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Frequency Analysis of Critical Meteorological Conditions in a Changing Climate—Assessing Future Implications for Railway Transportation in Austria

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Abstract: Meteorological extreme events have great potential for damaging railway infrastructure and posing risks to the safety of train passengers. In the future, climate change will presumably have serious implications on meteorological hazards in the Alpine region. Hence, attaining insights on future frequencies of meteorological extremes with relevance for the railway operation in Austria is required in the context of a comprehensive and sustainable natural hazard management plan of the railway operator. In this study, possible impacts of climate change on the frequencies of so-called critical meteorological conditions (CMCs) between the periods 1961–1990 and 2011–2040 are analyzed. Thresholds for such CMCs have been defined by the railway operator and used in its weather monitoring and early warning system. First, the seasonal climate change signals for air temperature and precipitation in Austria are described on the basis of an ensemble of high-resolution Regional Climate Model (RCM) simulations for Europe. Subsequently, the RCM-ensemble was used to investigate changes in the frequency of CMCs. Finally, the sensitivity of results is analyzed with varying threshold values for the CMCs. Results give robust indications for an all-season air temperature rise, but show no clear tendency in average precipitation. The frequency analyses reveal an increase in intense rainfall events and heat waves, whereas heavy snowfall and cold days are likely to decrease. Furthermore, results indicate that frequencies of CMCs are rather sensitive to changes of thresholds. It thus emphasizes the importance to carefully define, validate, and—if needed—to adapt the thresholds that are used in the weather monitoring and warning system of the railway operator. For this, continuous and standardized documentation of damaging events and near-misses is a pre-requisite.

Keywords: climate change; critical meteorological condition; frequency analysis; natural hazard management; railway transportation

1. Introduction

The railway transportation system of the Alpine country Austria plays an important role in the European transit of passengers and goods. In total, 11.7 million tons of goods were transported across the Austrian Alps in 2013, which is 28% of the total volume recorded for the inner Alpine Arc [1]. In addition, railway lines are essential for the accessibility of lateral Alpine valleys and thus contribute to their economic and societal welfare. The harsh mountainous nature of the Eastern Alps, in which around 65% of the national territory of Austria is situated [2], poses a particular challenge to railway transport planning and management. Relief energy and steep slopes limit the space usable for permanent settlements and infrastructure (e.g., amounting to 15%–20% of the whole Alpine Convention territory) [3]. Hence, railway lines often follow floodplains or are located along steep unsteady slopes, which considerably exposes them to flooding and in particular to Alpine hazards (e.g., debris flows, rockfalls, avalanches, or landslides).

The majority of (Alpine) natural hazards are triggered by extreme/severe (hydro-) meteorological events such as heavy precipitation, rapid snow melt, or extreme temperatures [4]. More than 1200 weather events that caused direct or indirect damage to Austria's railway infrastructure (e.g., heavy precipitation, heat waves, or storms) occurred between 1990 and 2011 [5]. In this context, direct damage is generally understood as damage resulting from physical contact with the relevant natural event (e.g., structural damage to railway tracks), whereas indirect damage, such as service disruptions, occurs spatially or temporally outside the actual event [6].

Since meteorological, hydrological, and geological extremes can have great hazard potential for damage to railway infrastructure as well as for posing risk to the safety of passengers, they are of major importance for the risk management of railway transportation in Austria. However, the implementation of technical protection measures is often not feasible for either economic reasons or aspects of nature and landscape conservation [7]. Moreover, technical measures are limited in ensuring a commensurate level of safety for railway operations in Alpine topography. Hence, in recent years, natural hazard and risk management has shifted from pure technological and protective approaches towards a more integrated risk management strategy including a variety of non-structural measures in order to mitigate (residual) risks from natural hazards. Accordingly, the risk management strategy of the Austrian railway network operator, the Austrian Federal Railways (ÖBB), puts great emphasis on non-structural, precautionary, and preparatory risk mitigation measures, particularly with regard to weather monitoring and warning as well as immediately adapting operations in case of extreme weather events. In cooperation with a private weather service provider, a weather monitoring and warning system was implemented in 2005 along the Austrian railway network to provide current data and forecasts of a set of meteorological parameters to the local railway staff. Furthermore, thresholds for key weather phenomena, such as extreme low or high air temperature and very intense precipitation, were defined in order to identify imminent weather extremes putting railway operation at risk—so-called critical meteorological conditions (CMCs). These CMCs are extreme weather events with the potential to have a large-scale effect on railway operations requiring coordinated action on behalf of the ÖBB. In practice, they are derived from 72-hour-forecasts to allow sufficient time for the implementation of damage reducing measures.

Experiences from the heavy rainfall event in 2013 in the Central Alps showed that the system generally performed well even under extreme conditions. However, climate change is likely to alter the climatic conditions and thus might present new challenges in terms of weather monitoring and warning response.

Since the European Alps are constantly disclosed as being particularly sensitive to climate change [8], recent studies on climate change in Europe increasingly focused on this region. The analyses on future temperature trends consistently show a marked increase in mean air temperature in all regions (e.g., [9–16]). According to Eitzinger *et al.* [10], Gobiet *et al.* [11], and Strauss *et al.* [15], a significant annual mean temperature rise of approximately 1.6 °C until 2040 is expected. Zimmermann *et al.* [16] estimate a temperature increase of 1.8 °C to 4 °C for the period 2051–2080 (A1B scenario) using the average conditions from 1961–1990 as reference, whereby the least warming in the winter season and the highest warming during summer is shown. With regard to precipitation, the annual trend for Austria shows significant variations both in the seasonal and spatial pattern [17–19]. In addition to these changes, climate change is also likely to alter the frequency, intensity, and spatiotemporal distribution of (at least some) extreme weather events such as intense rainfall or heatwaves [20–22]. These changes will presumably have serious implications on the current hazard (and risk) profile of Austria, which consequently might also challenge the natural hazard management for railway transportation. Rising temperatures and extended heatwave periods, for instance, increase problems of rail buckling and thermal comfort for passengers in trains during the summer [22]. In the winter season, however, less extreme cold events can reduce related damages to infrastructure (e.g., point failures) and service disruptions. Intense rainfall events, as a further example, can cause various direct damages to railway infrastructure (e.g., structural damage caused by erosion), which would consequently also pose an imminent impact to railway operations.

Hence, in order to support decision-makers in the comprehensive and sustainable natural hazard management, we investigate possible changes in the frequencies of CMCs due to climate change and future implications for railway transportation in Austria. The upcoming section of this paper briefly presents the weather monitoring and warning system being implemented and operated by the ÖBB natural hazards management in cooperation with a private weather service provider to address the risks from CMCs and related Alpine hazards. In Sections 3.1 and 4.1 we look at the seasonal climate change signals for air temperature and precipitation between the periods 1961–1990 and 2011–2040 using simulations of four Regional Climate Models (RCMs). The RCM ensemble was subsequently used to evaluate the projected changes in the frequencies of CMCs (Sections 3.2 and 4.2). Sections 3.3 and 4.3 present the methods and results of the sensitivity analysis of CMC frequencies by varying some threshold values. Finally, the results are discussed and consequences for the risk management for Austrian railway transportation, as well as potential adaptation and mitigation strategies, are outlined (Sections 5 and 6).

2. The ÖBB Weather Warning and Monitoring System

To cope with the risks arising from CMCs, the ÖBB natural hazards management Department initiated a partnership with the private weather service provider UBIMET GmbH in 2005 to develop and implement a dense weather monitoring and early warning system along the Austrian railway network—the so-called "Infra:Wetter". The system combines data from both its own and external weather stations, radars, and satellites, as well as local and global weather projections with detailed information on the entire railway network in Austria. On this basis, current data and forecasts of a set of important meteorological parameters like temperature, wind speed, precipitation, snowfall, and the snow line can be provided at the local level. The main features of Infra:Wetter are (1) both short (*i.e.*, hours) and mid-term (*i.e.*, up to three days) weather warnings and forecasts along individual railway lines; (2) on demand (mid-term) forecasts of weather-related hazards (e.g., occurrence of flash floods, snow drifts, black ice, thunderstorms, fire) and (3) detailed long-term forecast (*i.e.*, up to seven days) of the general weather development [23]. The issuing of an alarm by the early warning subsystem of Infra:Wetter is based on a variety of threshold values for relevant CMCs. For instance, more than 100 mm of rainfall or 20 cm of snowfall in the Alps within 24 h are classified as a critical meteorological condition possibly impacting the railway operation. An overview of currently applied thresholds for CMCs being relevant for this study is provided in Table 1a. These thresholds were jointly defined by the ÖBB and the private weather service UBIMET on the basis of expert knowledge.

In the case that a threshold exceedance can be forecast at least 72 h in advance (thus allowing sufficient pre-warning and reaction time), a weather warning is issued and a plan of procedures is implemented (see Figure 1). First, it is classified into one of five different alarm levels. Subsequently, potentially affected railway sectors are identified and an internal meeting with the general management is held in order to decide on the adequate plan of emergency measures. If such a contingency plan is already available for the respective situation, its measures are implemented. If no contingency plan is available for this situation, a regional weather warning is issued and consultations with the engineering department in charge take place. If threshold values are exceeded, or a weather warning has been issued for an event with a lead time of less than 72 h, a weather alarm is issued and an incidence command is installed that decides on operational safety precautions, such as speed limits, track closures, or temporary mitigation measures. For instance, in the case that heavy snowfall is predicted, measures such as a revised planning of human resources and provision of winter services or the preheating of switch points can be taken to ensure the operability of the network. In addition, the weather warnings are continually reviewed and daily reports of possible weather-related problems are provided to the first train of the day on remote tracks. The system is also used to analyze which parts of the rail network were affected by CMCs such as extreme rainfall, heavy snowfall, or heat waves so that the operation managers can be informed about potential problems and impose temporary speed limits, where necessary. The weather monitoring system, in combination with the early warning system, thus aims to facilitate the demands for a reliable provision of services and to meet the top priority of the operator in order to achieve a maximum possible level of safety for passengers and staff.

Table 1. Section (**a**) shows the original threshold criteria for Critical Meteorological Conditions (CMCs) for railway transportation in Austria. In Section (**b**), the modified threshold criteria used for the sensitivity analysis are depicted.

(a)		**(b)**	
Critical Meteorological Condition (CMC)	**Threshold Criteria**	**Critical Meteorological Condition (CMC)**	**Threshold Criteria**
Very intensive rainfall—Alps	⩾100 mm/24 h	*Very intensive rainfall—Alps*	⩾80 mm/24 h
Very intensive rainfall—Lowlands	⩾ 60 mm/24 h	*Very intensive rainfall—Lowlands*	⩾50 mm/24 h
Intensive rainfall with high antecedent soil moisture	Precipitation sum of ⩾100 mm within max. three preceding days, and precipitation event with an intensity of ⩾50 mm/24 h on the fourth day	*Intensive rainfall with high antecedent soil moisture - variant 1*	Precipitation sum of ⩾100 mm within max. five preceding days, and precipitation event with an intensity of ⩾50 mm/24 h on the sixth day
		Intensive rainfall with high antecedent soil moisture—variant 2	Precipitation sum of ⩾80 mm/max. three preceding days, and precipitation event with an intensity of ⩾25 mm/24 h on the fourth day
First heavy seasonal snowfall (September, October)—Alps	⩾20 cm/24 h	*First heavy seasonal snowfall (September, October)—Alps*	⩾15 cm/24 h
First heavy seasonal snowfall (September, October)—Lowlands	⩾10 cm/24 h		
Extreme cold	⩽−20 °C	*Extreme cold*	⩽−15 °C
Heat wave	⩾+35 °C, duration of at least five days	*Heat wave*	⩾+35 °C, duration of at least three days

Between 2006 and 2014, 499 weather warnings were issued (excluding storms and thunderstorms) [24]. Heavy snowfall events accounted for the greatest proportion of warnings (273) followed by heavy rain (226). According to the ÖBB damage database for railway service and infrastructure, damage related to extreme rainfall events accounted for approximately 37% of all entries from 1991 to 2011 [5]. Therefore, rainfall-related CMCs rank among the most important ones for risk management of railway infrastructure. In the same period, snowfall and snowdrift events had a 17% share of all damaging events [5] and have thus also been of major importance for ÖBB risk management.

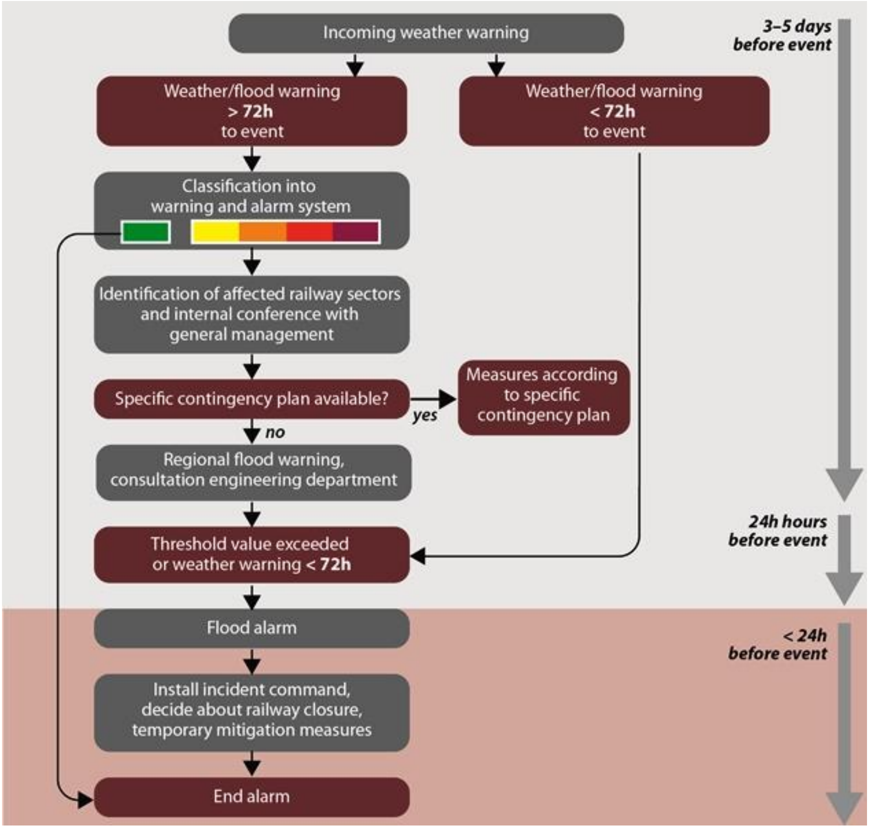

Figure 1. Flowchart of procedures in case a threshold value for a CMC is exceeded and a weather warning (and/or flood warning) is issued. (Source: ÖBB).

3. Data and Methods

3.1. Climate Change Signals for Austria

Climate change signals at a national or regional scale are generally investigated by means of RCMs instead of Global Circulation Models (GCMs), since their spatial resolution is much higher and complex topography as well as heterogeneous land cover is finer-scaled and, hence, better represented [25]. RCMs result from either statistical or dynamical downscaling procedures of GCM results and are associated with a number of uncertainties regarding spatial resolution and temporal accuracy of the obtained results [26]. However, in recent years the variety and number of simulations were enlarged, related uncertainties were mostly identified, and the model quality has been improved accordingly [27]. Thus, the level of confidence in RCMs has grown especially for mean temperature and precipitation projections, but also with regard to extremes [28].

To investigate the climate change signals for Austria, an ensemble of high-resolution RCM simulations for Europe, which has been produced within the EU-project ENSEMBLES (http://www.ensembles-eu.org), was accessed. Since all simulations represent a realization of an equally probable future, there is no criterion to choose only one simulation as the most suitable for the Alpine region or Austria. To account for the variability of possible projections, four RCMs were selected that represent the maximum difference in projected precipitation and temperature trends for Europe and thus likely consider the entire projection bandwidth provided by the given ensemble of simulations [29]. Table 2 specifies the model runs available. Dosio *et al.* [29] showed that the KNMI-model roughly represents the average of the twelve RCMs regarding precipitation and temperature trends in Europe, whereas the DMI-model tends to be rather warm and dry, while the METO-HC-model tends towards cold and wet conditions. Moreover, the MPI-model was added in order to enlarge the ensemble of climate models, which finally led to a selection of four models (see Table 2). The RCM datasets have been bias corrected by Dosio *et al.* [25] prior to the study at hand. All available climate variables and underlying data specifications are listed in Table 3.

Table 2. List of model runs available for this study (adapted from Dosio *et al.* [29]). The selected models are highlighted in bold characters. (For a full description of the Institutes' and model acronyms see Christensen *et al.* [30]).

Institute	Regional Climate Model (RCM)	Driving Global Circulation Model (GCM)	Emission Scenario
METO-HC	**HadRM3Q0**	**HadCM3Q0**	**A1B**
MPI-M	**REMO**	**ECHAM5**	**A1B**
C4I	RCA3	HadCM3Q16	
ETHZ	CLM	HadCM3Q0	
KNMI	**RACMO2**	**ECHAM5-r3**	**A1B**
SMHI	RCA	BCM	
SMHI	RCA	HadCM3Q3	
SMHI	RCA	ECHAM5-r3	
DMI	HIRHAM5	BCM	
DMI	HIRHAM5	ARPEGE	
DMI	**HIRHAM5**	**ECHAM5**	**A1B**
CNRM	RM5.1	ARPEGE	

Table 3. List of RCM variables considered in this study and data specifications. Bias correction was conducted by Dosio *et al.* [25].

Variable	Definition	Specifications
pr	Bias-corr. rainfall (mm)	Spatial resolution: 25 × 25 km Spatial coverage: Europe Temporal resolution: daily time step
psno	Bias-corr. snowfall (cm)	
tavg	Bias-corr. mean air temperature (°C)	
tmax	Bias-corr. maximum air temperature (°C)	
tmin	Bias-corr. minimum air temperature (°C)	

According to the Intergovernmental Panel on Climate Change (IPCC) [31], climate model projections on mean air temperature based on different emission scenarios diverge only marginally in the near future (*i.e.*, by 2050). These magnitudes are, however, significantly different for the rest of the projection period (2050–2100). Considering this, we selected the periods 1961–1990 (reference period) and 2011–2040 (projection period) as the basis for our analyses in order to allow for the availability of only data referring to the A1B scenario and thus increase the representativeness of this case study. Another justification lies in the fact that, from the ÖBB natural hazard management perspective, the near future is more of a concern with regard to non-structural risk management than the far future.

3.2. Frequency Analysis of CMCs in A Changing Climate

The core of this study was to assess the climate change-related alteration of frequencies of CMCs until 2040. The underlying threshold criteria for CMCs were directly drawn from the weather monitoring and warning system Infra:Wetter (see Section 2 and Table 1a) and applied to the individual RCM simulation runs. It must be noted that the original list of CMCs contains further thresholds (*i.e.*, criteria of snow-breakage, floods, and storms). Due to RCM data availability constraints, however, an analysis of these CMCs is currently impossible and they are, therefore, neglected in this study. The analyses on very intensive rainfall and intensive rainfall with high antecedent soil moisture were conducted on the basis of the pr variable, the heat wave frequencies were assessed using the tmax variable, the extreme cold threshold is referring to the tmin variable, and the psno variable was used to quantify the CMC frequencies regarding first heavy seasonal snowfall (see Table 3). While the RCM datasets were used on a seasonal basis concerning climate signals in Austria, the CMC frequency analyses now are referring to the entire time period, with one exception: The criterion for first heavy seasonal snowfall is truncated to only early seasonal events *(i.e.,* September and October), since these are of particular interest for railway operation purposes with regard to the commencement and coordination of railway winter services. Another exception is made for the regionalization of CMC occurrences. Due to the insufficient resolution of the available RCMs (25 km), the frequency analyses are not consistently differentiated by specific regions (e.g., federal states, operational sections), but mainly provide information at the national level. The CMCs for very intensive rainfall and first heavy seasonal snowfall, however, are applied separately for the Alpine area and the lowlands of Austria in order to account for the differing threshold criteria for each of these greater areas (see Table 1a).

In a first step of the frequency analyses, the absolute number of days of threshold exceedance in the individual RCM datasets for both the reference period and the projection period were quantified for each CMC. Next, the percentage change of threshold exceedances as compared to the reference period was analyzed. Finally, the mean percentage change over all model-specific CMC frequencies was computed on the basis of (1) the mean of the model-specific absolute number of days of threshold exceedance in the reference period; (2) the mean of the model-specific absolute number of days of threshold exceedance for the projection period.

3.3. Sensitivity Analysis

In order to obtain an indication of the sensitivity of the results, the frequency analysis was repeated using modified threshold values. Table 1b displays the new threshold criteria of the meteorological extremes under consideration. The very intensive rainfall criteria have each been modified towards a reduction of the rainfall intensity for both regions. With respect to the criteria for intensive rainfall accompanied by high antecedent soil moisture, we likewise defined two new variants that both intended to reduce the intensity of underlying precipitation events. The sensitivity of first heavy seasonal snowfall was tested by decreasing only the threshold value for the Alpine region by 25%, since the threshold value for the Austrian lowland is being considered as already appropriate. Extreme cold days were redefined by changing the minimum air temperature from initially −20 °C to −15 °C. Finally, we modified the heat wave criteria with respect to the required duration of the event to be "critical". All modifications are derived from internal discussions with railway experts and based on the premise that respective original CMCs are likely to be underrated and, as such, less extreme thresholds can already pose similar risks to railway operations.

4. Results

4.1. A Glance at Austria's Potential Future Climate

The following section presents the seasonal climate signals for air temperature and precipitation for Austria in order to provide a general overview of the characteristics of the RCM datasets used for the subsequent frequency analyses (see Sections 3.2 and 4.2), and to assess the robustness of the climate change signals.

Figure 2 depicts the mean percentage difference of rainfall in the winter season as projected by the selected RCMs. Three out of four models project a maximum increase in rainfall varying between around 14%–19% for the central and eastern part of Austria, whereas for the country's western part the rainfall is likely to decrease by up to around 9%. Regarding the spatial patterns, the DMI-model, the KNMI-model, and the MPI-model agree quite well. The METO-HC-model, however, is contradictory to the other models, since it indicates an opposite spatial trend in rainfall. In order to further evaluate the depicted signals, the percentage averages of rainfall change for Austria are specified in Table 4. Herein, the average changes show a marginal increase of approximately 5%–10% for the models DMI, KNMI, and MPI, whereas the METO-HC-model is likewise contradictory by calculating a slight decrease of around 4%. According to IPCC [31], a simple approach to assess the robustness of climate change signals is to check the matching rate of simulation results with respect to the direction of change. They define a signal direction as being "likely" if more than 66% of all results agree in the respective direction. Following this approach, the mean rainfall in the winter season in Austria can be considered as likely to (marginally) increase until 2040.

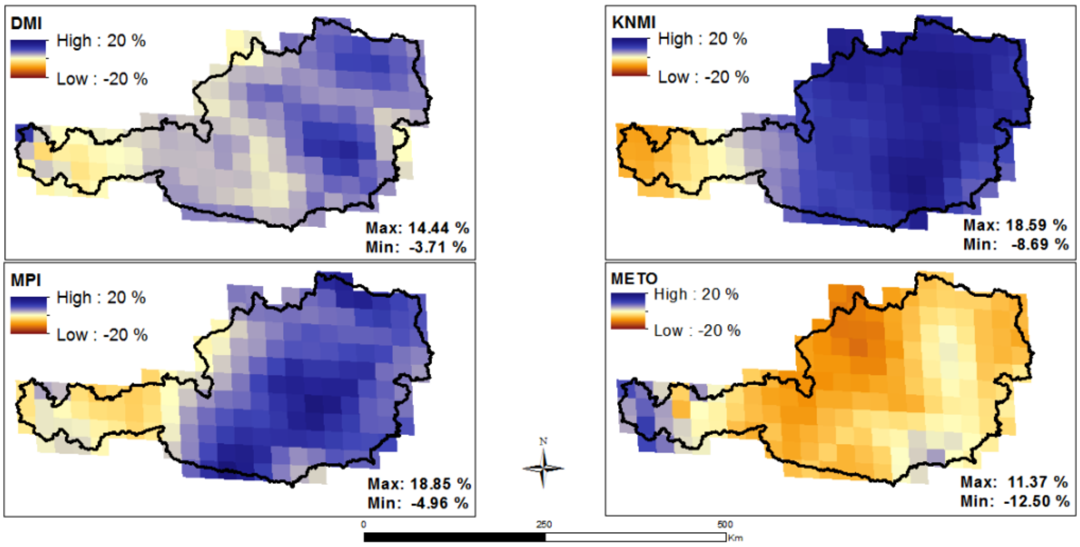

Figure 2. Percentage difference of mean rainfall in the winter season (DJF) between the periods 1961–1990 and 2011–2040.

Table 4. Arithmetic mean values (m), standard deviations (s), and coefficients of variation (CV) of changes in temperature and precipitation in Austria according to the different RCM results (DJF: winter season; JJA: summer season).

	DMI			**KNMI**			**MPI**			**METO-HC**		
Temperature (K) DJF	0.67	0.06	0.09	0.98	0.09	0.09	1.17	0.19	0.16	2.16	0.09	0.04
Temperature (K) JJA	0.22	0.15	0.69	1.00	0.07	0.07	0.92	0.08	0.09	1.07	0.05	0.05
Rainfall (%) DJF	4.79	3.46	0.72	10.21	6.83	0.66	7.11	5.63	0.79	−4.25	4.76	1.11
Rainfall (%) JJA	9.55	6.01	0.62	−3.92	2.47	0.62	−2.82	4.59	1.62	7.74	3.47	0.44
Snowfall (%) DJF	−5.26	6.06	1.15	−6.89	4.27	0.61	−8.80	4.99	0.56	−32.43	10.91	0.33
	m	s	CV	m	s	CV	m	s	CV	m	s	CV

Figure 3 illustrates the projected trends of mean snowfall in winter. All four models agree in a moderate to strong decrease in snow precipitation throughout most of Austria until 2040. The METO-HC-model again stands out, since its calculated average is substantially lower than the other ones, however, the standard deviation is also the highest one in the model set of this study (see Table 4). Although the projected maximum relative decrease in snow quantity between the selected periods is varying considerably over all models ranging from approx. −18% to −48%, the climate change signals show a robust negative direction when assessed by the approach of IPCC [31].

The changes in absolute mean air temperature in the winter season until 2040 are illustrated in Figure 4. As clearly indicated by the climate signal maps, all RCMs show an increase in air temperature throughout Austria. While the DMI-model is showing the smallest increase, ranging from approximately 0.5 K to more than 0.8 K, the KNMI-model and the MPI-model both compute a maximum increase in air temperature amounting to approximately 1.1 K and 1.4 K, respectively. The METO-HC-model behaves again exceptionally, since its results show a significantly stronger increase in mean temperature in winter season than the other models, varying between approximately 1.8 K and 2.4 K. Regarding the spatial patterns, the projections mostly agree that the lowland areas of Austria (*i.e.*, the east of the country), experience the largest relative increase, whereas for the Alpine region a comparatively lower increase can be expected. Looking at the statistics, the model's mean values are ranging from approximately 0.7 K (DMI) to 2.2 K (METO-HC), accompanied by moderate standard deviations spanning from 0.06 K (DMI) to 0.2 K (MPI), which finally leads to low variation coefficients in the data. In conclusion, the findings on the increase in mean air temperatures in Austrian winter seasons until 2040 are considered to be robust in the IPCC terminology.

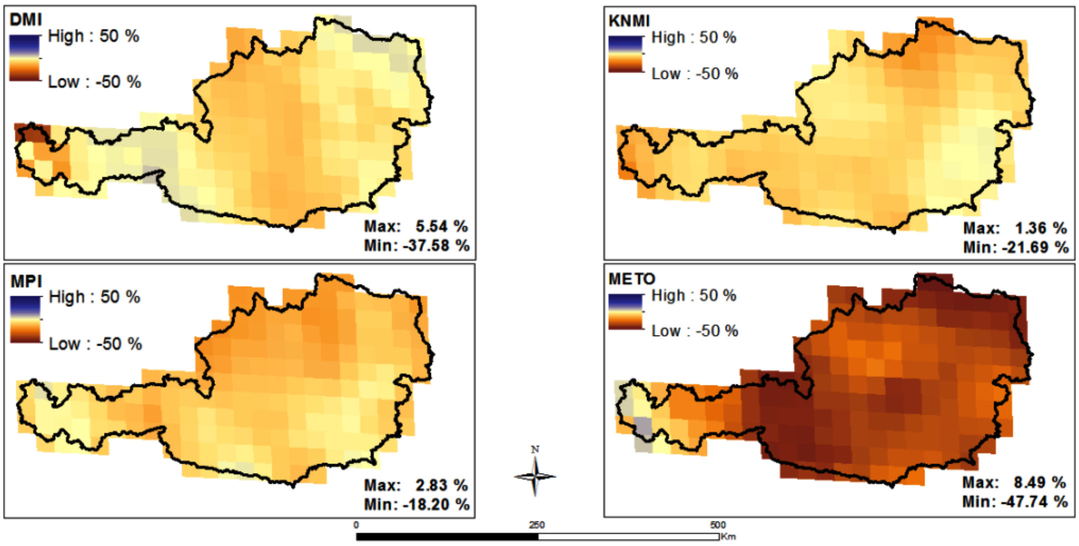

Figure 3. Percentage difference of mean snowfall in the winter season between the periods 1961–1990 and 2011–2040.

In the summer season (JJA) only rainfall is considered, since snowfall rarely occurs or in extremely low quantities even in the high mountainous regions of Austria. The percentage differences of mean rainfall for JJA based on the RCM selection are illustrated in Figure 5. The models disagree in the direction as well as the quantities of projected changes in Austria, since the mean percentage changes range from around −4% (MPI) to −12% (METO-HC) in the negative direction, and from around 2% (KNMI) to 34% (DMI) in the positive direction. Furthermore, there is only scarce consistency in the projections with respect to the depicted spatial patterns of changes. The DMI-model and the METO-HC-model indicate an overall increase in summer rainfall, whereas the KNMI-model and the MPI-model assume an overall decrease. Looking at the regional level reveals further disagreements particularly in the high Alpine area of Austria (*i.e.*, in the far west). These discordances are also reflected in the basic statistics of the data sets (see Table 4). Therein, the DMI-model and the METO-HC-model show a positive arithmetic mean value of percentage change, whereas the other two models indicate an overall negative direction. Thus, the model ensemble does not give robust information on the development on summer rainfall until 2040.

Finally, the results of the analysis for mean air temperature change in the summer season are displayed in Figure 6. The general trend observed in the winter season is also obvious here, since all model results show an increase throughout the country for the summer season until 2040. Herein, the DMI-model is showing the greatest span ranging from no changes to a maximum increase of more than 1.3 K, however, large parts of the Austrian territory only face a very small increase in mean air temperature. The results of the remaining three models are closely related, as their projected bandwidths are of a similar nature ranging from roughly 0.8 K to 1.3 K. Reviewing the statistics likewise shows a significant temperature rise in three out of four models amounting to around 1 K. Since the respective coefficients of variation are far below 1, only marginal data scattering is indicated. The DMI-model, however, breaks ranks by stating a lower increase of approximately 0.2 K on average, although the coefficient of variation is considerably higher for these data. Nevertheless, following the IPCC [31] guidelines, the projected increase in mean air temperature in the summer season can be described as robust.

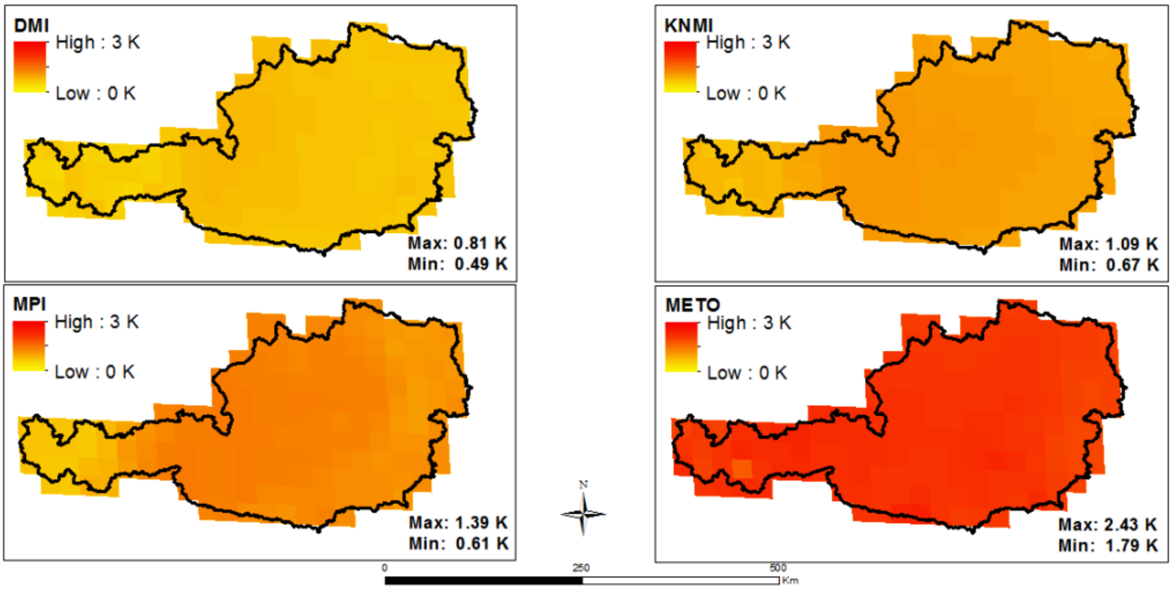

Figure 4. Absolute difference of mean air temperature in the winter season (DJF) between the periods 1961–1990 and 2011–2040.

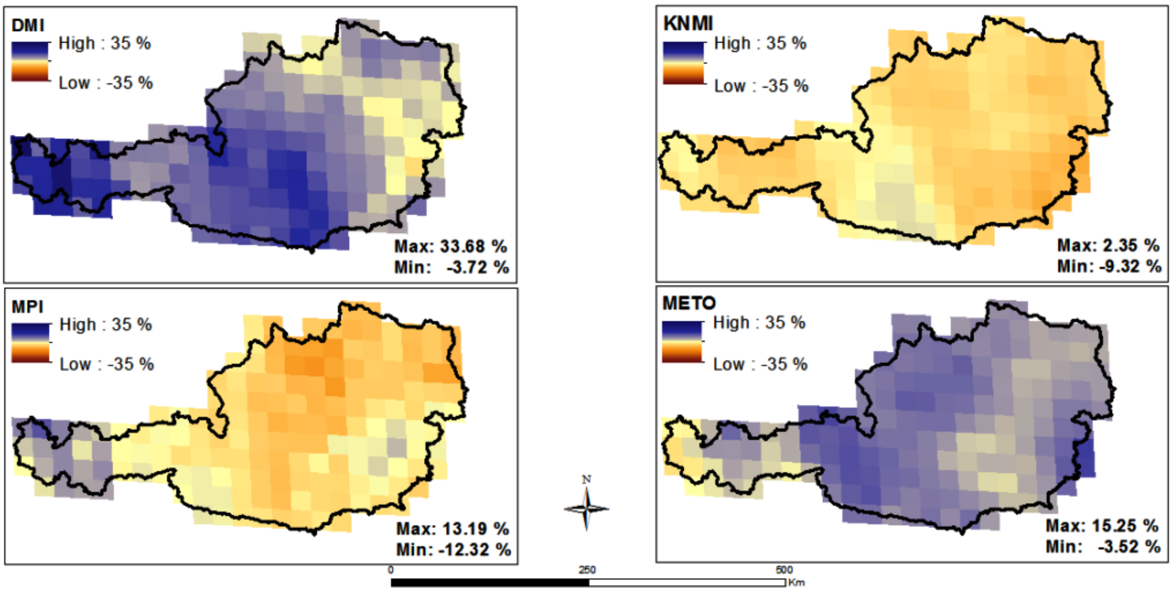

Figure 5. Percentage difference of mean rainfall in the summer season (JJA) between the periods 1961–1990 and 2011–2040.

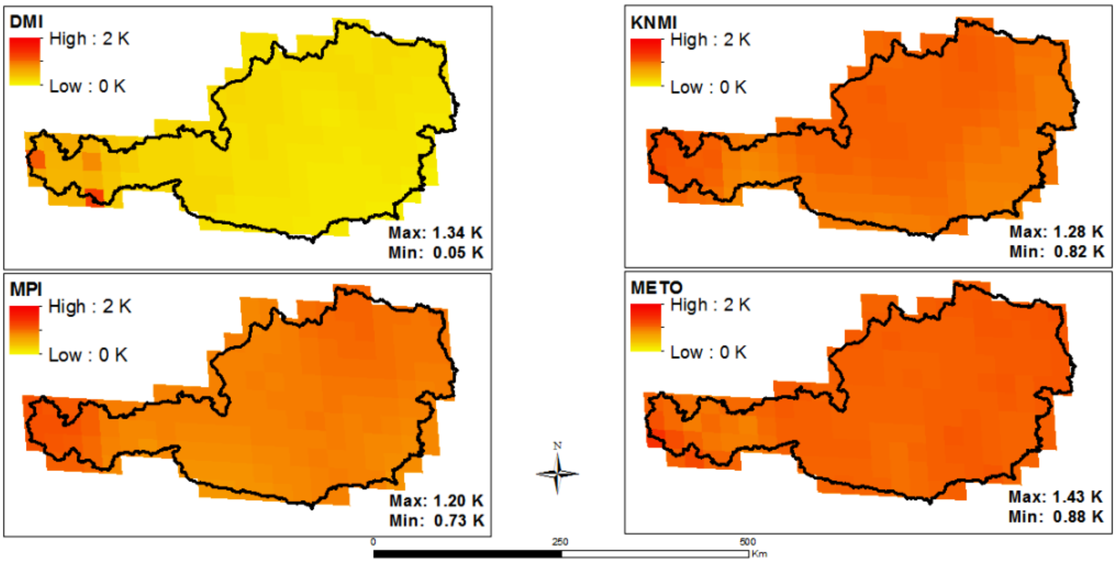

Figure 6. Absolute difference of mean air temperature in the summer season (JJA) between the periods 1961–1990 and 2011–2040.

4.2. Climate Change Impacts on the CMC Frequencies

In the next step, possible impacts of climate change on the frequencies of CMCs in the projection period were investigated. Table 5a shows the detailed results for all RCMs and every CMC. On average, the very intensive rainfall frequency (⩾100 mm/24 h) undergoes a relative change of +36% in the Alpine region, which clearly indicates a significant increase in days with extreme rainfall events for the future period. This finding is also reflected in the individual model results, since all changes in frequencies show a positive direction. This also applies for the Austrian lowlands (⩾60 mm/24 h), since a strong relative increase of 70% on average is calculated. Considering the absolute number of days with critical rainfall in the reference period, the DMI-model indicates a conspicuously high value for the Alpine region, whereas the other three models widely agree in the total number of events. In this respect, the model outcomes for the lowland area are more balanced.

The results for the frequency analysis of intensive rainfall accompanied by high antecedent soil moisture draw a different picture. The DMI-model, indeed, stands out again by indicating exceptionally high event occurrences in the reference period compared to the other RCMs in the ensemble. However, in contrast to the results for the CMC very intensive rainfall, two specific disparities can be identified: (1) the intensive rainfall accompanied by high antecedent soil moisture frequency seems to remain more or less the same showing a marginal decrease of 5% on average and (2) the models disagree in the direction of change.

With respect to first heavy seasonal snowfall in the early seasons until 2040, the CMC frequency analyses show a slight overall decrease of 9% in the Alps. Three out of four models agree in the decline of heavy snowfall in September or October. Contrary to the two previous precipitation criteria, however, the KNMI-model now behaves exceptionally instead of the DMI-model by indicating a relative increase of around 30%. Another peculiarity is that the individual reference values show a certain convergence compared to the previous precipitation-related indicators. In the Austrian lowlands, future first heavy seasonal snowfall frequencies overall are markedly decreasing by around −35%. Interestingly, the METO-HC-model now suggests a positive direction in the frequency alteration of first heavy seasonal snowfall, whereas the KNMI-model shows no change at all. The underlying numbers of events in the reference period are, as expected, considerably lower than those for the Alpine region.

Table 5. Changes in frequencies of critical meteorological conditions (CMCs). Section (**a**) shows the changes in frequencies of CMCs (see Table 1a) between the reference period 1961–1990 and the projection period 2011–2040 based on individual RCM simulations. The mean relative change of the individual CMC frequency for the projection period is calculated on the basis of the absolute mean values of all model results for both periods (see text for the abbreviations). In Section (**b**), the changes in frequencies of CMCs resulting from the modification of the threshold criteria (see Table 1b) are depicted. The mean relative change of the individual CMC frequency for the projection period is calculated on the basis of the absolute mean values of all model results for both periods.

(a)				**(b)**			
Critical Meteorological Condition (CMC)	**Regional Climate Model (RCM)**	**Number of CMCs in the Reference Period**	**Relative Change of Frequencies in the Future Period**	**Critical Meteorological Condition (CMC)**	**Regional Climate Model (RCM)**	**Number of CMCs in the Reference Period**	**Relative Change of Frequencies in the Future Period**
		(1961–1990)	**(2011–2040)**			**(1961–1990)**	**(2011–2040)**
Very intensive rainfall—Alps	DMI	65	17%	*Very intensive rainfall—Alps*	DMI	106	19%
	KNMI	1	100%		KNMI	6	83%
	METO	2	200%		METO	2	1050%
	MPI	1	900%		MPI	7	300%
	mean	**17**	**36%**		**mean**	**30**	**55%**
Very intensive rainfall—Lowlands	DMI	3	233%	*Very intensive rainfall—Lowlands*	DMI	11	118%
	KNMI	6	17%		KNMI	12	42%
	METO	7	86%		METO	14	114%
	MPI	7	29%		MPI	21	5%
	mean	**6**	**70%**		**mean**	**15**	**60%**
Intensive rainfall with high antecedent soil moisture	DMI	78	−9%	*Intensive rainfall with high antecedent soil moisture—variant 1*	DMI	100	−10%
	KNMI	2	−50%		KNMI	4	−25%
	METO	1	300%		METO	2	200%
	MPI	2	50%		MPI	2	500%
	mean	**21**	**−5%**		**mean**	**27**	**-2%**
				Intensive rainfall with high antecedent soil moisture - variant 2	DMI	175	12%
					KNMI	23	−26%
					METO	19	42%
					MPI	26	19%
					mean	**61**	**12%**
First heavy seasonal snowfall—Alps	DMI	37	−43%	*First heavy seasonal snowfall—Alps*	DMI	81	−42%
	KNMI	33	30%		KNMI	59	22%
	METO	54	−17%		METO	95	−21%
	MPI	76	−4%		MPI	131	−24%
	mean	**50**	**−9%**		**mean**	**91**	**−20%**
First heavy seasonal snowfall—Lowlands	DMI	4	−75%				
	KNMI	1	0%				
	METO	4	25%				
	MPI	8	−50%				
	mean	**4**	**−35%**				
Extreme cold	DMI	206	−16%	*Extreme cold*	DMI	825	−19%
	KNMI	178	−20%		KNMI	817	−19%
	METO	486	−33%		METO	904	−52%
	MPI	165	−73%		MPI	1264	−19%
	mean	**259**	**−34%**		**mean**	**953**	**−27%**
Heat wave	DMI	0	-	*Heat wave*	DMI	4	225%
	KNMI	0	-		KNMI	3	133%
	METO	1	100%		METO	7	814%
	MPI	2	1150%		MPI	7	0%
	mean	**1**	**933%**		**mean**	**5**	**333%**

The days of extreme cold are likely to decrease in Austria in the projection period, since the mean percentage change is amounting to approximately −34%. All RCMs show the same tendencies, however, both the individual absolute values and the percentage changes differ markedly. Despite the indicated decrease, the CMC extreme cold seems to remain the most frequent extreme weather event in the projection period.

Finally, an extreme mean relative increase in heat wave events of approximately 933% is projected until 2040. This high amount is, however, due to the low absolute number of such events in the reference period. Furthermore, all RCMs agree with respect to the direction of change, which demonstrates a high robustness of the results. Since the DMI-model and the KNMI-model showed no events in the reference period, the calculation of corresponding relative change of these frequencies is mathematically not possible. In total, although heat waves only play a very minor role for natural hazards management so far, they are likely to become more important in the future.

4.3. How Sensitive are CMC Frequencies to Changes in Threshold Values?

The threshold criteria for the CMCs as shown in Table 1a were modified according to Table 1b and the frequency analysis was conducted again with the aim to obtain an indication of the impacts of threshold modification on the changes of frequencies of extreme weather events until 2040 (see Section 3.3). Table 5b provides the respective results for all modified CMCs. The reduction of the intensity for very intensive rainfall by 20 mm led to a considerable increase in the mean percentage change of 55% in future frequencies in the Alps. The underlying reference values also increased except for the METO-HC-model, which suggests the same number of events in the reference period by simultaneously signalizing a much higher increase in future frequencies compared to its results based on original thresholds. Regarding very intensive rainfall in the lowlands, the reference values likewise increased consistently, however, the mean relative change shows a lower increase in the future frequency compared to the original results.

The threshold criteria for the CMC intensive rainfall accompanied by high antecedent soil moisture were modified in two different ways (see Table 1b). The results for the modification variant 1, which comprises an increase in the maximum number of days to reach the threshold of precipitation to be defined as critical antecedent rainfall, show only a marginal change both in the mean percentage change and the reference values in comparison with the previous findings. Furthermore, the initial order of magnitudes of the reference values among the different models in principle remained the same, since the DMI-model still states an exceptional high number of past events. The model-specific frequency changes, however, were significantly altered. Now, the MPI-model suggests the highest relative increase in intensive rainfall events accompanied by high antecedent soil moisture while maintaining the number of past events. The modification variant 2 is premised on a reduction of the precipitation sum of antecedent rainfall as well as a halving of the precipitation sum of the final rainfall event. As a result, considerable differences are revealed in the magnitudes of both the number of past events and the percentage change until 2040 as compared to the results based on the original criteria. While the former markedly increased in all models, the latter even changed the direction from a very small decrease to a notable increase in the frequency of approximately 12%. On the model level, the KNMI-model is now the only RCM that still issues a decrease in the frequency for the projection period, whereas the DMI-model joined the estimation of the METO-HC-model and the MPI-model with respect to the direction of change.

Critical snowfall events in the early season were only modified for the Alpine area (see Section 3.3). The reduction of the event intensity led to a marked increase in the number of events in the reference period in all four RCMs. The mean percentage changes in the projection period, however, retained their individual direction of change, whereby the KNMI-model is still the only RCM indicating an overall positive trend in the future frequency of snowfall events. Furthermore, the mean percentage change over all models significantly changed towards a stronger decline of CMCs in comparison to the values resulting from the original threshold, which is mainly due to the considerable variation of the MPI-model.

The decrease in the intensity of extreme cold events had a strong impact on the registered CMCs in the reference period in all RCMs as all absolute values have multiplied. However, the mean relative changes until 2040 almost remained the same in the DMI-model and the KNMI-model. Changes are more significant in the METO-HC-model, which depicts a stronger decrease in the future frequency of around 19%, and the MPI-model, which suggests a difference of more than 50% towards a lower decrease of the future frequency. Overall, the mean percentage change of extreme cold occurrences based on the modified threshold criteria is marginally lower than the original mean estimation.

Finally, looking at the averaged results for heat wave shows (1) a quintupled number of events in the reference period; and (2) a less sharp rise in the future frequency amounting to 333%. In contrast to the previous results (see Section 4.2 and Table 5a), all individual RCM simulation runs now contain a certain number of events in the reference period. Interestingly, the MPI-model, which initially calculated the highest increase in heat wave events for the future period, now concludes that there will be no change in their frequency.

5. Discussion

The main objective of this study was to analyze possible climate change impacts on frequencies of extreme weather events jeopardizing railway operations in Austria. For this, the RCM ensemble simulations for two periods (*i.e.*, 1961–1990 (reference period) and 2011–2040 (projection period)) were used in order to (1) investigate the projected changes in the occurrence of critical meteorological conditions (CMCs) for railway transportation and (2) test the sensitivity of frequencies of extreme weather events for varying threshold criteria. The climatic elements of air temperature and precipitation are the decisive factors for relevant extreme weather events, wherefore the respective climate change signals as well as the robustness of the directions of change are characterized and discussed first. All analyses presented in this paper may involve a considerable degree of uncertainty, mainly because the underlying RCMs possess only limited validity—in particular in the complex topography of Alpine regions [15,32,33], where small-scale orographic conditions and related influences on weather dynamics cannot be fully reproduced. This aspect must be considered in drawing conclusions based on the provided results.

The investigation of projected mean changes of air temperature and precipitation as provided by the selected RCM ensemble yielded different results. First, the recurrent deviations of the METO-HC results in comparison to the rather similar signals provided by the other three RCMs are striking. This general observation can be explained by the fact that the climate produced RCM largely reflects the climate variability of the driving GCM [34]. Hence, since the METO-HC model is the only model in the ensemble driven by the GCM "HadCM3Q0", whereas the other three models are driven by the GCM "ECHAM5" (see Table 2), the different characteristics of these two GCMs are also reflected to a certain extent in the results of the RCMs.

With respect to changes in rainfall, the simulations rather disagree either in seasonal and in spatial patterns except for the broad agreement in a marginal increase in mean rainfall in the winter season. Accordingly, the investigation of precipitation change revealed no robust tendency in the direction of change. The marked deviations in the RCMs clearly indicate that there is still high uncertainty in the model projections related to rainfall, which is also reflected in the high value of the coefficients of variation of the data. These results are in broad agreement with several previous studies on precipitation under climate change in Europe, which likewise have discovered substantial variations and disagreements of rainfall trends both in terms of seasonal and spatial patterns (e.g., [17,18]). The snowfall signal, however, draws a different picture, since the selected RCMs widely agree in a significant decrease in snowfall quantities for most of the area of investigation until 2040. Results on temperature signals are even more unambiguous with respect to the direction of change towards a significant rise in air temperature for both seasons and the whole of Austria. The latter findings equally concur with other studies on climate change in Europe, and particularly the Alps, which likewise show a significant increase in mean air temperature in all seasons and in all regions (e.g., [9–16]).

Extreme rainfall events rank among the most important meteorological hazards for risk management of railway transportation in Austria (see Section 2). Besides the considerable damaging potential of this event type itself, (very) intensive rainfall is furthermore an important trigger for other natural hazards such as (flash) floods, torrential processes, and debris flows.

The frequency analysis indicates a significant increase in intensive rainfall in the projection period (+36%). By reducing the threshold, the number of past events noticeably increased in all RCM results. Additionally, these changes led to an even higher increase in future frequency in the Alpine region, whereas the frequency in the lowlands is projected to experience a slightly lower increase. Although such analyses are subject to a variety of limitations and uncertainties, all RCMs give indications towards a considerable increase of extreme rainfall events in the projection period. This finding is also confirmed by several related studies, which also come to the conclusion that the frequencies and intensities of extreme rainfall events must be expected to rise in Europe and, depending on the season, also in the Alps [22,28,35]. The projected change in the precipitation-related risk is likely to intensify problems such as overloading of the drainage systems leading to (flash) flooding and/or scouring of track lines and other infrastructure elements.

The CMC intensive rainfall with high antecedent soil moisture is closely linked to the previous rainfall indicator, since unfavorable high antecedent soil moisture is mostly a result of either continuous rainfall or a couple of rainfall events occurring in a close sequence. Hence, a change in rainfall frequencies, sums, and/or intensities mostly has an effect on the soil moisture conditions in the affected region. Rainfall-related extreme events are therefore considered to have a significant impact on the hazard profile confirming the strong need of consideration with regard to natural risks management. Based on the original CMC threshold, the frequency shows a marginal decrease of 5% in the projection period. We modified this specific CMC according to two different variants (see Table 1b). The first variant considered a reduction of precipitation intensity in the preceding time. In this case, the result related to projected frequencies shows only marginal sensitivity to the modification. A different picture emerges for the second modification variant, in which the intensity of the final precipitation event was reduced. Although the mean relative increase in the frequency for the projection period is manageable, the reference value is distinctively higher than in the previous results. Similar to the effects associated with preceding rainfall-related threshold modifications, an aggravation of the risk, at least in susceptible areas, must be taken into account in the future.

With a 17% share of all damaging events between 1991 and 2011 [5], first heavy seasonal snowfall events are also of certain importance for ÖBB risk management. Looking at the projected frequencies of this CMC shows a slight (Alps) to significant (Lowlands) decrease. The reduction of the critical threshold value in Alpine areas led to a further decrease from the initial −9% to −20%. This shows a certain sensitivity of the CMC occurrence to changes in the threshold criteria. Nevertheless, since there is a robust signal in the RCM ensemble towards a considerable mean temperature increase in the projection period, as well as a decrease of mean snowfall, the projections for the direction of future first heavy seasonal snowfall event frequencies are considered to be generally robust as well. Hence, the likely changes can be considered as having an overall positive effect on railway operations. Winter services, for instance, will probably be somewhat relieved at the beginning of future winter seasons, since switch malfunctions caused by snow fall or snow drift potentially decrease—at least during September and October.

Extreme cold is the by far most frequent meteorological extreme in the study area. This CMC can cause frost damage to infrastructure elements such as the freezing of switch points, which can lead to significant service disruptions and associated costs. The frequency of extremely cold days is likely to decrease markedly by around one third when applying the original CMC thresholds. This result is in accordance with the projected increase in mean air temperature in the winter season (see Section 4.1). However, besides the positive effects for railway infrastructure maintenance and winter services, this change might also have negative effects. A reduction of frost days could, for instance, lead to the thawing of permafrost and thus cause destabilizations of masses of rocks and debris, for example—especially in areas showing a particular susceptibility to mass movements [36]. Subsequently, an increase of hazardous landslide and debris flow-related events must be taken into account. Warmer temperatures in winter can also cause unfavorable wet snow that is able to generate serious snow loads (e.g., on trees or catenary). Such loads, in turn, can cause significant direct or indirect damage to railway infrastructure and services [36].

Heat waves have been of comparatively low importance in the ÖBB natural hazards management so far. Since 1991 only two damaging heat waves (in 1994) have been recorded in the ÖBB damage database, which amounts to less than 1% of all critical meteorological events [5]. Since the frequency analyses indicate a high relative increase until 2040, management of heat waves is likely to become more important in the projection period. The reduction of the CMC-threshold from five to three days caused a considerably less strong relative increase in heat wave frequencies until 2040 compared to the initial criterion. However, the reference values are considerably higher, meaning that in absolute terms heat waves of shorter duration occur more frequently both in the reference and in the projection period. In general, the sensitivity analysis demonstrated a high sensitivity of the models with regard to this CMC threshold. Potential future implications of the projected increase of heat wave frequencies are, for example, (1) thermal stress for passengers, staff, tractive units [37], and electronic infrastructure elements such as signals [38]; (2) increasing risk of wild fires [22]; and (3) increasing risk of rail buckling [39]. On the first aspect, heat waves can overstress, *inter alia*, the air-conditioning systems in trains and thus cause significant thermal stress in particular to elderly passengers and infants. Secondly, high temperatures and dry weather conditions increase the risk of wild fires along tracks due to flying sparks occurring during the braking procedure of trains, which can cause considerable service disruptions. The last implication poses a great threat to railway operation due to the high risk of derailment as well as significant costs caused by speed restrictions. Using the south-east region of the UK as an example, Dobney *et al.* [39] showed that railway infrastructure is already at risk of severe rail buckling within a temperature range of approx. 25 °C and 39 °C (ambient air temperature) depending on the condition of the track. The risk is assumed to significantly increase with the increase in the duration of high temperatures. The exceptionally hot summer in 2015 in Europe might provide more empirical data to derive representative thresholds for heat stress on railway infrastructure.

6. Conclusions

The frequency analysis of extreme weather conditions in a changing climate revealed a noticeable to strong alteration of the current hazard profile in Austria. Notwithstanding the fact that climate change impacts can also have positive effects on some sectors (e.g., winter service), the occurrence of the most relevant type of CMC analyzed (*i.e.*, very intensive rainfall events) is likely to increase significantly in the future, which, overall, leads to new challenges for the ÖBB natural hazards management. If no action is taken, the costs due to extreme weather events must be expected to rise in the future. Based on historical experiences (e.g., from the extreme rainfall event in 2013), the weather monitoring and warning system Infra:Wetter proved to be a rather cost-effective non-structural risk mitigation measure. However, the modification of the thresholds for the identification of CMCs revealed that frequencies of extreme weather events are quite sensitive to changes of this decisive factor. In the context of climate change, this result emphasizes the importance to carefully define and constantly adapt and validate the thresholds in order to optimize the effectiveness as well as the adaptive capacity of a weather monitoring and warning system. Since the necessary data for an empirical evaluation of the threshold are currently not available in respect to data quality and temporal coverage, the importance of continuously collecting detailed event and damage data following a standardized procedure is striking. Event documentation including "near misses" can enable risk managers to better understand and learn from historical events and thus adapt natural hazards management according to future changes. For example, a comprehensive data basis would facilitate a reliable assessment of expected impacts in a quantitative way (e.g., estimation of expected damages and/or service disruptions in the projection period).

While the ÖBB already collects detailed damage data due to natural hazards, and currently further elaborates this system, no such reporting exists in many other European member states or at the European level. The existence of a European damage database for natural hazards could, however, significantly contribute to improving the understanding of damaging processes to railway infrastructure, the proportional share of different natural hazards to overall losses, and thus to the development of strategic risk management. For instance, a risk assessment of the Trans-European Transport Network (TEN-T) could provide guidance on where to invest European Community funds in risk reduction. This appears especially important given the substantial investments of EUR 26.25 billion into transport infrastructure up to 2020 [40]. In order to enhance risk management of railway infrastructure at the European level as well, the reporting system according to Regulation (EC) 91/2003 of the European Parliament and of the Council on rail transport statistics could be complemented with information on the impacts of natural hazards. These statistics on rail safety are required by the commission "in order to prepare and monitor Community actions in the field of transport safety" (EC 91/2003). While accidents resulting from collisions, derailments, accidents involving level crossings, accidents to persons caused by rolling stock in motion, fires in rolling stock, and 'others' are accounted for, damage due to natural hazards is currently not an individual category. How and what type of information to include in such a European database could be informed by the experience gathered by national railway operators such as the ÖBB.

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