter in frequency and magnitude along with climate change (IPCC). The perception and awareness of stakeholders regarding the impact of climate change has increased significantly in recent years. Therefore, mitigation measures focusing on the elimination of greenhouse gas emissions need to be complemented by adaptation efforts to reduce the vulnerability of the system and increase its resilience to the impacts.
The derivation of future changes in the occurrence of such weather events until 2100 may, thus, serve as a basis for designing appropriate adaption programs. These changes depend on which scenario mankind follows throughout this century, e.g., SSP3-RCP7.0 which depicts an energy intensive development that is mostly covered using carbon fossil fuels or the SSP1-RCP2.6 scenario, which represents the timely and drastic reduction of GHG emissions to keep global warming below two degrees by the end of this century in comparison to the second half of the 19th century.

A central step in the assessment of future hazard threat potential is the change in the occurrence of weather patterns that trigger hazardous damage events. Those weather patterns are described by so-called hazard trigger patterns (HTPs) that depict the preceding weather development. While those HTPs are addressed in this deliverable, deliverables 2.3 and 2.4 focus on future developments of these patterns via the establishment of so-called hazard development corridors (HDCs), that depict the frequency changes of HTPs.

The identification of HTPs may be done subjectively based on expert knowledge through the definition of certain thresholds, e.g., precipitation thresholds for a number of days until the considered hazard event takes place, see Guzzetti et al., 2008, or objectively by applying multivariate statistical techniques linking observed weather developments to hazard occurrences (Enigl et al., 2019). For the latter approach, however, the available data must meet specific requirements. As extreme events are rare, data should be of high spatio-temporal density and quality as well as stretch many decades back in time to allow for a robust statistic. Temporal extent is of outstanding importance because three decades, e.g., are already required for determining climate (WMO, 2017). Hence, describing rare events far off the average requires substantially more observations. Unfortunately, both prerequisites concerning weather observations as well as hazard occurrences are nearly never met. Therefore, it is important to establish a solid data basis allowing for statistically robust analyses.

In the course of this deliverable, this premise requires us to not only consider the damage events induced by the extreme events identified in D2.2 for the derivation of HTPs, but to use all recorded

[2] https://ajdawson.github.io/eofs/latest/

damage events in the target region from 1961 onwards. As of this year, the highly-resolved gridded observational dataset SPARTACUS is also available on a daily basis with a spatial resolution of 1 km, covering both target regions East Tyrol and Carinthia as well as South Tyrol.

Hence, the focus of Deliverable 2.1 is twofold. First, establishing a solid database of hazardous damage events and second, creating a relationship between the 'event component' and the 'impact component' by identifying characteristic precipitation patterns that can potentially induce damaging weather events based on historical records. Particular attention is thereby given to damage events caused either by floods or gravitational mass movements, i.e., slides and flows. Furthermore, the limit of predictability using this approach is discussed. Further emphasis is laid on limited predictability as well as on the potential of the HTP approach for retrospective numerical simulations oriented to risk assessment.

2. Data

o Austria

Damage Data

WLK

The Austrian Service for Torrent and Avalanche Control ("Wildbach und Lawinenverbauung" (WLV)), founded in 1884, is a subordinate agency of the Austrian Federal Ministry of Agriculture, Regions and Tourism (BMLRT). WLV traditionally deals with torrents and avalanches, which mainly occur within the alpine region. Amongst WLV's tasks are: declaration of danger zones potentially yielding settlement-prohibitions, civil protection management and providing advisory capacity towards climate-change adaption. These (and many more) responsibilities require diligently collected long-term records of hazard-processes that are compiled in the "Wildbach- und Lawinenkataster (WLK)" (WLV, 2017). It covers fluvial sediment transport processes, which are floods containing amounts of solids up to one fifth their volume; debris-flow-like processes – as before, but with a fraction of solid material exceeding one fifth; mud flows, carrying solid contents exceeding 50%; flooding; and surface water. Landslides are distinguished into rotational slides, which are movements exhibiting a rotation about an axis parallel the slopes; translational slides, i.e. slides with negligible rotation; earth- and debris flows, where the material sliding down is subjected to strong deformation; shallow landslides; individual blocks with block sizes up to 1 m; large blocks with sizes exceeding one meter; as well as rock creeps (Enigl et al., 2019).

GEORIOS

Founded in 1849, the Geological Survey of Austria ("Geologische Bundesanstalt" (GBA)) is a subordinate agency of Austrian Federal Ministry for Education, Science and Research (BMBWF). Fields of activity encompass geological mapping, process-monitoring and issuing of maps featuring high-risk areas for planning purposes. Just as in case of WLV, the accomplishment of GBA's governmental obligations requires a highly dependable, comprehensive, and statistically robust data basis. Such sound, conscientiously collected, long-term records of damage-events are compiled in "Geologischen Risiken Österreich (GEORIOS)" database (Tilch et al., 2011). Therefore, various observation systems are employed. Amongst these are, for example, remote-sensing, field surveys, geographical photographs, systematic expert-inventories of indexed areas, reports from the population and the

[2] https://ajdawson.github.io/eofs/latest/

digitization of historical archives. To avoid inhomogeneities, which may result from different formats, quality criteria and degrees of information content, GBA devotes a substantial fraction of its resources to maintain an extensive quality assurance program, ensuring just that. GBA-records used in this study start in 1950 and cover the following gravitational processes: slides, flows, falls, general mass movements, mass movements in loose rock, and complex large-scale movements (Enigl et al., 2019).

Meteorological data

Weather data are taken from SPARTACUS, the “Spatiotemporal Reanalysis Dataset for Climate in Austria” (Hiebl and Frei, 2015; 2017). It provides high-quality, daily temperatures and precipitation-totals from 1961 onwards on a 1 km grid across Austria and South Tyrol. SPARTACUS has been generated in an international collaboration from irregularly distributed weather stations maintained by ZAMG, has already found application in several studies (Duethmann and Blöschl, 2018; Schroeer and Kirchengast, 2018) and is operationally kept up-to-date at ZAMG (Enigl et al., 2019).

○ TRENTINO – SOUTH TYROL

EURAC Research has provided us with the following databases comprising damage events induced by both hydrological and geological processes.

ED30 hydrological event data base

The “Event Documentation of the 30th Division of the Autonomous Province of Bolzano (ED30)” (Macconi and Sperling, 2010) started in 1998. Over the years, the ED30 system, which allows organized and standardized surveys of hydrogeological events on watercourses (floods, debris flows, landslides, falls and avalanches), has been continuously improved. After the notification of an event that has occurred, the investigation procedure starts with the dispatch of a documentalist and, if necessary, with the organization of a reconnaissance flight with the helicopter. The field work includes the collection of the main data of the process, the photo documentation and the elaboration of maps in the appropriate scale (at least 1:25,000). All these data are further digitized and archived in a database structured in modules. This dataset is a mere event database comprising over 1700 hydrological events in South Tyrol. Its 14 attributes contain information on the exact location (point geometry) and time on a daily basis of the event, details on the prevailing processes as well as on the affected water bodies; information about damages induced by these hazards are not included in this database. The ED30 hydrological event data base comprises the following hazard categories: “Overbank sedimentation”, “Landslide”, “Flood (inundation)” and “Urban flood”.

IFFI

The Geological Survey of Italy manages the national Italian landslide registry (“Inventario dei fenomeni franosi in Italia (IFFI)”). This inventory aims at identifying and mapping gravitational mass movements over the whole Italian territory, following standardized criteria.
This very comprehensive dataset includes over 11 000 landslide events characterized by 174 attributes for South Tyrol. These comprise information on the geographic location (district, municipality, point geometry), the type of hazard and its activity status, as well as - in about one fifth of entries -

[2] https://ajdawson.github.io/eofs/latest/

the exact date of the event. Other features deal with the damages induced by these events: personal injuries (deads, evacuated or injured), physical damages (e.g. to critical infrastructure) and costs. It has to be mentioned that not all information is available for every event. Regarding hazard categories, IFFI differentiates between
"fall/topple", "rotational/translational slide", "complex", "fast flow", "deep-seated movement", "slow flow", "area with diffuse falls/topples", "area with diffuse shallow slides", "subsidence" and "area with diffuse subsidence".

○ VENETO

We have also received event or damage data for Veneto from EURAC Research. These very detailed and rich databases contain a wealth of information about gravitational mass movements such as the prevailing hazard, the affected municipalities and the exact location. Unfortunately, these records do not contain information about the event date. Thus, they are regrettably not useful for the subsequent analyses and will not be further considered. A small exception are the records about VAIA, in which the event date is included. However, these events are too few to allow a statistically robust derivation of HTPs.

3. METHODOLOGY

○ COMPILATION OF THE EVENT SPACE

As previously noted in the data section, different hazard categories are used within different data sources. In order to integrate these data sets into one, the application of a uniform vocabulary is essential. For this deliverable, the vocabulary from the code list "Specific Hazard Type"[1], an extension of the Austrian Inspire Registry established within the CESARE project[2], is used.

<u>WLK and GEORIOS</u>
In the case of the Austrian data sources "WLK" and "GEORIOS", we combine WLK's processes "fluvial sediment transport (*Fluviatiler Feststofftransport*)", "debris-flow-like processes *(Murartiger Feststofftransport*)", "surface water (*Oberflächenwasser*)" and "floods (*Hochwasser*)" into the main category "floods". In terms of gravitational mass movements, we merge GEORIOS' "deep-seated gravitational slope deformations (DSGSDs) *(Tiefgründige Hangdeformationen*)", "medium-depth slope deformations (MDGSDs) *(Mittelgründige Hangdeformationen)*", "shallow landslides *(Seichte Hangdeformationen)*", "hillslope debris flows (*Hangmuren*)", "earthflows (*Erdströme*)", "debris avalanches (*Schuttströme*)" and "debris flows (*Muren*)" as well as WLK's "earthflows and debris avalanches *(Erd- und Schuttstrom)*", "mud flow *(Murgang)*", "shallow landslide *(Hangmure)*", "translational slide *(Translationsrutschung)*" as well as "rotational slides *(Rotationsrutschung)*" into "mass movements – slides/flows".

[1] https://registry.inspire.gv.at/codelist/SpecificHazardTypeValue
[2] https://projekte.ffg.at/projekt/3307382

~~[2] https://ajdawson.github.io/eofs/latest/~~

South Tyrol
With respect to the South Tyrolean data sources, the processes “rotational/translational slide”, “fast flow”, “area with diffuse shallow slides”, “complex”, “slow flow”, “deep-seated movement” and “mud flow *(Murgang)*” have been added to the main category “mass movements – slides/flows”. Regarding hydrological hazards, “overbank sedimentation *(Übersarung)*”, “Flood (inundation) *(Überschwemmung - Hochwasse* (sic!)*)*” as well as “urban flooding *(Urbane Überschwemmung)*” have been merged to the main category “floods”.

The resulting data set is stored in long-form in a Geopackage file, featuring the following attributes: (i) “date” representing the event date, (ii) “category” describing the main category, (iii) “season” differentiated between MAM, JJA, SON or DJF, (iv) “region” giving information on the target region (ST or ET-C) and (v) “geometry” representing the location of events as point locations.

○ Derivation of Hazard Trigger Patterns

Derivation of Hazard Trigger Patterns (HTPs)
The objective derivation of HTPs is based on the intersection between damage data and meteorological data. In order to perform this derivation, an event time and an event location (ideally as a point localization) must be known for each event in the damage dataset. For each event, the nearest grid point in the gridded meteorological dataset is then identified and the mean between it and its four nearest-neighbours is calculated. This is not only done for the event day, but also for the precedent week. This information is stored in a n x 8 matrix; n representing the number of events and 8 illustrating the precipitation values in the vicinity of the event on the target day and the week before. Subsequently, the eigenvectors for this matrix are determined, representing the sought-for hazard trigger patterns. The associated dimension, in which the subsequent EOF analysis is applied, is an abstract 'event index'. The EOF pattern itself is derived in the time dimension, based on the sequence of preceding events. Hence, the EOF patterns represent a weather sequence with a corresponding index in the form of the event occurrence day, called 'target day', or ‘t-0’, as well as the preceding days ('target day minus one', ‘t-1’, up to 'target day minus 7', ‘t-7’).
In general, this approach has a number of degrees of freedom, which depend on a specific application and can be determined in a validation procedure (see section “Limit of predictabiliy” for further details).

The workflow to calculate HTPs can thus be summarized as follows:

- Determination of plausible predictors for the investigated hazard-event
- Blending climate and damage data, i.e. setting up a matrix consisting of n rows for n events and 8 columns representing the precipitation at the event’s location on target day and the precedent week ;
- Conduction of the EOF analysis
- Extraction of the significant EOF patterns i.e. the Hazard Trigger Pattern using e.g. North's rule of thumb for EOF significance (North et al., 1982).

Within this deliverable, we derive HTPs for two categories, i.e., mass movements – slides and flows as well as floods. We do that separately for both target regions East Tyrol-Carinthia in Austria and

[2] https://ajdawson.github.io/eofs/latest/

South Tyrol in Italy. As we want to investigate potential seasonal differences, we derive HTPs for every season. Therefore, we conduct in total 16 different analyses and yield 16 different hazard trigger pattern which are dependent on hazard, region and season.

The employed algorithm is implemented via Python and stored via a git version-control system. The principal component analysis is conducted using the eofs package[2], which is based on Singular Value Decomposition (SVD).

Validation

In general, a validation procedure consists of training a model on a subset of the data and testing it against the complementary, independent ('unseen') subset of the data. Other, so-called, split-sample techniques are e.g. leave-one-out cross validation (a model is trained on all data points but one which is then used for testing and the whole procedure is repeated for every data point), *k*-fold cross validation (split the data into *k* groups, train on *k-1* groups, test on the one left out and repeat *k* times), or bootstrapping (random resampling with, or without replacement for a subset of the available data and repetition of this procedure for *n* times). The latter is especially useful if the sample size is low. A comprehensive overview on different validation techniques can be found in e.g. Hastie et al., 2009.

For the validation procedure, the EOF pattern is calculated using the training, as well as the full data. The EOF patterns can then be evaluated in their robustness (i.e. does the pattern change substantially?). Furthermore, the calculated PCs of both samples can be evaluated for the congruent events. Most importantly, the subset of the data which was left out for the training set can be projected into the EOF space, which nets, so called, 'Pseudo Principal Components (PPCs). These can then be compared to the underlying 'base' state of PCs (again using the subset of congruent events), which is given by the PCs calculated from the full data. Thereby, the predictive power of the training EOF pattern is evaluated. Positive results suggest robust and significant EOF patterns, which allows them to be used reliably for climate projections. The validation workflow is depicted in figure 1.

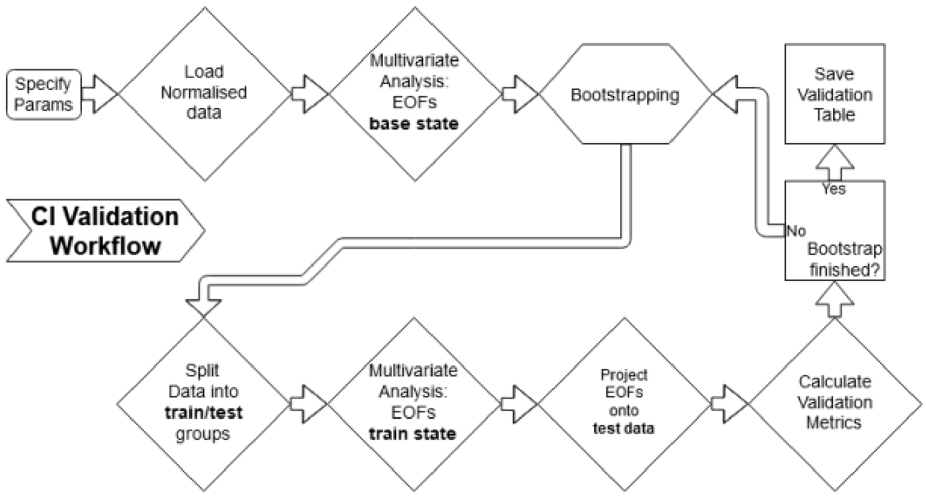

Fig. 1: Schematic flowchart for the validation of the HTP model

[2] https://ajdawson.github.io/eofs/latest/

○ Limit of predictability

To assess the limit of predictability, reconstructed precipitation patterns via the HTP-model can be compared to the observational data and thereby validated. Correlation coefficients between those are calculated for each combination of region, category and season to allow distinct quantification of model performance.

4. Results

○ Event Space

Combining the data sets of the WLV and GBA for Austria with those of the IFFI and the ED30 database for South Tyrol and subsequently applying the translation scheme of the established vocabulary results in the event space used for further analyses. The event space covers the period from 1961 to 2021 and stretches over Carinthia and East Tyrol in Austria as well as South Tyrol (Alto Adige) in Italy.

This newly established database includes 1302 events on the Austrian side; 672 of them describe flood events, 633 entries relate to mass movements – flows and slides. In the case of South Tyrol, the event space comprises 623 flood events and 2229 mass movements.

Figure 2 illustrates the spatial distribution of events, differentiated between hazard categories. The spatial density of flood events is highest in East Tyrol and in the border region to South Tyrol. The detailed figure for the recorded mass movements reveals the richness of the IFFI database for South Tyrol, covering nearly the entire South Tyrolean territory. The spatial coverage of events in Carinthia is considerably lower for both hazard types. A large number of flood events occur along the largest rivers in Carinthia; other flood events refer to small Alpine torrents.

The seasonal distribution of events for both hazard categories as well as target regions is demonstrated in Figure 3. When considering flood events, the pronounced maximum of registered events in the Austrian target regions occurs within the summer months (June, July, August). The right panel, however, indicates different results for South Tyrol; the maximum number of registered events appears in autumn (September, October, November). Considering mass movements, a similar picture emerges for South Tyrol and Carinthia/East Tyrol. The maximum of registered events occurs during summer, followed by the autumn months. Moreover, this figure also exhibits the number of registered mass movements in the Italian target region being significantly higher than those on the Austrian side.

[2] https://ajdawson.github.io/eofs/latest/

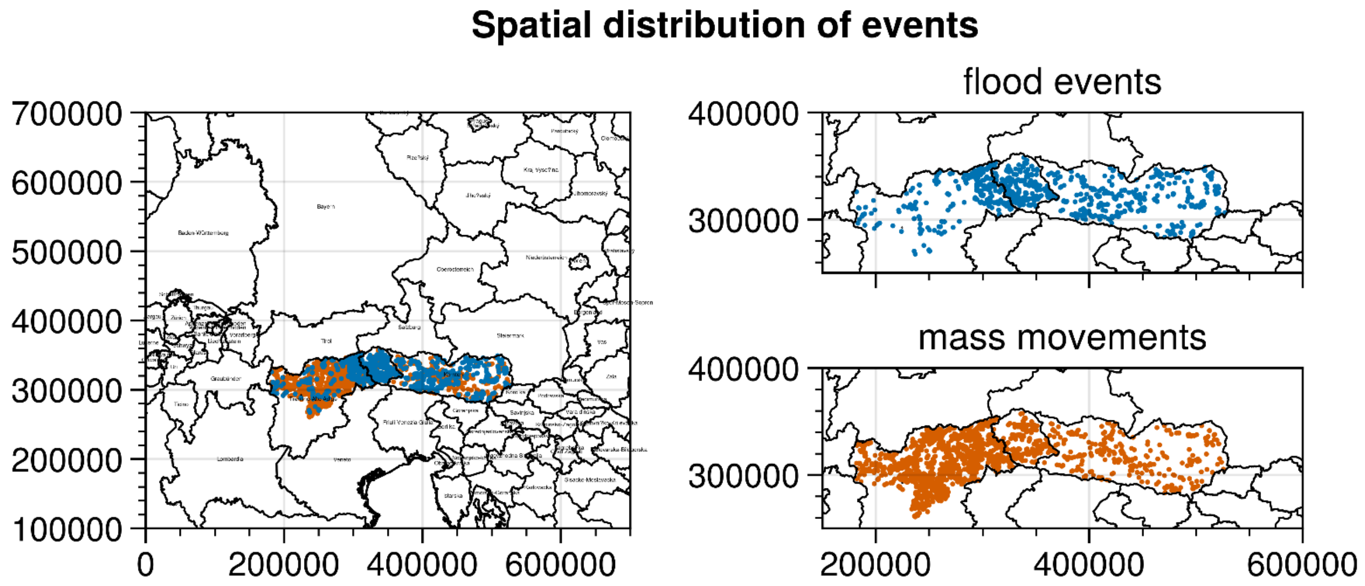

Fig 2.: Spatial distrubution of flood events (blue) and mass movements (orange) in the target regions Carinthia/East Tyrol and South Tyrol.

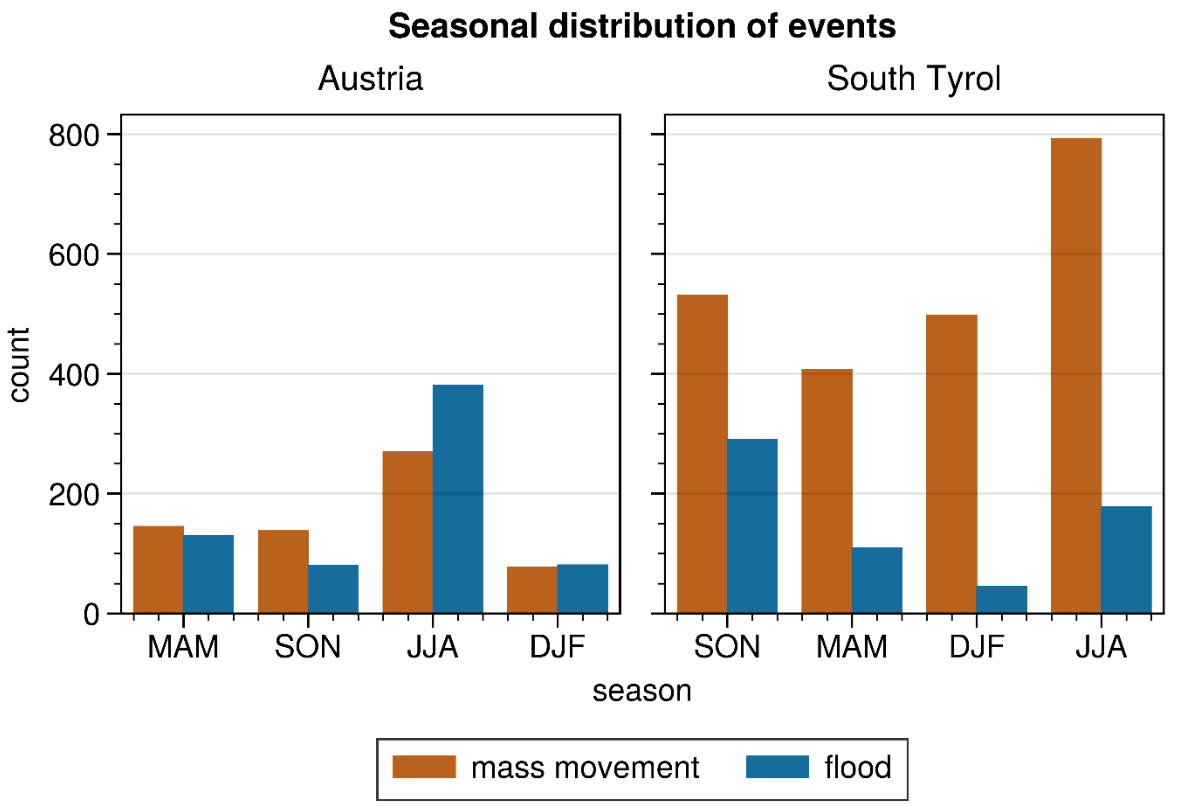

Fig 3.: Seasonal distribution of flood events (blue) and mass movements (orange), differentiated between the two target regions Carinthia/East Tyrol and South Tyrol.

[2] https://ajdawson.github.io/eofs/latest/

o Hazard Trigger Patterns (HTPs)

The following plots are all arranged in the same manner: the first row depicts from left to right the region considered, the scree plot examining the variances explained of the EOFs and a histogram, showing the distribution of precipitation sums of the eight-day-sequences corresponding to events. The second row illustrates the three leading EOFs, which represent the sought-for hazard trigger patterns. The abscissa describes the distance to the event occurrence the days preceding the event.

Results for floods during summer (JJA)

Figures 4 and 5 show the results for the category “floods” within the summer months June, July and August for both target regions. Focusing on the outcomes for the Austrian region “East Tyrol – Carinthia", the histogram exhibits the majority of events featuring an 8-day precipitation sum of 0 to 50 mm. Only very few events exhibit a precipitation sum the week before the event of more than 100 mm. The first EOF, which has an explained variance of 24%, is characterized by a weather sequence revealing high precipitation amounts 7 days before the event. The curve falls in the following two days and reaches a minimum on day 5 prior the event. After that, precipitation amounts are on the rise again and reach a plateau from day two before the event to the target day itself. This indicates slight dependence on medium-range pre-moistening and substantial precipitation activity at the event day as well as up to 2 days prior. EOF 2, however, exhibits a profoundly different characteristic with an explained variance of 20%. Starting from low values, it reaches a first maximum of day 6 before the event. After falling to day 4 and rising to a second maximum on day 2, precipitation amounts significantly decrease on the target itself. Therefor, this pattern indicates mostly variable pre-moistening from the medium- to short-range. EOF 3, exhibiting an explained variance of 16%, also reveals substantial pre-moistening conditions in the second half of the precedent week, which are terminated at day 3. After that, precipitation amounts rise again up to the event day, but with a less substantial weight than the pre-moistening.
In contrary, results for South Tyrol illustrate different triggering characteristics. Due to a lower number of events recorded for this combination of parameters, the histogram looks more variable overall. Nevertheless, if the actual precipitation sums are compared, the same general structure can be seen. Contrary to that, the patterns indicate differences. EOF1, featuring an explained variance of 23%, is defined by variable pre-moistening during the day 6 to day 2. Precipitation amounts strongly decrease from day 2 to the target day, hence this pattern indicates short-term pre-moistening as the (numerically) most important trigger factor. EOF2 (explained variance of 19%), on the other side, exhibits continuously rising precipitation amounts during the week before the event occurrence, reaching its maximum on the target day itself and thereby giving much more weight to immediate precipitation amounts, contrary to EOF1. Note though, that the explained variance of both patterns is numerically comparable and therefore both patterns can be interpreted of comparable importance. EOF3, having a simulated variance of 16%, bears strong resemblance to EOF1 pattern-wise, but is numerically (y-axis) in the EOF-space smaller, thereby signalling a fewer weight on precipitation amounts.

[2] https://ajdawson.github.io/eofs/latest/

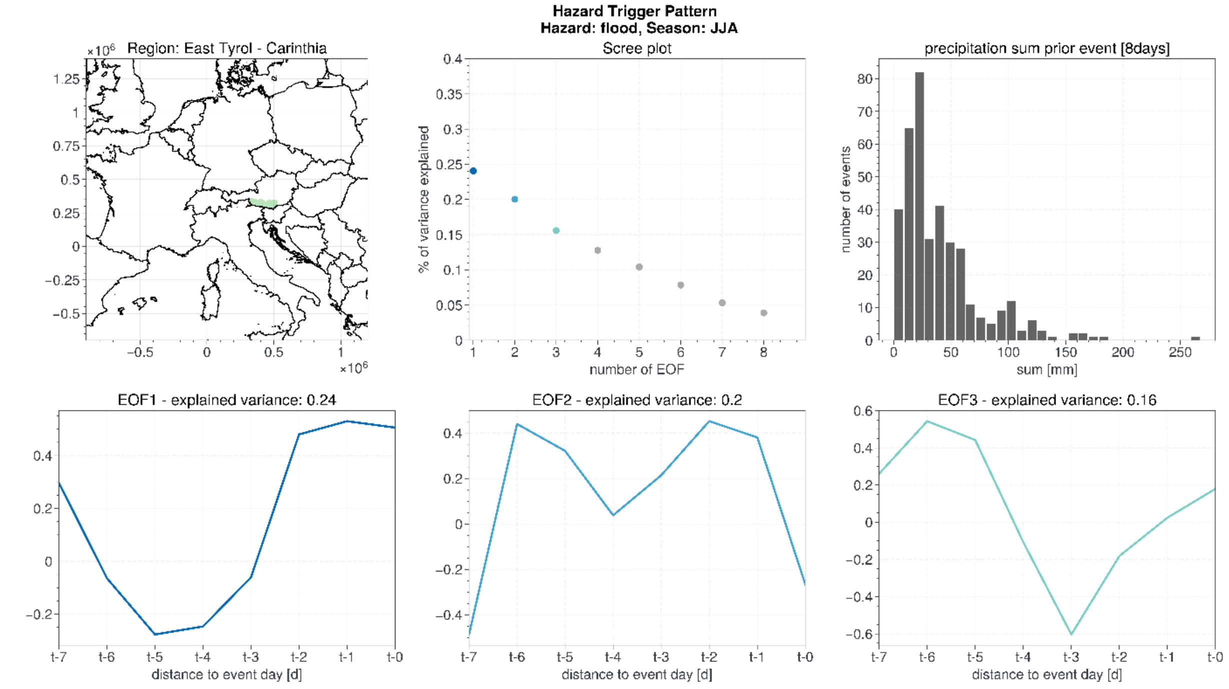

Fig. 4.: Hazard Trigger Patterns for floods in the target region Carinthia and East Tyrol for JJA.

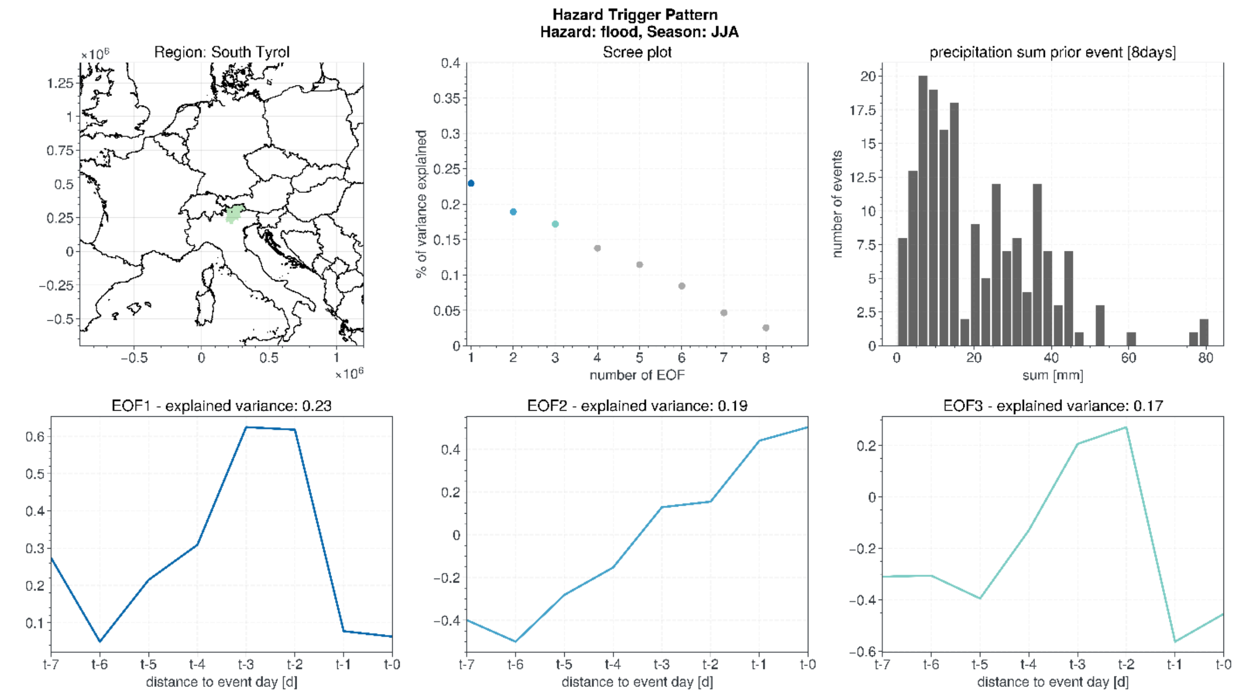

Fig. 5.: Hazard Trigger Patterns for floods in the target region South Tyrol for JJA.

Results for floods during autumn (SON)

[2] https://ajdawson.github.io/eofs/latest/

Figures 6 and 7 represent the results for the category “floods” in both target regions. Looking at the histogram of 8-day precipitation sums, it is revealed that the majority of events feature precipitation totals between 50 and 100 mm. This assessment for South Tyrol, however, illustrates strikingly different outcomes as most events exhibit precipitation sums of lower than 20 mm.
EOF1 in Figure 5 exhibits an explained variance of 28%. The weather sequence is characterized by high pre-moistening in the first half of the week which ends in a precipitation minimum on day 4 pre-event. After that, precipitation amounts rise and reach their maximum on the target day, with roughly the same weight as the peak of the pre-moistening. EOF2, featuring a simulated variance of 23%, also represents pronounced pre-moistening, especially from day 4 to 1 before the event, again indicating short-range pre-moistening. On the event day itself, precipitation recedes. EOF3, however, exhibits a weather pattern that is shaped by ups and downs, signifying variable precipitation the preceding week, without a strong consecutive signal either way.
Outcomes for South Tyrol depict different trigger patterns. EOF1, featuring a simulated variance of 34%, reveals a curve starting from high values on day 7 and continuously falling, with a temporary maximum on day two, until the event day. EOF 2 (explained variance of 21%) shows little precipitation amounts at the beginning of the precedent week, which steeply increase up to day 4 before falling again and reaching a minimum on day 2. The curve rises again up to the event day, giving the most importance to t-4 as well as immediate precipitation amounts. EOF3, having an explained variance of 16%, the pattern indicates pre-moistening in the medium-range, with a pause in between and increasing precipitation amounts up to the event day.

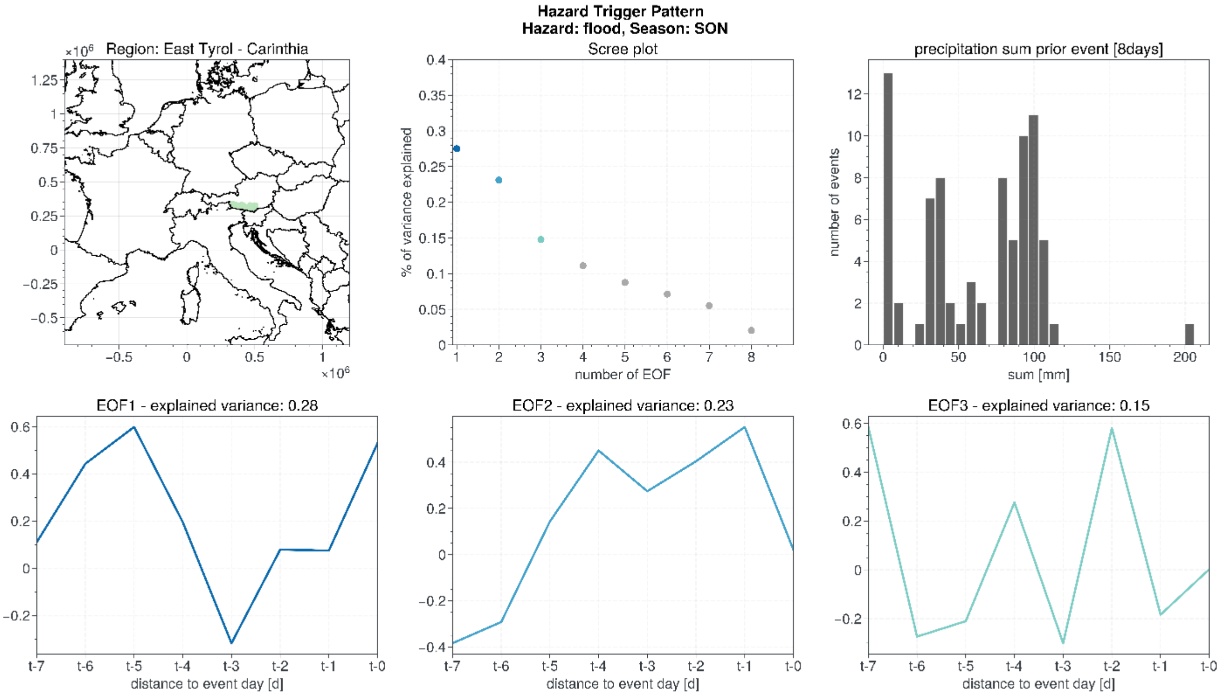

Fig. 6: Hazard Trigger Patterns for floods in the target region Carinthia and East Tyrol for SON.

[2] https://ajdawson.github.io/eofs/latest/

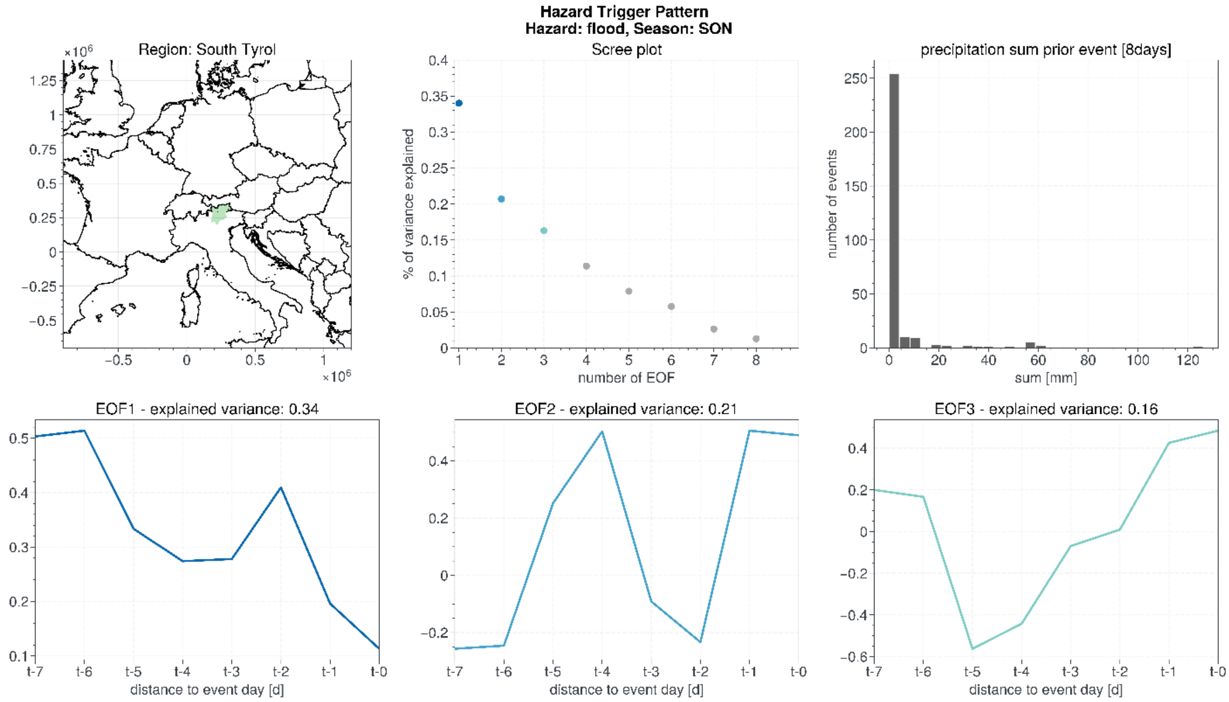

Fig. 7: Hazard Trigger Patterns for floods in the target region South Tyrol for SON.

Results for mass movements during summer (JJA)

Figures 8 and 9 show the results for the hazard category mass movements in both target regions. Considering the outcomes for the region “East Tyrol and Carinthia” (see Fig. 7), EOF1, featuring an explained variance of 22%, exhibits a weather sequence that is characterized by wet conditions 7 days prior the event, before reaching a minimum on day 5. From that on, the curve rises again and reaches a maximum on days 1 and 2 prior the event. Precipitation amounts decrease at the target day itself, thereby giving most importance to short-range pre-moistening primarily and secondarily weaker importance to event day precipitation. EOF2, having a simulated variance of 18%, reveals a quite similar picture. Opposed to EOF1, however, the maximum shifted backwards by roughly 2 days and resides at 4 days prior to the event and additionally even smaller importance is given to event day precipitation. EOF3 (explained variance of 15%), is also characterized by pre-moistening conditions, even more so than the previous patterns, with the smallest importance of event day precipitation. Precipitation reaches its maximum on day 3, before strongly decreasing to the event day.
In the case of South Tyrol, EOF1 (explained variance of 21%) reveals similar characteristics to the first EOF for the Austrian target region, with the strongest importance on short-range pre-moistening. EOF2, showing a simulated variance of 15% bears resemblance to EOF1, as it reaches a precipitation minimum on day 4 and maximum values on days 1 and 2. One distinct difference to EOF1 is the already decreasing importance toward the end of the preceding period. EOF3 indicates high pre-moistening medium- to short-range prior to the event. On the event day itself, however, precipitation reaches its minimum.

[2] https://ajdawson.github.io/eofs/latest/

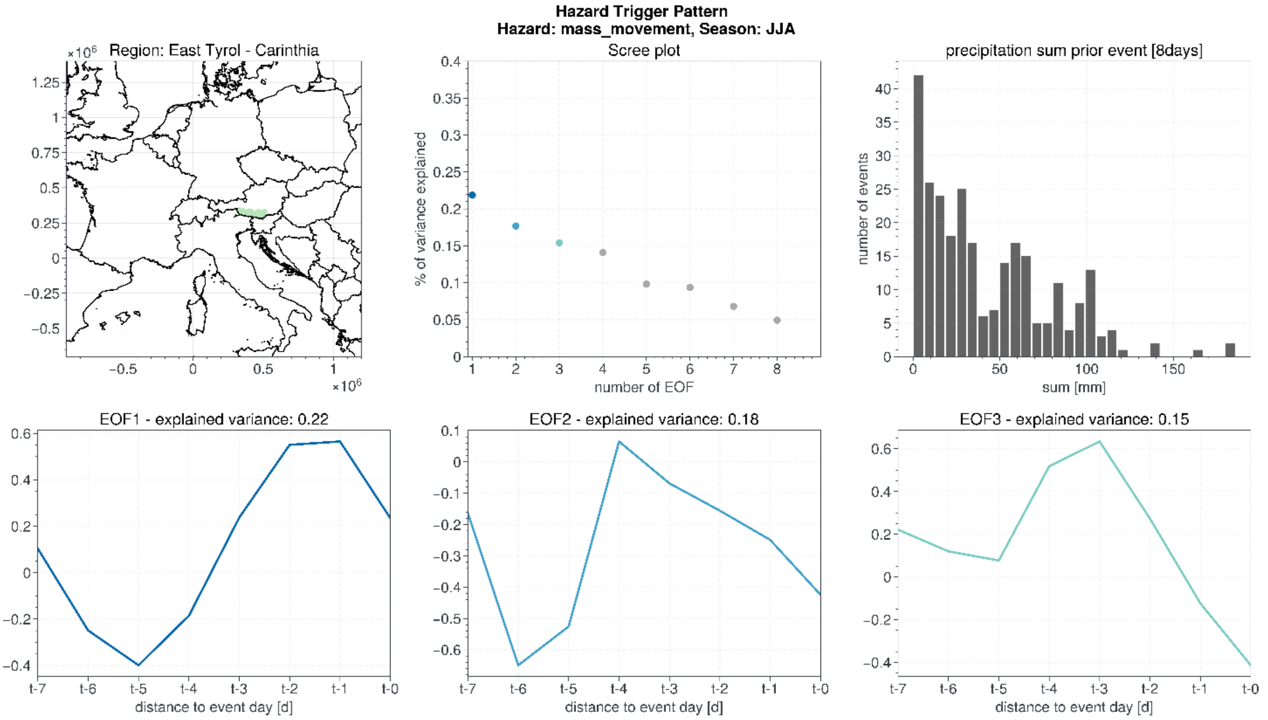

Fig. 8 Hazard Trigger Patterns for slides in the target region Carinthia and East Tyrol for JJA.

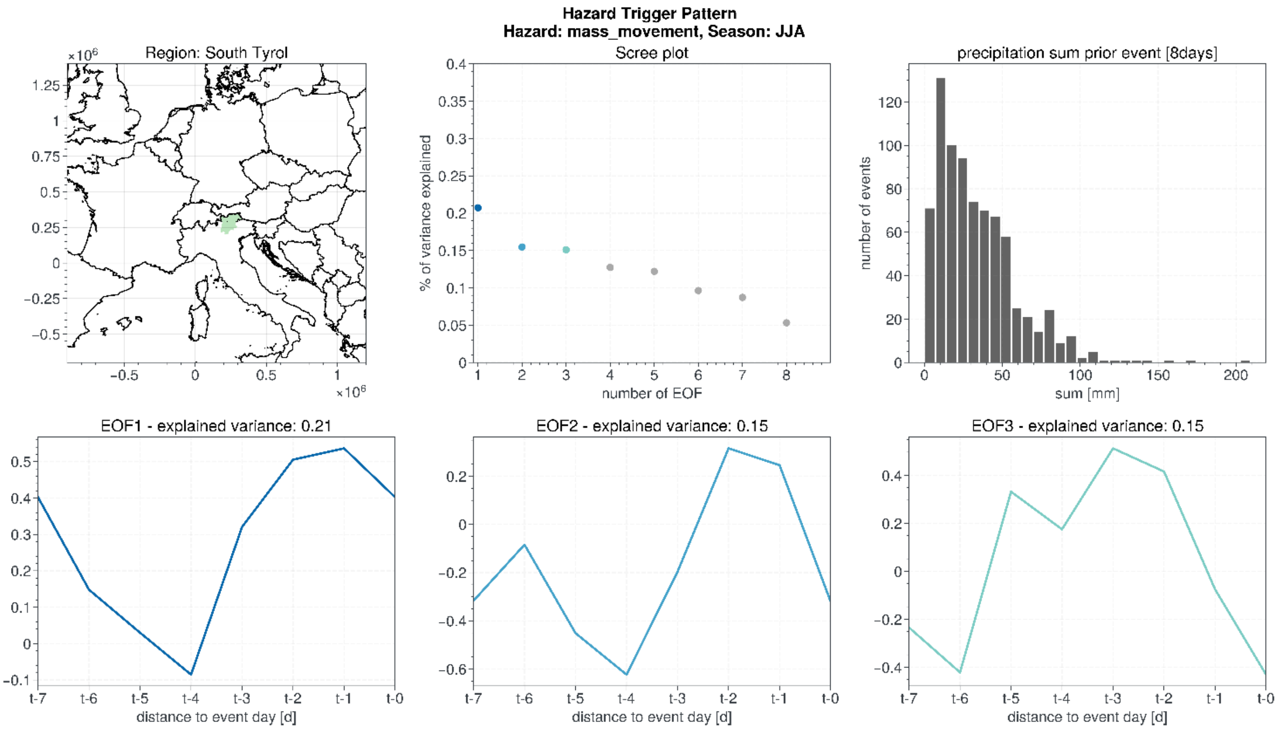

Fig. 9.: Hazard Trigger Patterns for slides in the target region South Tyrol for JJA.

Results for mass movements during autumn (SON)

Figures 10 and 11 refer to the outcomes for the hazard category “mass movements” during the autumn months September, October and November. Results for the Austrian target region “East

[2] https://ajdawson.github.io/eofs/latest/

Tyrol and Carinthia" indicate that the majority of events feature an 8-day precipitation sum before the event of 50 to 100 mm. EOF1, having a simulated variance of 28%, reveals pronounced premoistening conditions up to the short-range, illustrating high precipitation amounts from day 6 to day 1 prior the event. On the target day, however, precipitation decreases sharply with minimum importance. EOF2, featuring an explained variance of 16%, is characterized by "ups and downs". The week before event occurrence starts with wet conditions before precipitation reaches its minimum on day 5. Subsequently, the curve rises steeply and arrives its maximum on day 2 before falling again. At the event day, precipitation amounts slightly increase again. EOF3, on the other side, indicates less precipitation in the first half of the precedent week and rising amounts from day 3 to day 1 pre-event occurrence. On the event day itself, however, the curve is decreasing.
Results for mass movement in the season SON for the target region South Tyrol show that the majority of events feature an 8-day precipitation sum between 0 and 50 mm. The first orthogonal function, showing an explained variance of 27%, reveals a similar pattern than EOF1 in the Austrian target region. It is characterized by pre-moistening, especially in the first half of the precedent week of event occurrence. In the second half, precipitation amounts lower significantly. EOF2 (explained variance of 25%) bears strong resemblance to EOF1 with a slight difference on the target day. In this pattern, precipitation rises again after having reached its minimum on day 2 and 1 prior the event. EOF3, featuring an explained variance of 14%, is also strongly influenced by pre-moistening, starting on day 7 before the event and reaching the maximum precipitation on day 3, before slightly decreasing again.

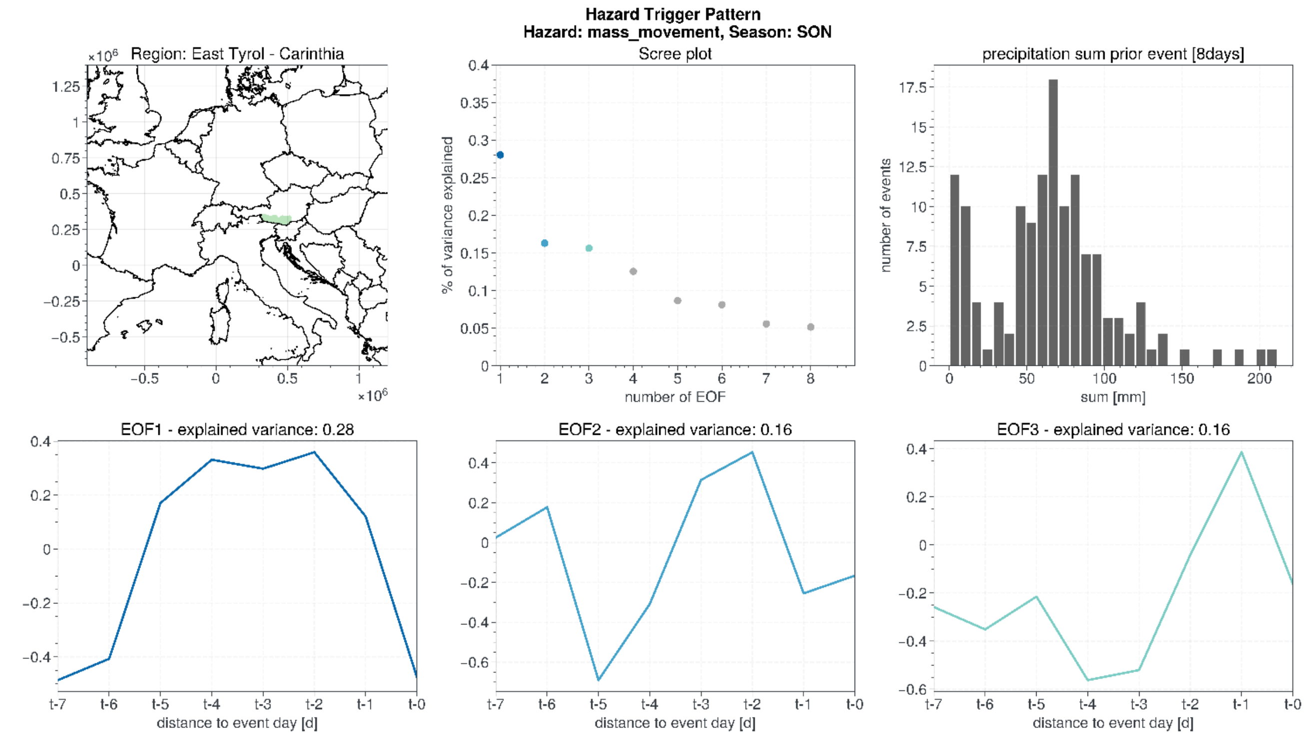

Fig. 10: Hazard Trigger Patterns for slides in the target region Carinthia and East Tyrol for SON.

[2] https://ajdawson.github.io/eofs/latest/

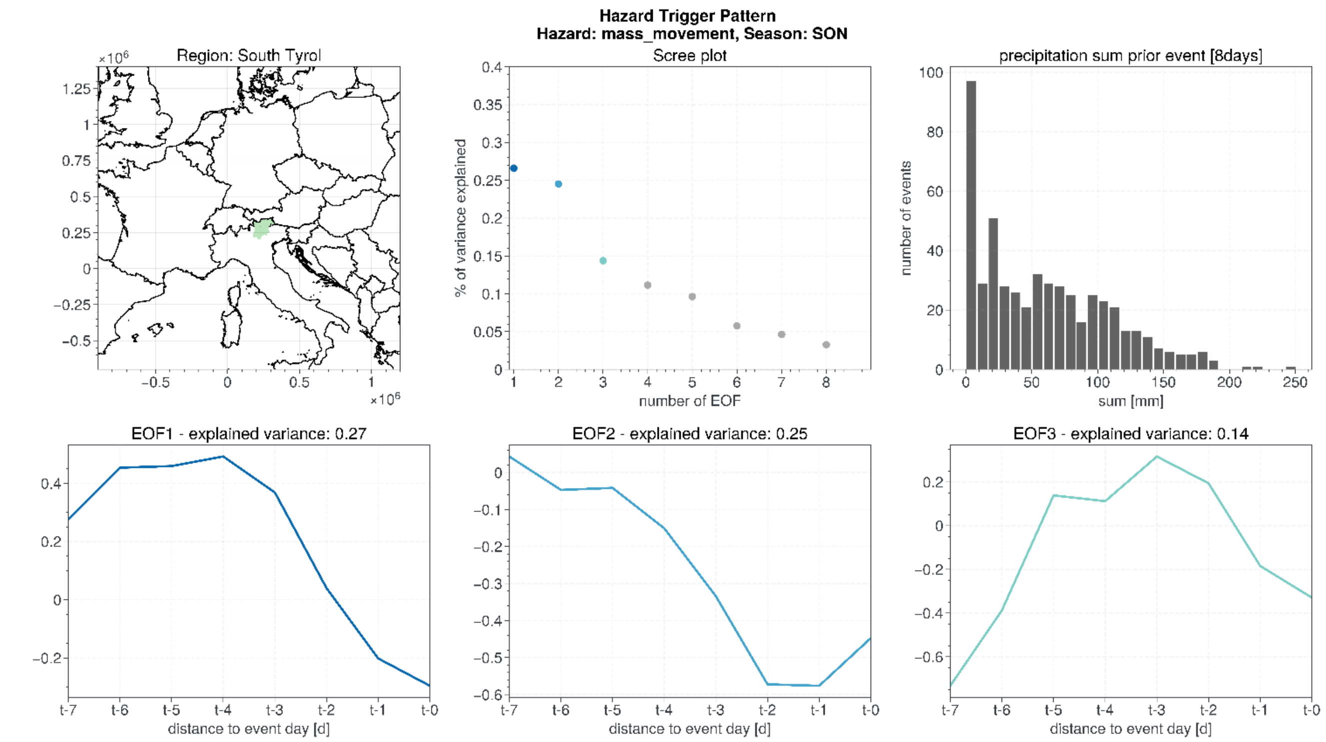

Fig. 11: Hazard Trigger Patterns for slides in the target region South Tyrol for SON.

Discussion and Conclusion

The main statement of this deliverable is the significance and uniqueness of the derived hazard trigger patterns tied to each single hazard-category-region-season pairing (totaling up to 16 HTPs: two hazard categories (mass movements – slides and flows as well as floods) in two target regions (East Tyrol-Carinthia in Austria and South Tyrol in Italy) and four seasons (DJF, MAM, JJA and SON), respectively).

As can be seen from the plots and the discussion of each HTP, there are striking differences between the hazard categories floods and mass movements, but also between regions and seasons. Overall, pre-moistening plays a crucial role in all category-hazard-seasons combinations. As a result, it often takes no or very little precipitation amounts on the event day itself to initiate an event. Nevertheless, some patterns also underline the significance of event-day precipitation as important and/or supporting triggers.

In the case of floods, it is important to mention that the precipitation, in this case, was drawn directly from the event location. This can also explain the circumstance why the maximum of precipitation does not take place directly on the event day itself, but some days before. The consideration of precipitation data at the event location is a weak point of the current methodology, especially for large-scale flood events. Phenomenologically, it is more precise to consider the precipitation over the catchment area of the river under investigation. The approximation via retrieving precipitation information at the event location fits better for small-scale torrent processes.

Likewise, retrieving precipitation data is more appropriate in the vicinity of the registered events in the case of mass movements. In general, the HTPs are more similar to each other for mass movements than for floods. The first two HTPs show thereby predominant process types.

The first indicates a one-day time-lag between weather-development and the thereby initiated hazard-process, that is related to the soil moisture. This phenomenon is sometimes referred to as a

[2] https://ajdawson.github.io/eofs/latest/

“delayed reaction”, as opposed to an instantly triggered slide directly caused by high rainfall intensity. In the second case, precipitation sums take on their minima one and two days prior the events, while both attain their maxima at target day itself – i.e., “instant trigger” in experts’ terms. The difference between “instant” and “delayed” hazard-initiation may arise from geomorphological conditions as well as differences in the water saturation of the soil and finally the absolute precipitation totals.

Results derived in this deliverable are to be used for climate model projections for the future, thereby deriving, so-called, “Hazard Development Corridors (HDCs)” which are the focus within the deliverable D2.4.

○ VALIDATION

Reconstructions

In order to evaluate our model’s ability to reconstruct the existing 8-day time series before every event registered, we used both EOFs and corresponding principal components to compute reconstructed timeseries. In particular, we investigated all possible combinations of hazard, region and season (totaling up to 16 combinations) and compute the correlation coefficient between reconstructions and observations. Figures 12 and 13 represent two examples by illustrating both the reconstructed time series in grey and the original time series in blue. Figure 11 shows the temporal evolution of precipitation before the flood event that occurred on July 30th, 2014 in South Tyrol. Figure 12 depicts the observed and reconstructed time series for a flood event that took place on September 20th, 2012 in the region East Tyrol – Carinthia. It can be seen that the weather sequence is well reproduced in terms of its pattern, but not with respect to the precipitation amounts, which are overestimated by our models.

[2] https://ajdawson.github.io/eofs/latest/

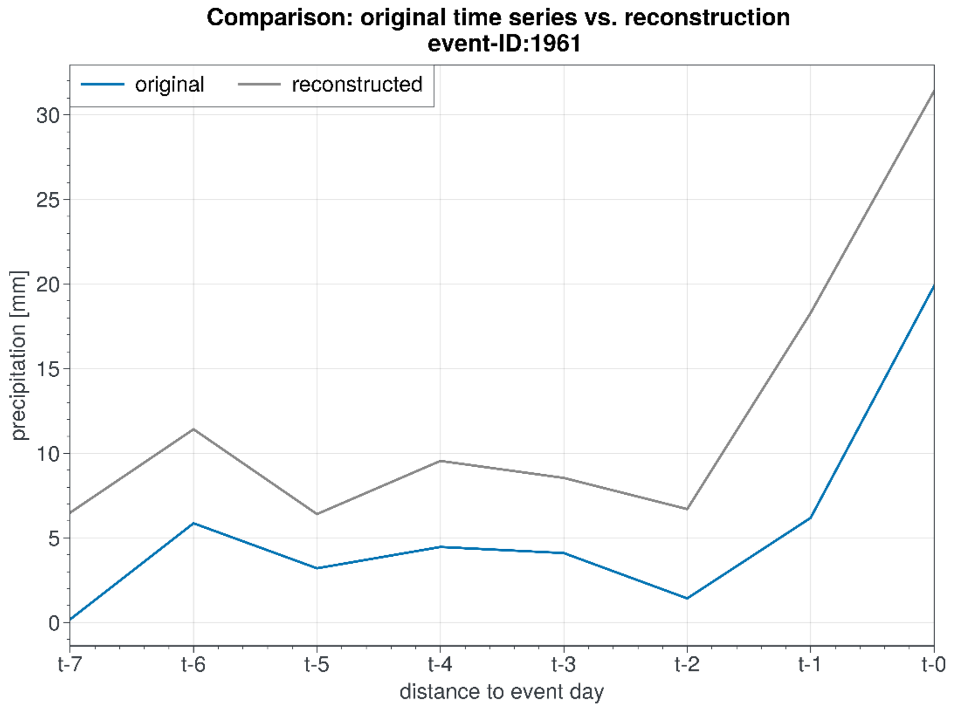

Fig. 12: Comparison between original (blue) and reconstructed (grey) time series for a flood event occuring on July 30th, 2014 in South Tyrol.

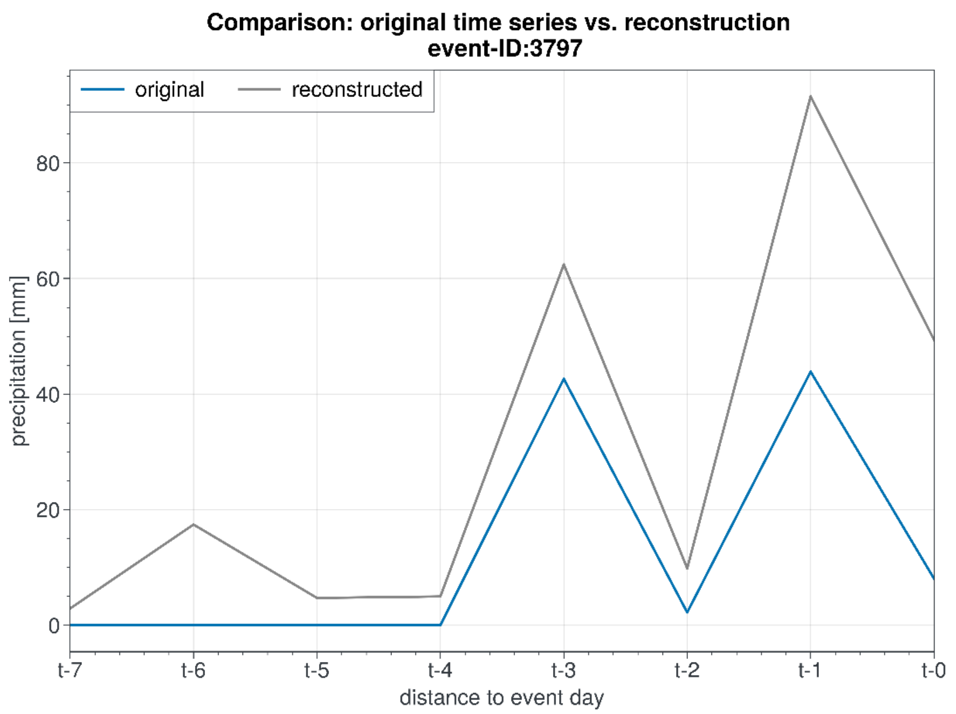

Fig. 13: Comparison between original (blue) and reconstructed (grey) time series for a flood event occuring on September 20th, 2012 in the region East Tyrol - Carinthia.

Table 1 shows correlation coefficients between reconstructions and original time series for the different category-region-season combinations. The correlation coefficients vary roughly between 0.76 and 0.89, indicating good performance for the truncated (3 EOFs) reconstructions from the HTP Model over the historical period. The least performance can be measured during the summer months JJA, which is because of the more convective nature of summertime precipitation and due

[2] https://ajdawson.github.io/eofs/latest/

to the limited resolution of the model, which therefor suffers more when processes are involved, that cannot be resolved on the resolution of the model.
The reconstructed timeseries over all events are depicted in figures 14 and 15, for flood/ST/MAM and mass_movement/ET_C/JJA respectively. Between those two cases a clear distinction can be seen, which was also partly concluded from the HTPs. Namely, that for ST the pre-moistening carries seemingly more weight, while for ET_C the short-range and immediate precipitation is of more importance to an event. Although it has to be noted, that due to the latter representing the convective-active summer months the distinction seems bigger than it is. JJA patterns for ST also have more weight on the short-range to immediate precipitation, but not as much as in ET_C.

Table 1: Correlation coefficients between reconstructed weather sequences using n=3 EOFs and historical event records.

Category	Region	DJF	MAM	JJA	SON
mass_movement	ET_C	0.848	0.829	0.795	0.768
	ST	0.891	0.836	0.760	0.846
flood	ET_C	0.803	0.838	0.866	0.833
	ST	0.879	0.777	0.808	0.872

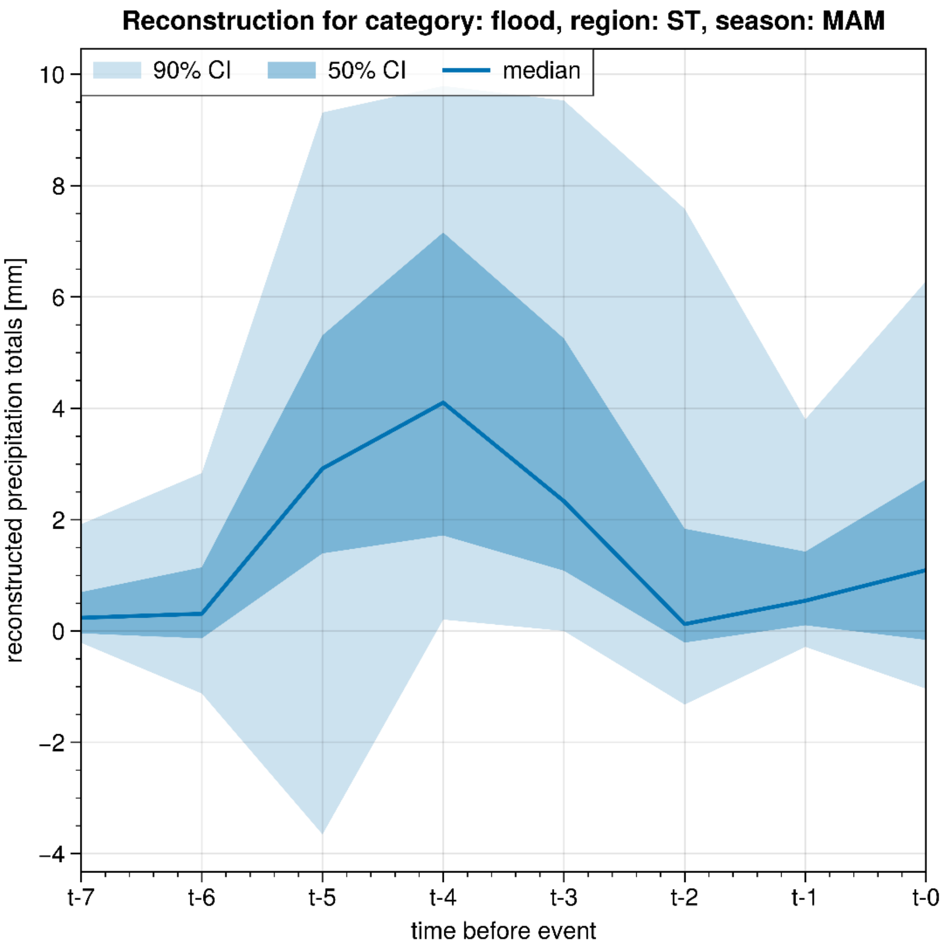

Fig. 14: Median, 50% and 90% confidence interval for reconstructed (3 EOFs) timeseries for the category flood, region ST and season MAM.

[2] https://ajdawson.github.io/eofs/latest/

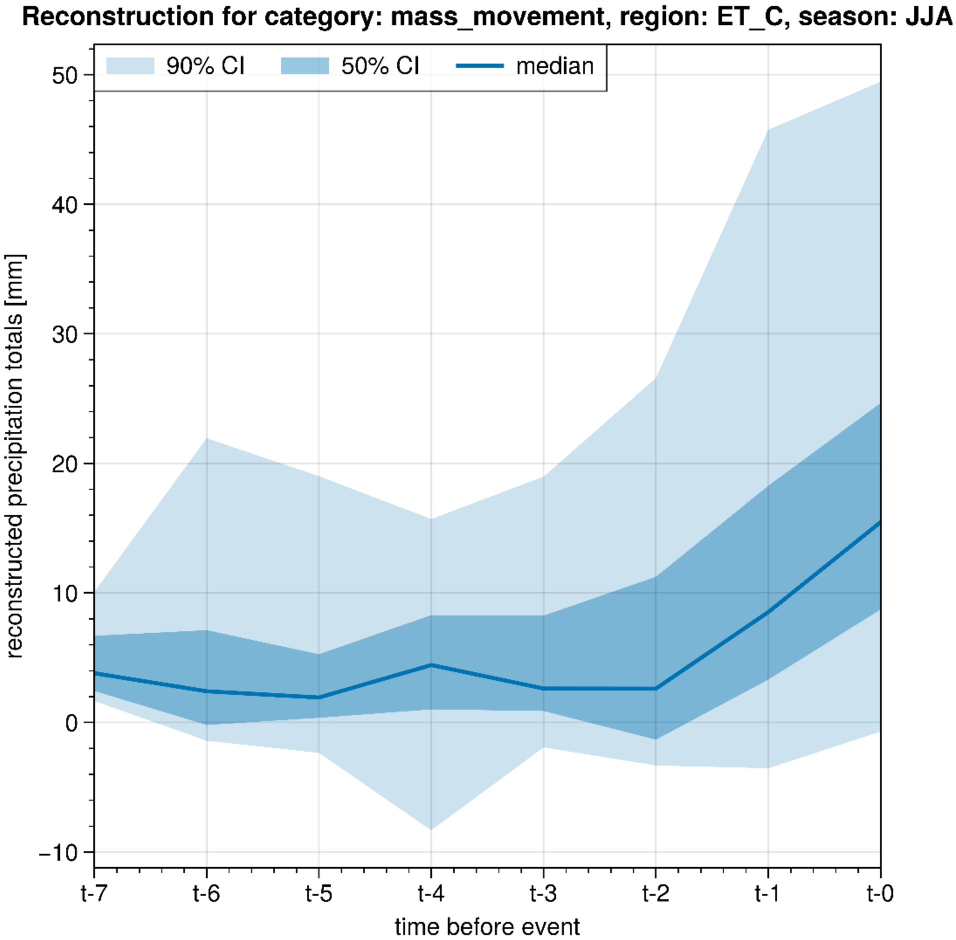

Fig. 15: Median, 50% and 90% confidence interval for reconstructed (3 EOFs) timeseries for the category mass_movement, region ET_C and season JJA.

○ LIMIT OF PREDICTABILITY

Degrees of freedom for Hazard Trigger Patterns

Within the derivation of HTPs, multifarious degrees of freedom can be identified. These do not only depend on the hazard under investigation, but also on the affected region. As for hazard processes like falling-rocks or excessive snow fall, solely precipitation totals might not be sufficient for the determination of significant EOF patterns. Therefore, it is essential to investigate and validate multiple predictor pairs. Hence, the selection of suitable predictors represents a degree of freedom. Having said that, slide and flood processes were already investigated beforehand and it was found that precipitation totals is a sufficient sole predictor for the derivation of HTPs.

Furthermore, the length of the considered time period before the event occurrence is not identical for all process categories due to their different trigger characteristics.
Flash floods occur on a shorter 'build-up' timescale and are mainly induced by heavy rainfalls and an immediate surface run-off. Floods on the other hand are often characterized by large precipitation-totals accumulating over multiple days; the moisturization of soil in the preceding days of an

[2] https://ajdawson.github.io/eofs/latest/

event is an important key factor for mudslides as well as the surrounding surface characteristics. Such characteristics are – especially in global climate models – not always readily available and are therefore a possible source of uncertainty. The effect of event characteristic can e.g. be seen in the lower correlation coefficients for the HTP-model in the summer months, where processes are involved that are not fully resolved in the underlying data and therefor another source of uncertainty.

Finally, the number of EOF patterns used to describe a HTPs also constitutes an important degree of freedom which can be determined with various validation methods, or in a more direct way using a scree plot. Again, from previous analysis it was concluded that 3 EOFs are sufficient for the model. More EOFs add of course more explained variance but not to the degree that the depiction of the underlying signal increases significantly.

Additional factors influencing event occurrence

Floods

Other meteorologic factors besides precipitation that affect the amount of runoff are temperature, dewpoint, winds, radiation, or other elements affecting snowmelt or evaporation. Apart from these, other parameters also have a strong influence on the occurrence of flood. Once the runoff has started, its pattern is controlled by the topographic properties of the drainage basin, especially if the precipitation falls in the form of rain. These characteristics may be either surface or underground features. Most topographic features are relatively stable, such as the size of the drainage area, the altitude or the amount of land slopes; others are variable, such as kind of ground cover, land use or state of cultivation (UGSG, 1963). These parameters, however, are not included in the above introduced HTP approach. It has to be stressed out, that this approach solely focuses on the precipitation trigger mechanisms that potentially induce flood events.

Mass movements – slides and flows

Due to its strong influence on groundwater levels as well as pore water pressure and thus on slope stability, precipitation is one of the main triggers of landslide events (Wood et al., 2016; Crozier 2010). However, the response of a slope to meteorological conditions varies depending on the landslide type (Enigl et al., 2019), volume, and depth (Crozier 2010). The occurrence and amplitude of landslides also strongly depend on the properties of the corresponding catchment areas, especially in terms of its topography, land use and vegetation (Freudenschuß et al., 2021).

[2] https://ajdawson.github.io/eofs/latest/

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[2] https://ajdawson.github.io/eofs/latest/

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