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Call 2012: Road owners adapting to Climate Change

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Conference of European Directors of Roads

Climate projection data base for roads: CliPDaR

Final Report

Deliverable D3.2

The **CliPDaR** Consortium:

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DWD

ZAMG

CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMME
Call 2012

Design guideline for a transnational database of downscaled climate projection data for road impact models - CliPDaR

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Preliminary remark

Concerning the CEDR DoRN 2012 Call "Road owners adapting to Climate Change" the Project CliPDaR ("Design guideline for a transnational database of downscaled climate projection data for road impact models" (long title)) refers exclusively to the objective "A.1 - Review, analysis and assessment of existing (regional) Climate Change projections regarding transnational highway networks (TEN-T) needs". Regarding the questions of this objective the project CliPDaR is engaged in

- Assessment of statistical/dynamical downscaling: to facilitate a proper procedure that deals with the uncertainties of the future climate with respect to the needs of future budgets and maintenance issues
- Assessment of ensemble simulations and climate projections as well as the definition of a pragmatic data provision for decision making
- Assessment of future cold winters and hot summers in Europe.

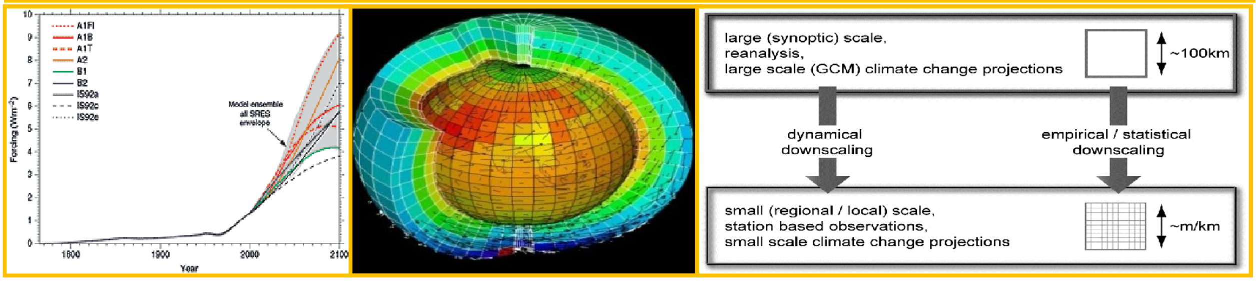
Because of the given short time line and the very limited budget a provision of data is not foreseen within the frame of this project and emphasis is given to the results from already ongoing projects, in particular VALUE (http://www.value-cost.eu/) and KLIWAS (www.kliwas.de), to contribute to a paper of recommendations for the involved national road agencies.

The mission of CliPDaR is to identify and describe risk related areas of European transport corridors in the context of climate change.

Dissemination Strategy

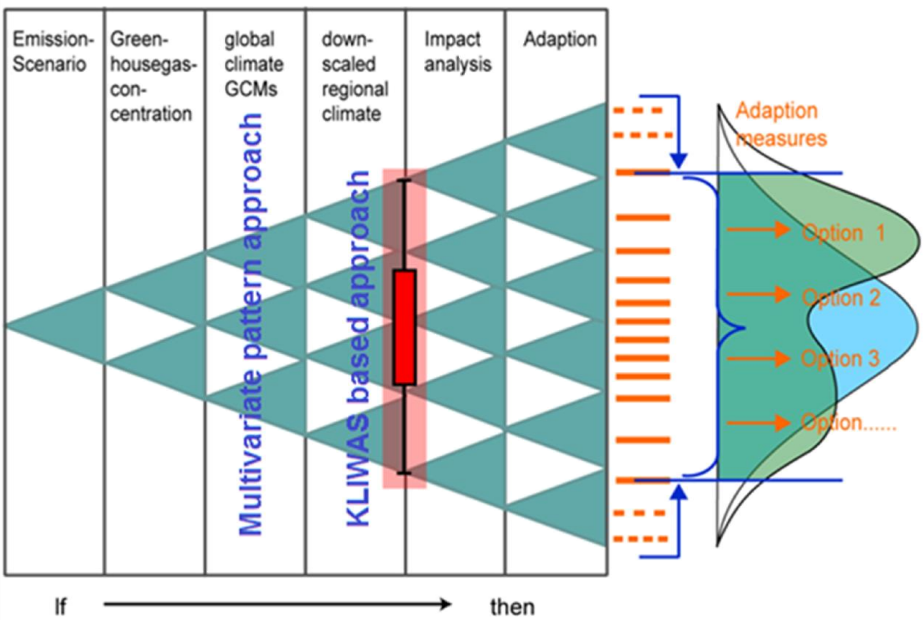
CliPDaR was presented at a number of international/national conferences:

- Klimatag 2013 – Vienna (Austria) in April, 2013
- EGU 2013 – Vienna (Austria) in April, 2013
- FEHRL FIRM 2013 – Brussels (Belgium) in June, 2013
- DACH 2014 – Innsbruck (Austria) in October, 2013
- EMS&ECAM (short intro) – Reading (UK) in October, 2013
- MeteorologInnenTag 2013 – Feldkirch (Austria) in November, 2013
- Klimatag 2014 – Innsbruck (Austria) in April, 2014
- TRA 2014 – Paris (France) in April, 2014
- EGU 2014 – Vienna (Austria) in May, 2014
- Six deliverables and one guideline to the CEDR
- Scientific, peer-reviewed paper "Design guideline for a Climate Projection Data base and specific climate indices for Roads: CliPDaR, C. Matulla [et al.] (sciencesconf.org:tra2014:17592)".



Q 1. What can be said about the robustness of downscaling techniques used to generate regional to local scale climate change scenarios in the context of the entire uncertainty coming with climate change modelling?

Background: Regional scale climate change scenarios (henceforth called “origins”) are the proper basis for decision making on future requirements for construction and design, reinforcement measures and maintenance work of European transport corridors in the context of climate change. The creation of origins involves a handful of analysis steps each inherently associated with uncertainties. **Figure 1** depicts the production process starting with scenarios of how mankind may evolve, which are translated into emission scenarios (first column) forcing global climate models (GCMs, second column) mimicking the response of the climate system to 1.1 this forcing. These projections of possible future physical states of the climate system are consistent on the so called *skillful scale*, which is about 8 times 8 the grid distance (Joannesson et al. 1995), but not below. As such a further analysis step called “Downscaling” (von Storch et al. 1993) is needed to retrieve information on the scale representative for the European transport system. There are four Downscaling techniques available - weather classification schemes, regression methods, weather generators and dynamical downscaling (Wilby and Wigley 1997).



<u>**Figure 1:**</u> *Starting from a particular emission scenario the uncertainty grows with every step that is necessary to derive different adaptation measures to deal with the impact of climate change (schematic diagram). Please note the two approaches “Multivariate pattern” and “KLIWAS” used here to address the “extreme cold winter and hot summer season issue”, which will be used to answer CEDR questions in this guideline later. Source: after Viner 2002, adapted.*

Answer: The performance of the Downscaling techniques depends on the local scale target variable (e.g. temperature, precipitation), the future period (e.g. 2021−2050, 2071−2100), the geographical area (e.g. Central Europe) and the time step (e.g. months, seasons, days).
1.1 Any Downscaling technique needs to be evaluated in a so called “validation process” describing its capability to reproduce observations. This is important information understanding the fraction of uncertainty, which is contributed by the Downscaling step to the entire approach connecting socio-economic scenarios (leftmost column of Figure 1) with adaption measures (rightmost in Figure 1). Let us suppose, for instance, the temperature span introduced by different Downscaling techniques is 1.0 °C. This may be judged as large when considering e.g. the spawning conditions of graylings. If, however, another step contributes a larger fraction, let’s say the span coming from different GCMs is twice as large. Then the Downscaling step does not appear to be the “problem”. This trivial example just highlights the importance of putting the involved steps into perspective, relative to each other as well as relative to the entire process. **Figure 2** lists the target figures of CliPDaR the transport assets and the damage risk causing processes, the so called Climate Indices (CIs). Damages may be pecuniary losses, insured or not-insured damages to property, injuries to health or losses of lives.

1.2

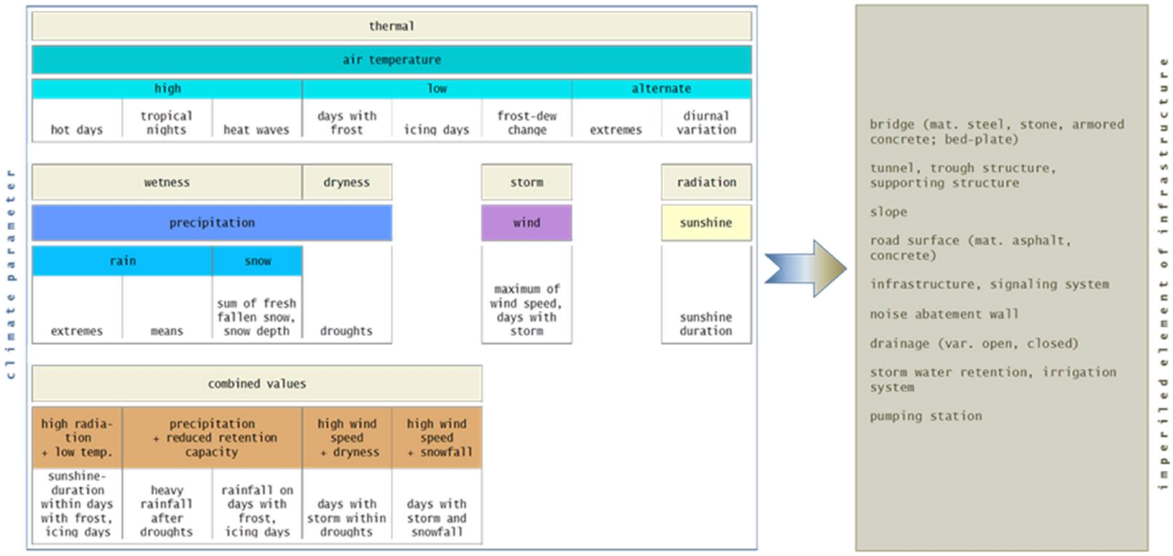
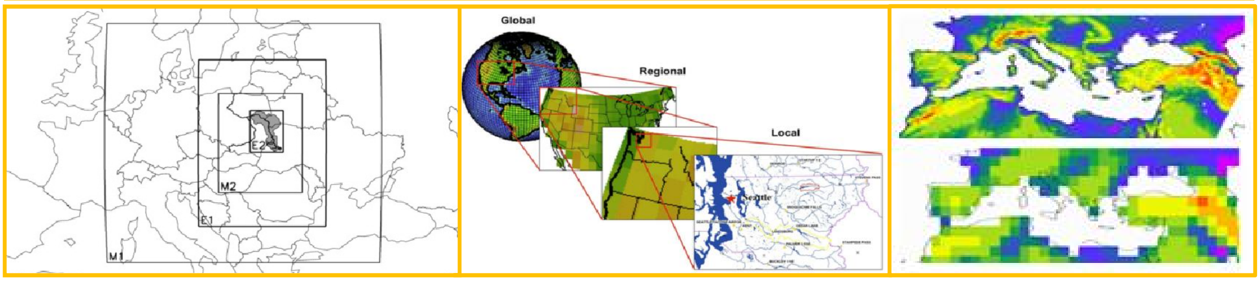


Figure 2: *Some infrastructure elements and climatological indices (CIs) causing financial and other loss. This is part of the Cause-Effect-Tensor (see e.g. CliPdaR_D2.1 or Matulla et al. 2014).*

- **Global Climate Models (GCMs) calculate the Earth’s reaction to human forcings (socio-economic scenarios) on large scale grids; Results called ‘projections’ are valid at continental scales;**
- **Empirical (‘EDS’) and Dynamical Downscaling (‘DDS’) are used to derive regional scale climate change projections from GCM projections; DDS does that by highly resolved physical models (RCMs) for regions driven by GCMs output at the edges; EDS derives statistical functions between the GCM scale and the regional scale and generates scenarios by applying them to GCM projections;**
- **Downscaling uncertainty is small compared to that of socio-economic scenarios;**
- **The Cause-Effect-Tensor is the central object of the impact analysis of transport systems comprising functional contexts between assets and Climate Indices. CIs describe the potentially harmful physical mechanisms.**

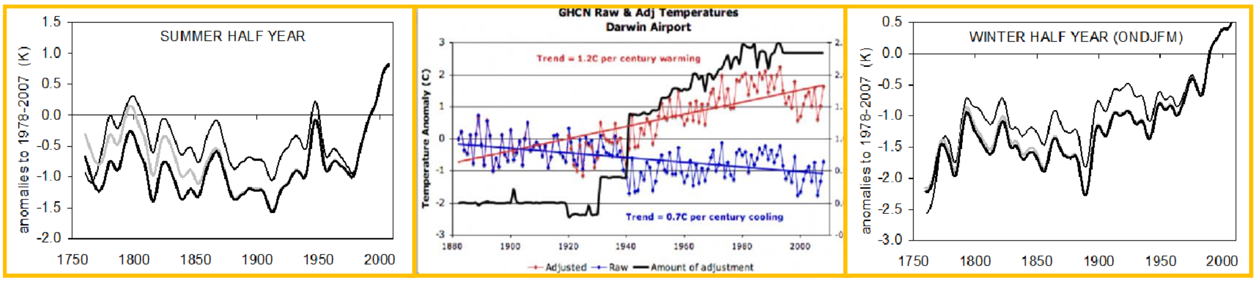


Q2. What kind of downscaling should be applied to dynamically produced Climate projections in case a further refinement is required?

Background: This question refers to a situation where RCMs produced regional scale climate change projections with a resolution still too coarse for the desired application (e.g. damage potential of highways running through complex, deep structured terrain).

Answer: Two ways are generally possible. The first is to re-apply the RCM one more time 1.3
to its own output to produce results on finer scales (called “double nesting”). Using RCMs to derive regional scale climate change data is called “Dynamical Downscaling”. The other way is
to apply Empirical Downscaling techniques. Empirical downscaling requires independent local 1.1
scale information as, for instance, measurements at stations. Given the stations are located next to a transport corridor close enough to each other, all is fine. We have the required information along the transport route in high resolution, ready to be entered into impact models. Unfortunately this is not the case in general and we have to apply GIS methods to interpolate between the sparsely distributed sites in space (as it very likely may be) to obtain information (e.g. temperature) along the transport routes. A process generating areal information from point data is in this context sometimes called “upscaling”.

- **A dynamical generated regional scale projection can be refined by:**
  - **applying DDS another time using the results of the first nesting (of an RCM into a GCM) to drive an RCM running on still smaller grid distances (GCM⊂ RCM);** 3.1
  - **using EDS which transfers information from the RCM grid to stations located within the area of interest. In case the stations are not all located in the area of interest they have to be interpolated there using e.g. GIS methods.**



Q3. Which data should be used by the European road authorities as a basis for decision making regarding the design, reinforcement and operation of the road networks in the context of climate change?

Background: Safety on roads depends on current weather at the transport level (e.g. heat on the roads), on the situation in the immediate vicinity of the corridors (e.g. soaked hillsides, infiltration and deformation procedures prior landslides), but also on conditions that have lead to accumulation away from the roads throughout preceding periods of time (e.g. snowpack) in combination with current conditions as strong winds, frost-thaw-cycles and rising temperatures (e.g. snow drifts, avalanches and flooding of roads). All such conditions may cause accidents, downtimes and massive maintenance works.

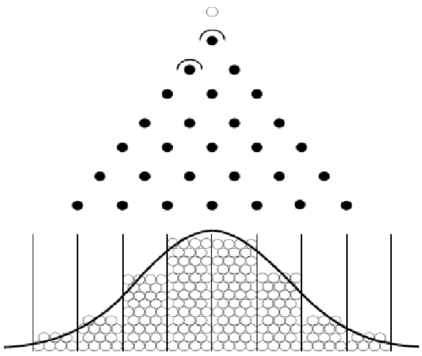
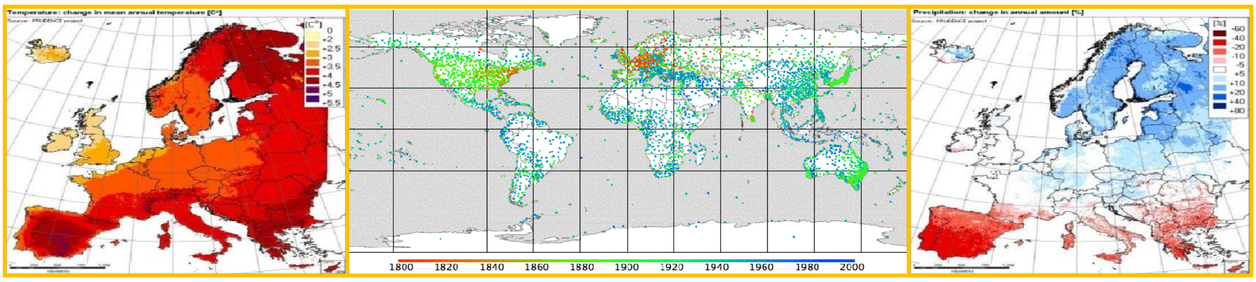


__Figure 3:__ *A Galton board plus the distribution of a lot of balls tossed into it on its top, separated in several pins on its bottom.*

Answer: The database should be made up by daily observations covering as many decades of the past as possible; at least a half-century with records of many climatological elements (temperature, precipitation, air pressure, sunshine duration, cloudiness, etc.). This period of time should contain all sorts of weather conditions.
1.2 Such data are a proper basis for Empirical Downscaling methods. Monthly data which extend far back in time can be very useful as well, for they contain aside from average conditions information on extreme events too (pers. comm. Reinhard Böhm). Extremes are more critical for roads safety than averages. Empirical and Dynamical Downscaling techniques need daily/monthly reanalysis data.

For the projection period (in the future) GCM projections driven by various socio-economic scenarios are required. The temporal resolution (daily, monthly, seasonal) depends on the problem under investigation. In any case it is important to have on hand ensembles consisting of many large scale GCM projections. The use of such ensembles allow for probability statements, which are necessary to generate a meaningful picture of the future climate. This may be understood by the example of Galton's board (**Figure 3**). The position on the bottom of the board of just one ball, tossed in on top of it doesn't tell us much about its probability. Many balls need to be thrown into the board on top to assign a probability to each position on the bottom.

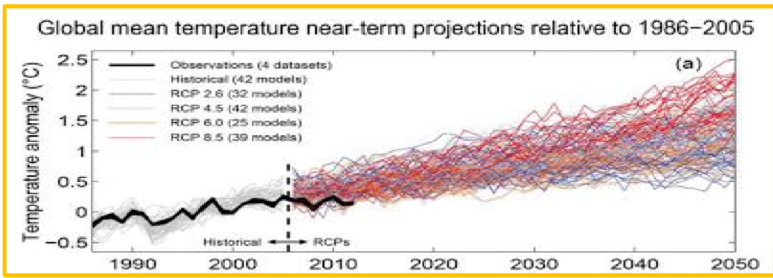
- **Empirical and Dynamical Downscaling are in need of reanalysis date reaching far back in time. Long time series are needed to assess the performance of the method. This is indispensable to assess the uncertainty introduced by this step into the modelling chain from socio-economic scenarios to adaption measures;** 1.3
- **Empirical Downscaling needs further: a proper dataset to answer transport network questions regarding future road assets' safety is a regional scale, homogeneous daily/monthly dataset covering many decades of different climate elements throughout the past;** 1.1
- **For the derivation of future local scale climate it is crucial to make use of many member ensembles of projections; from a methodological point of view it is sensible to use ensembles from both Downscaling approaches.** 2.2

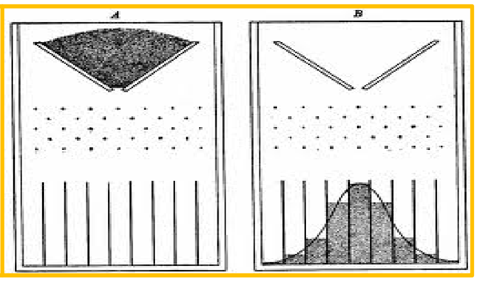


Q4. Which regional scale climate change projections may be used for the assessment of climate change across Europe?

Answer: One important requirement such projections have to meet is the coverage of the whole region of interest by each of the projections within the ensemble. Here this would be the total of Europe. There shouldn't be gaps in the data along borders which is presently often the case since many countries make use of different datasets to assess the impact of climate change within their specific region. This yields to the unsatisfactory situation that climate change is largest across the borders of different European states. There are three main reasons for that. The first refers to the measurement procedures in the broadest sense. Often datasets over different European regions referring to the very same climatological element are not of the same
2.1 kind, just because different measurement instructions, different gauges, different times at which the measurements are taken and different mathematical formulas used to calculate e.g. daily means or totals, are applied. Sometimes the measurements at one and the same place change considerably over time since the surroundings of the station changes (e.g. houses are built,
2.2 trees grow).The farther back in time the larger the discontinuities get in general. HISTALP for instance (www.zamg.ac.at/histalp) is a successful example for the creation of a homogeneous dataset across political borders for the Greater Alpine Region in Europe. The creation of future datasets is easier manageable. They all have to refer to the same region including Europe and fulfill certain quality criteria (see e.g. www.euro-cordex.net).

- **Homogeneity of the data is most important together with the compliance of quality definitions;**
- **The entire of Europe should be covered by all used datasets with no gaps along political borders;**
- **That applies to all datasets used − to the observations in a broad sense (station records and reanalysis data) just as well as to the ensembles of projection data.**





Q5. Is one single climate change projection a sufficient basis for decision making or should an ensemble be used?

Background: An ensemble consists of a multitude of climate change projections, in some cases driven by the same socio-economic scenario.

Answer: An ensemble has to be used. Even if we would know the initial conditions of all the matter in the atmosphere, the ocean and all components of the climate system, which is not the case, it would be impossible to calculate the behavior of the climate system exactly ahead (Laplace's demon). Even weather forecasts, which do not account for the dynamics of the ocean for instance and which are far less complex than climate projections, are based on 2.2 ensembles of numerical simulations. So ensembles are all the more necessary for climate projections that have to include the simulation of a range of important processes of the climate system. As such, decision making regarding complex problems involving the climate decades ahead ought to be based on a comprehensive ensemble. Such ensembles should include dynamical and empirical techniques in the production of origins.

- **Decision making regarding important issues such as transport networks and traffic safety in the future, decades ahead, must be based on ensembles of regional scale climate change projections. In case there is a limitation (money, time restriction, etc.) to a small number of projections they have to be rather different in order to warrant the diversity of the climate variability and uncertainty.**

Q6. How have summers over the Iberian Peninsula developed across the past half century

Background: Figure 4 shows the evolution of summer (JJA[1]) temperature In Europe and over the Iberian Peninsula. Overall, the European temperatures and temperatures over the Iberian Peninsula are strongly related. As expected, the average temperature development over the Iberian Peninsula exhibits larger variance than the corresponding evolution over Europe and the North Atlantic. This is as averages over large areas tend to even out small scale very high or low temperature values. So, both time series (the European/North Atlantic's and the Iberian Peninsula's) are smaller then the corresponding averages during roughly the first half of the total period and larger than the averages during the second half. The transition takes place in the late 1970s and early 1980s.

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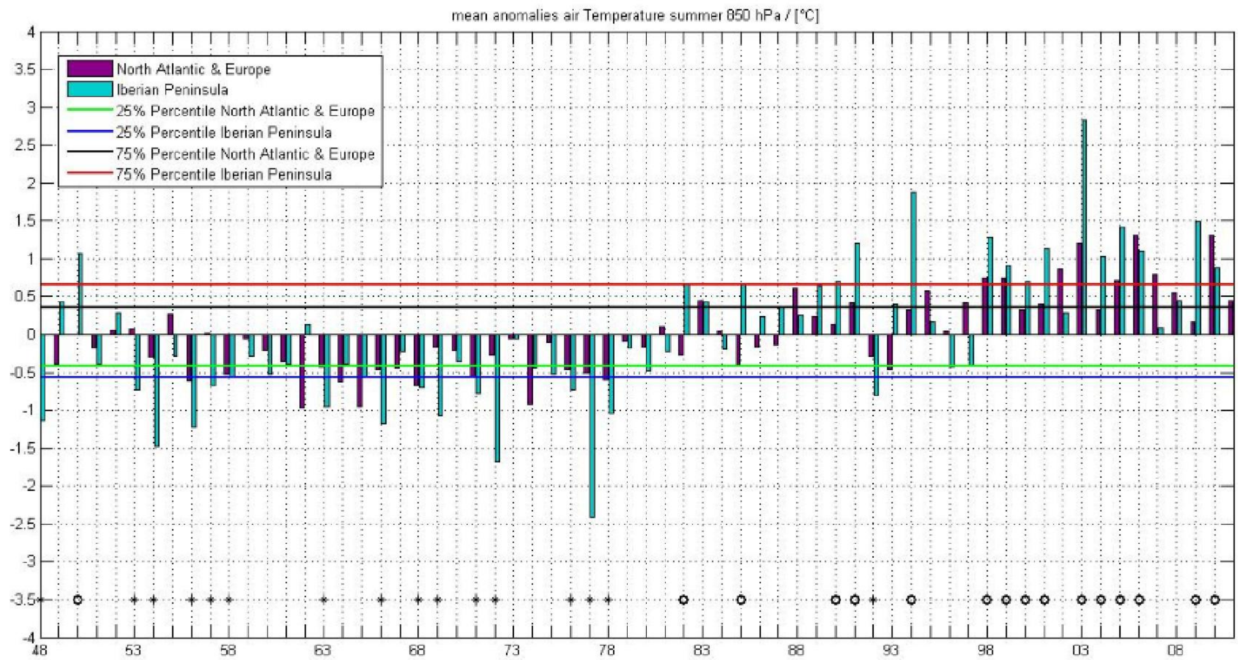


Figure 4: *Time series of summer temperature anomalies at 850 hPa (of the period 1948−2011) averaged over (i) the North Atlantic and Europe (purple) as well as (ii) Iberian Peninsula (turquoise). Horizontal lines indicate the percentiles below/above which summers are called very warm/cold. Asterisks/circles mark these very warm/cold summer seasons. The dates are retrieved from the NCEP/NCAR reanalysis archives.*

Almost all very cool summers over the Iberian Peninsula lies in the first half and all the significant warm summers are located in the second half. The coolest summer was that of 1977 and the hottest that of 2003, when tents of thousands Europeans died during the extreme heat wave that lasted for weeks and hit the entire continent (see **Figure 4**). Another fact is rather striking – since 1998 every summer with just a few exceptions exceeded the 75th percentile

[1] JJA June-July-August

referring to the whole period. This makes the fifteen most recent summers to the hottest period on record. So, albeit the most recent summers are hot in comparison to almost all summers of the shown record they are not comparable to the summer of 2003.

This means that already by now the risk of rutting is substantially higher than during some decades ago. Given that summer temperatures remain on that high level or increase even further road owners have to adapt road surfaces to that new situation. Building regulations that are derived from observations just a few decades ago are not sufficient making road surfaces withstand current or even hotter summer temperatures. This applies to all European regions that have experienced a related temperature evolution than the Iberian Peninsula. This concerns in particular transport infrastructure in the Mediterranean region. Furthermore, another important rutting factor is about to change or has already changed − the weight of the Lorries. Europe has in parts already allowed so called 60-tonne super lorries, LHVs (longer, heavier vehicles). They may be greener as reducing the emitted CO_2 by carried ton, but they are also causing challenges to the transport infrastructures and one of these challenges is rutting.

High temperatures give way to other safety issues aside from rutting too. “Blow ups” of concrete road surfaces are a severe risk that may be even a threat to life. Last summer motorcyclists were fatally insured by blow ups north of Munich on highways (A9). They were hurled out of their course off the highway. Blow ups are the cause of a long list of different accidents. The joints of bridges in particular of prestressed concrete bridges are also affected by long lasting warm spells. They are worn down quickly, damaged and in risk of failing.

Answer: Almost all summers since 1998 exceeded the 75th percentile of the total distribution. So, yes the last fifteen most recent summers is made up by the hottest summers on record. In 2003 a record heat wave brought destruction all over Europe.

- **In the first half of the time series the Iberian Peninsula experienced cooler summers than on average, with the coldest one in 1977. Since 1982 the summers are mostly above average with the hottest one in 2003 (the record heat wave affecting most parts of Europe leading to the death of several tens of thousands of people). The past fifteen summers are among the hottest on record, so this period is extraordinary hot.**

Q7. Have recent winters in Fennoscandia been comparably cold to what has been experienced in the decades before?

Background: Again, as for the Iberian Peninsula, the positive link between temperatures
2.1 over Fennoscandia and Europe plus the North Atlantic is visible from the NCEP[2]/NCAR reanalysis data. However, the connection is weaker and the correlation is lower than in the case of the Iberian Peninsula's summer temperatures. There are regularly periods of time within which the European/North Atlantic average temperature is close to its average or even somewhat above it and Fennoscandia temperatures are low (see **Figure 5**).

3.1

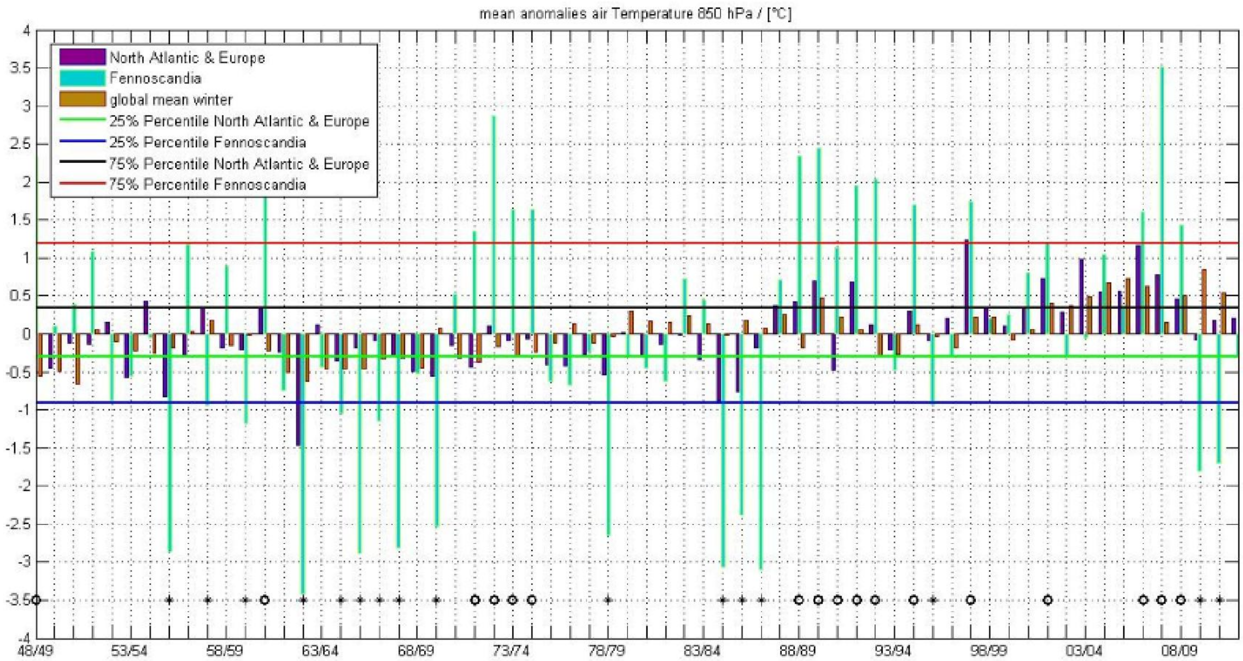


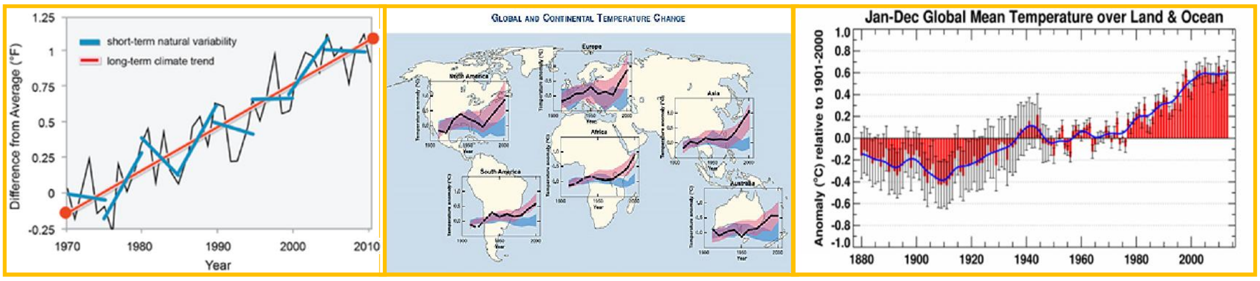
Figure 5: *Time series of winter temperature anomalies (to the period 1948−2012/13) averaged over (i) the North Atlantic and Europe (purple) as well as (ii) Fennoscandia (turquoise) and (iii) globally averaged. Horizontal lines indicate the percentiles below/above which winters are called very cold/warm. Asterisks/circles mark these very cold/warm winter seasons. The data are retrieved from the NCEP/NCAR reanalysis data.*

This shows that regional scale atmospheric anomalies are generally evened out when the averaging is extended to larger regions as for instance the vast area of Europe and the North Atlantic. However, both temperature curves show below average temperatures in the first decades of the displayed period (see **Figure 5**), whereas temperatures in the second half tend to be warmer than the appendant averages. In the late 1970s temperature anomalies stopped increasing and turned back to negative values before they start to rise again. This change of temperatures can be found in the well-known curve of the global evolution. Most of the very

[2] National Centre for Atmospheric Research, Boulder, Colorado, USA.

warm winters are to be found from the 1980s onwards. During the last twenty years or so, Fennoscandia experienced mild winters, with temperatures exceeding the 75th percentile. This explains why most recent winters (2009/10, 2010/11 and 2011/12) with temperatures falling below the 25th percentile, are perceived as particularly fierce. Maintenance works (the frequent employment of snow clearing fleets) were certainly very different and costly compared to the decades before.

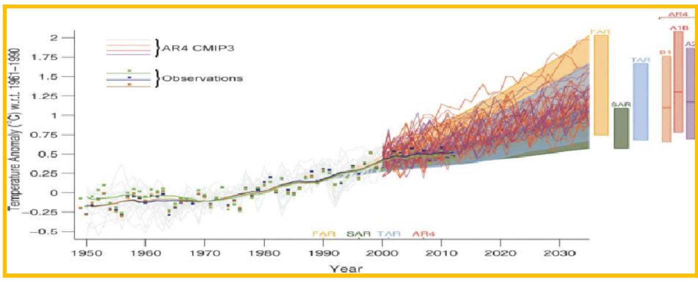
- **Recent winters in Fennoscandia have been cold compared to the decades before. However, they haven't been cold on the European nor the global scale.**

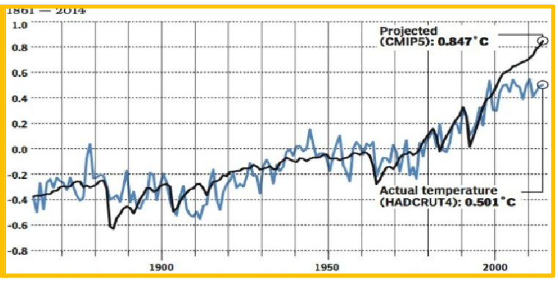


Q8. Are these cold Fennoscandian winters in contradiction to global warming?

Answer: “Global warning” is a term occurring in almost all discussions on climate change and it “is the unequivocal and continuing rise in the average temperature of Earth's climate system". This is one of the very central statements of the recent IPCC assessment report (2013). Climate is the statistics of weather over a long enough period of time and the World 3.1 Meteorological Organization (WMO) enjoins that this period of time has to consist of at least thirty years. So, thirty years of temperature and precipitation measurements in Trondheim characterizes the climate of the European motorway E6 route where it passes the city center there. If, for instance, there are measurements in Trondheim from 1951 to 1980 and from 1981 to 2010 we can assign tow climates to Trondheim, one of the period 1951−1980 and the second from 1981 to 2010. In case the statistics (e.g. the mean or the standard deviation) are different from each other we speak of climate change. If the temperature measurements from all places at which they are on hand from 1951 to 1980 are put together to one distribution and the same is done for the period 1981−2010 then “global warming” says that the mean of the latter distribution is larger than the mean of the distribution belonging to the first period. This does not imply that every single station shares this feature nor does it imply that every year is warmer than the year before. So, if temperatures in Fennoscandia happen to decrease to cold temperatures all of a sudden this is by far no contradiction. As long as Fennoscandia's decrease is offset by other regions “global warming” continues.

- **Cold winters in Fennoscandia and at other places on Earth are not contradicting global warming as long as the decreases are offset by other regions.**





Q9. Are the observations consistent with the output of Global Climate Models?

Background: Before we can judge whether a model fails or not we have to know what it was designed to do. GCMs are computerized mathematical tools to answer the question which changes our planet will undergo in case the forcings that run the climate system are altered. GCMs should help to understand the behavior of the climate system in relation to its forcings 1.1
and thereby GCMs calculate estimates of future states of the climate system under scenarios of changed forcings. GCMs divide the atmosphere, the oceans, landmasses, etc. into a grid and calculate the values of a set of variables such as temperature, precipitation, humidity, pressure, wind, etc. at each grid point for every time step of the calculation period as a function of the 2.2
forcings that are used to drive the GCMs. Their grid spacing (~200 km) is small enough to capture continents and the periods of time their calculations refer to are decades. As such we expect GCMs to model the climate of continents for climatic periods according to a given run of the forcings over thirty years or so.

Answer: Presently there is an ongoing discussion about the so called “temperature hiatus”, which should be named “warming hiatus” since it is the increase in temperature, not the temperature itself that haven't been observed over the past twelve years or so. Fact is that globally averaged temperatures are not increasing albeit CO_2 concentrations rise. It is also true that just three GCMs out of 114 (or so) GCMs simulate this warming hiatus. The unagitated, technically correct answer is that the large number of GCMs, which can not reproduce the observations, is indeed surprising. However, the period is still too short to judge all of them are failing. If this situation constant temperatures and increasing CO_2 concentrations remains in effect for another decade we can be sure that there is an important process going on in the climate system that is not realized in the computer models. Scientists have already identified a list of candidates.

- **Differences between the output of GCMs and observations that refer to periods short compared to climatic periods (about thirty years) don't prove GCMs to fail their purpose, which is to properly simulate the reaction of the Earth to changes in the forcings driving it;**
- **The presently experienced “warming hiatus” actually too short to prove GCMs' disabilities, but the period is long enough to closely follow what happens in the near future;**
- **If GCMs fail to correctly describe all the forcings – feedback relationships (that would be the outcome in case GCM estimates deviate significantly from the observations for another decade) the missing process will be hopefully singled out and implemented in the next GCM generation. That is what a substantially prolonged “warming hiatus” would mean. Other findings of climate research during the past decade are not affected.**

Q10. Will such cold outbreaks affecting the maintenance budgets reoccur more frequently in the future?

Background: Recent winters in northern Europe were relatively cold, seemingly contrary to expectations ("global warming" - warmer winters), and raised questions by road owners. We have already answered a couple of these questions but haven't touched the possible mechanisms behind. The reason is that the associated scientific debate is going on and possible explanations are a matter of research. The point is that the extend of the financial expenses, the frequency the maintenance fleets is required, the repair works needed to ensure the smooth accomplishment of the traffic volume and so on (i) directly depends on the mechanism causing the sudden onsets of heavy snowfalls or more general the beginning of deep winter conditions and (ii) the physical mechanism determines to a (large) extent for how long road owners have to be aware of the consequences, or differently put, when such interruptions are going to fade away.

Answer: The most debated mechanism is linked to the strong warming of the Arctic that has been observed over the past thirty to forty years. This leads to a strongly decreasing extent of the ocean area that is hidden underneath sea ice. Vanishing sea ice uncovers the dark ocean that absorbs vastly larger amounts of short wave energy and thereby warms the low laying air above the
2.1 ocean. This lets the frontal zone wobble and the connected polar jet meander. Polar and subtropical air masses are interacting and mix, reducing temperature and pressure gradients. This in turn weakens the polar vortex, yielding to more frequent outbreaks of cold winter Arctic air (perhaps another positive feedback next to the ice-albedo feedback at the beginning of the process) forcing deep winter conditions southwards e.g. into
3.1 Fennoscandia. The mechanism is not fully understood yet. There is, for instance, a substantial time lag between the melting of Arctic sea ice and the cold outbreaks. Moreover past observations do not support this explanation. Anyway, given there is a mechanism not physically understood yet, GCMs that are based on all our present scientific knowledge of the climate systems may not be able to simulate it precisely. Within CliPDaR we can give answers based on the current scientific knowledge of science. As for the maintenance budgets a high frequency of future cold winter outbreaks would require a large, good working and always ready to start snow clearing vehicle fleet.

__Figure 6:__ *The idea of the scientifically unconfirmed mechanism says that the summer Arctic warming weakens the Polar Vortex (yellow arrows) and leads to an intensified meandering of the storm track (black arrows) causing cold air outbreaks.*

Based on the best knowledge available today we have addressed that question by the application of two methodologically different approaches – see **Figure 1**, the labelling in the diagram: **"Multivariate pattern approach"** and **"KLIWAS based approach"**. The latter approach is based on the use of RCMs (dynamical Downscaling) while the first method avoids RCMs and reduces the uncertainty introduced by the Downscaling step. This approach employs a multivariate technique known as Empirical Orthogonal Function Analysis (EOF analysis). It turns out that the probability of such events, yielding to cold winter outbreaks in Fennoscandia and other parts of the planet decreases with time. In the far future by the end of the century the probability is almost zero.

- **There might be a context between the melting of the Arctic sea ice and cold winter outbreaks in adjacent regions. The mechanism is yet not understood;**
- **The consequences however were felt by road authorities. Maintenance budgets caused by most recent cold winters were large compared to the winters of the decades before;**
- **Based on the best knowledge currently available we have calculated the occurrence frequency of such cold winters twice by different approaches and found that the future probabilities are small compared to the present climate. By the end of the century such events have a vanishing probability.**

Q11. What may be the future climate in Europe and Fennoscandia?

3.1 **Answer:** Low temperatures, which are associated with the lower tail of temperature distributions, are expected to occur with smaller probability in a warming climate than observed so far. Given that the shape of the temperature distribution does not change much in the future and the warming yields to a shift of the distribution towards larger temperature values (e.g. somewhat more than 4°C), we are going may see larger changes (**Figure 7**) in the index days (**Table 1**) closer to the middle of the distribution (frost and summer days), than in the ice and hot days, which are lying more outside in the (left and right) tails of the temperature distribution.

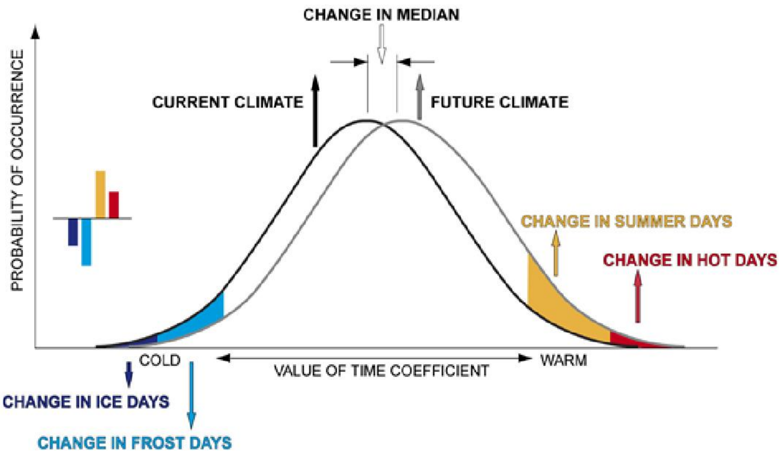


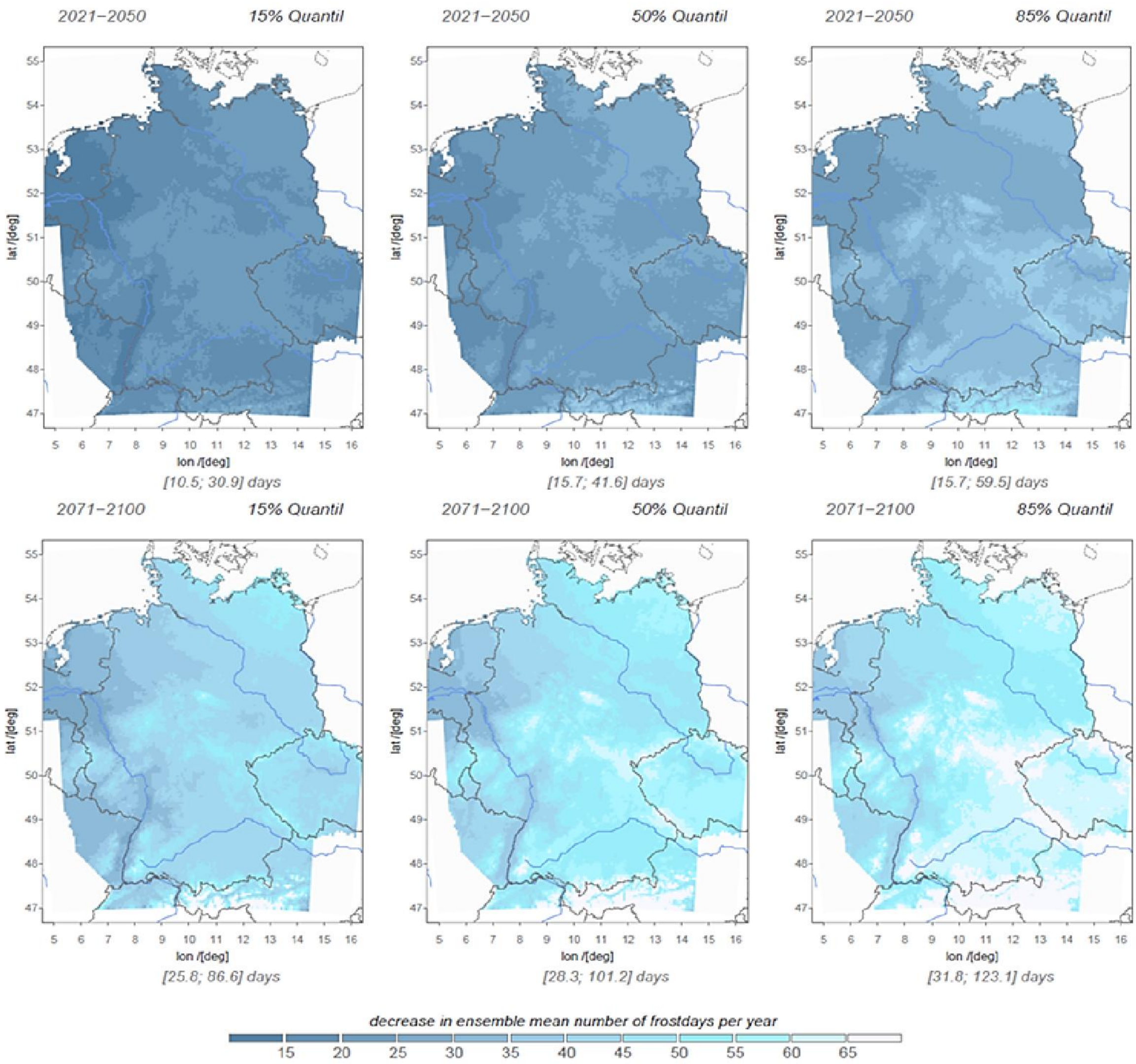
__Figure 7:__ *The black distribution represents the current climate and the gray one a possible future climate. So, climate change moves the past/black curve to the right into the future/grey curve. The decrease in ice days (dark blue vertical arrow) is small as there are not many of them. The decrease in frost days (light blue vertical arrow) is more pronounced as there are more of them and the first derivate of the distribution is increasing from the ice days to the frost days. The same but with a reversed sign of change (turning decreases into increases) applies to the warm index days. Increases in summer days (yellow vertical arrow) are larger than increases in hot days (red vertical arrow). The amount of changes are indicated as color bars (left hand side, next to the y axis).*

__Table 1:__ *Index days together with their definition and the units.*

Elements	Definition	Unit
Ice Days	Days with daily maximum of temperature < 0 °C	Number of days
Frost Days	Days with daily minimum of temperature < 0 °C	Number of days
Summer Days	Days with daily maximum of temperature ≥ 25 °C	Number of days
Hot Days	Days with daily maximum of temperature ≥ 30 °C	Number of days

Table 2: *Regional scale climate change projections used in this guideline. The first column indicates that the GCMs and in turn the RCMs are driven with present day forcing conditions (referred to as C20) for modeling the past and with the A1B socio-economic scenario for the future. RCMs (marked in bold type) indicates that a Bias correction has been carried out.*

Control run/ SRES scenario	GCM	RCM
C20/A1B	ARPEGE	HIRHAM5, RM5.1
	BCM2	HIRHAM5, **RCA3**
	ECHAM5r1	**CLM2.4.11**
	ECHAM5r2	CLM2.4.11
	ECHAM5r3	**HIRHAM5**, **RACMO2**, RCA3, **RegCM3**, **REMO5.7**
	HadCM3Q0	**CLM2.4.6**, **HadRM3Q0**
	HadCM3Q3	RCA3, HadRM3Q3
	HadCM3Q16	RCA3, HadRM3Q16



3.1

Figure 8: *The Figure shows the change in counts of frost days (T_{min} <0°C) for the period 2021−2050 (first row) or 2071−2100 (second row) relative to the past (1961−1990). The left hand side panel refers to the 15th percentile. The others are assigned to the 50th and the 85th percentile (to the right). Given we have 100 projections sorted from cold to warm than the left panel would be the 15th warmest (the first 'warmest' is the coldest) while the right panel refers to the 85th warmest panel. So 70% of the projections are in between them, giving a hint on the accordance or discordance (the spread) of the ensemble of projections. The middle panel is the median. Numbers in brackets below each panel refer to min and max values. Dark blue colors stand for little, light colors to much changes.*

Our results (using the "**KLIWAS based approach"** – see **Figure 1**) actually indicate a significant decrease of frost days in the near future and an even more distinct decrease in the remote future that extends over the entire region (**Figure 8**). Regional differences, however, are noticeable and a gradient from West to East can be seen. There is a perceivable link to topography. Elevated regions presently comprising largest numbers of frost days show highest reductions. Regions in the proximity to the North Sea as well as regions along the Rhine River Valley show, perhaps due to the stabilizing effect of bodies of water, not much decrease in frost days. Largest reductions amount up to over two months, reducing the cold season substantially. Overall the reduction in the remote future amounts to three quarters of the observed number of frost days. This is massive. However, from the perspective of transport business this is not bad news. Frost days (aside from ice days, which are part of the frost days) indicate days exhibiting at least one frost-thaw-cycle. So, damages to roads coming along with frost-thaw-cycles (as e.g. falling rocks, cracks in the surfaces, frost heaves and lots of other effects causing damages to the entire road body) will appear fewer frequent causing less costs in the future. The same applies to winter maintenance works, clearing of snow, snow drifts, avalanches, salting, etc. Such events will occur less frequent as well. It is important to notice that we do not say that each year will come with fewer damages than the year before. We just point out that the simulations we studied point to strong decreases of frost-thaw-cycle and that the period in the remote future shows substantial larger decreases than the near future. This comes from comparing periods over three decades (the past period 1961−1990 and two future periods 2021−2050, 2071−2100) not from investigating short periods or even single years; the overall decrease will be accompanied by a change in the affected parts of the transport network. Regions presently not being affected by freeze-thaw-cycles since temperatures are presently way below zero will become affected in the future. This is because an increase in temperature may turn days, which are presently ice days (no frost-thaw cycle) into frost days (frost thaw cycles). Such kinds of territorial changes will take place until there are no more frost days in regions through which transport corridors run. From this day on no appendant changes and no more damages of this kind can occur anymore. Once again, these statements rely on the correctness of the chain from the considered socio-economic scenarios, over the GCMs and the downscaling method. Moreover it is important that these statements refer to climate periods (thirty years) not to single years or a few years. There still is a probability of very cold winters producing lots of snowfall; their probabilities however decrease substantially the farther we proceed into the future.

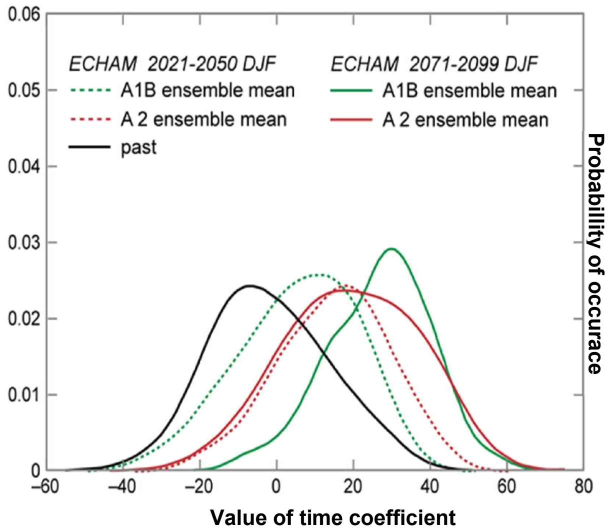


Figure 9: *Probability distributions of the first EOF's appearances throughout the past (black, solid line) the near future (coloured dashed lines) and the remote future (solid, coloured lines). Red lines refer to the A2, green lines to the A1B.*

The reduction of ice days is less pronounced but shares a lot of spatial features. The range of values in the near future spanned by the 15th percentile and 85th percentile (maximum minus minimum) is about 20 to 45 days. The median of the change (middle panel) does not exceed three weeks of reductions over large regions. In the remote future the 15th and 85th values change to about 61 to 91 days. So, there is an acceleration of change towards the end of the century which results in a higher spatial diversity (even more when considering the different timespans: between the past and the near future, there are 60 years, whereas between the near and the remote future, there are just 50 years).The observation that simulated frost days exhibit larger changes than the ice days is in accordance to the increasing first deviation of the probability density function from ice days to frost days (see **Figure 7**).

The results, which have been shown so far, focus on Germany and adjacent areas. The
questions raised by the CEDR, however, involve further regions and damaging mechanisms as
(i) Fennoscandia (standing for the Nordic countries) and damages caused by cold winters as
well as (ii) the Iberian Peninsula representing European regions, where hot summers are
triggering damages to transport corridors. So, we adopted another approach that gives an
impression of what may happen to occurrence frequencies of atmospheric patterns causing
extreme winters and summers (**Figure 1 − “Multivariate pattern approach”**). Hence, we
selected the regions Fennoscandia and the Iberian Peninsula and investigated the past
64 years that are on hand from reanalysis data[3]. We calculated therefrom time series of winter
temperatures for Fennoscandia and looked at their evolution (see **Q7** and **Q8**). The next step 3.1
was to figure out which large scale atmospheric pattern over the North Atlantic and Europe (an
area from 65N/50W to 35N/30) that covers most of the atmospheric influence on the region of
interest caused cold winter situations in Fennoscandia. The atmospheric pattern* we detected
appears with a negative sign in case winters were cold in Fennoscandia and with a positive sign
when winters were rather mild there. Then we took GCM projections for the future based on two
different socio economic scenarios A1B and A2 (which is even more economically oriented then 2.2
the A1B scenario that we used in the above RCMs based approach), and searched for the
occurrences of the large scale atmospheric pattern* in the GCM future projections Thereby we
avoided uncertainties introduced by the application of RCMs (in the “**KLIWAS based approach**” 3.1
– **Figure1**). The hypothesis is that if the pattern occurs with decreasing negative signs and
increasingly positive signs, cold winters in Fennoscandia will occur less frequently in the future.
The results of the investigations are shown in **Figure 9**. **Figure 9** contains several kinds of
information. In black, we see the intensities with which the atmospheric pattern*, we identified
with the occurrence of cold (negative values) and mild (positive values) winters in
Fennoscandia, have shown up in the past (winters of 1948/49 to 2012/13). The lower, left tail of
the black distribution refers to cold winters and the upper, right tail contains mild winters. The 2.2
dashed colored lines specifies the near, the solid colored ones the remote future. Green
belongs to the A1B and red to the A2 socio-economic scenarios.

Thus, the near future is marked by a clear shift of the maximum (the most likely state) towards warmer temperatures. However all states occurring in the past are still contained in the distribution assigned to the near future. The point is that the atmospheric states indicating very cold winters decrease in occurrence probability while the mild winters obtains a higher probability to take place. There is even a hint (the small upper tail part of the probability density function) to observe the atmospheric pattern* with an intensity not found in the past, albeit with small frequency. The remote future shows substantial differences, whereby the A2 scenario yields larger changes for the Fennoscandia than the scenarios driven by A1B. The A2 scenario shows still cold winters with a very low frequency but a lot of unprecedented intensities in the upper tail, standing for very mild winters. The maximum likelihood in the remote future is

[3] Reanalysis data are datasets that are built on all available observations and brought onto a regular three dimensional grids running through the atmosphere from bottom to top. The National Centre of Atmospheric research (Boulder, USA) for instance provide such a dataset starting in 1948, called the NCAR/NECP reanalysis.

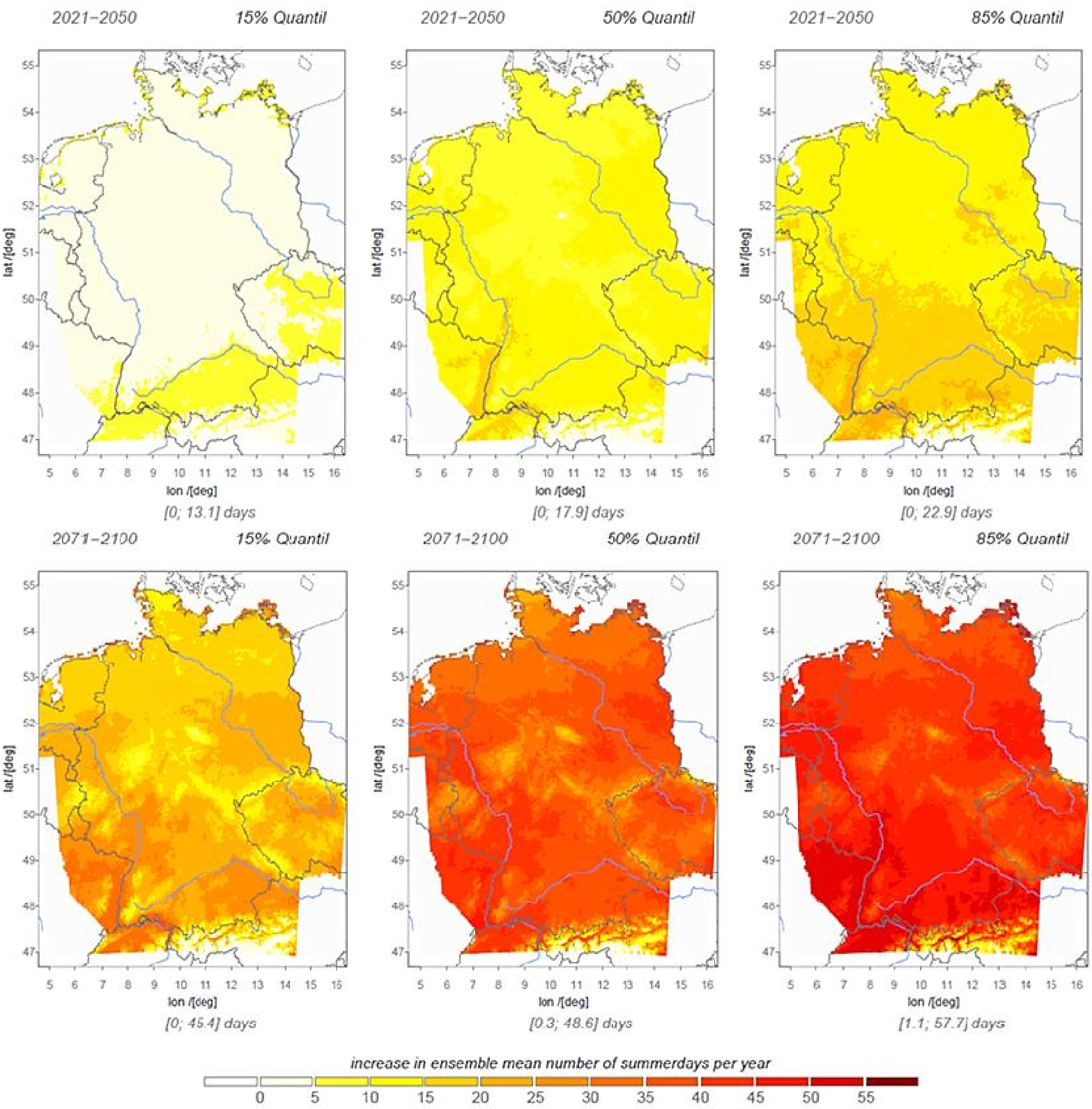
situated where in the past mild or very mild winters were located. The A2 variability is larger than the one of A1B. The A1B scenario does not feature very cold winters anymore takes on its maximum frequency where mildest winters of the past were observed. The upper tail is located at values, which haven't been experienced from 1948/49 to 2012/13.

- **Investigating the winters from 1948/49 to 2012/13 we have detected an atmospheric pattern over the North Atlantic and Europe that occurs with a negative sign when Fennoscandian winters are cold and with a positive sign when they are mild;**
- **The distribution of the occurrence frequency of this atmospheric pattern changes in the near and the remote future. In the near future all observed states are still to be found but with an altered frequency;**
- **Cold winters have a low occurrence probability; the most likely states in the near future are the mild winters of the past and the scenarios show warm states that have not been observed so far;**
- **In the remote future the very cold winters of the past cannot be found anymore; the new maximum likelihood is made up by states that were very mild in the past; many new states in the upper tail referring to the very mild future winters show intensities that have not been on record between 1948/49 and 2012/13;**

3.1

- **The RCM based results show for the changes in all cold index days relatively similar geographical patterns. There is a gradient from West to East to be seen and the ocean exerts a damping effect on close by regions. Topography has a significant impact on the amount of change;**
- **A detailed discussion can be found in CliPDaR 3.1.**

Q12. What may be the future climate in Europe and the Iberian Peninsula?



3.1

Figure 10: *The Figure shows the change in counts of summer days (T_{max} ≥25°C) for the period 2021−2050 (first row) or 2017−2100 (second row) relative to the past (1961-1990). The left hand side panel refers to the 15th percentile. The others are assigned to the 50th and the 85th percentile. Given we have 100 projections sorting them from cold to warm than the left panel would be the 15th warmest while the right panel the 85th warmest. So 70% of the projections are in between them, giving a hint on the spread of the ensemble of the projections. The middle panel is the median. Numbers in brackets are min and max values.*

Hot summer temperatures are associated with the upper, right tail of temperature distributions. The hottest measured summer in a thirty year period (e.g. 1961−1990) would be found on the rightmost position of the appendant record. The summer of 2003 in Europa for instance was such an extraordinary hot event. Given the climate would follow a fixed distribution (e.g. that of 1961−1990) we would have to wait in a statistical way hundreds of years for such a summer (return period). Within a changing climate, where temperatures would be two degrees higher, the summer of 2003 would still be remarkably warm, but not outstanding anymore. We think this is one main question of this commissioned work: Is it likely that the climate within the present century changes so much that extreme events, which were called extraordinary in the 20th century, will be called unusual but not extremely rare anymore?

Figure 10 provides an answer. Just as in the winter case above we focus on the not so extreme event of “summer days” than on “hot days”. The change in counts is larger for “summer days” and “frost days” and hence the changes are better visible than those in case of “ice days” or “hot days” (see **Figure 7**). The orographic pattern of the change in summer days is much related to that of the hot days (just as they were in case of the frost and the ice days).

Focusing on summer days and the near future (see **Figure 10**), we see increases of about
3.1 three weeks of days exhibiting maximum temperatures above 25°C along the Rhine River Valley and somewhat less increases along the North and Baltic sea coasts. The remaining part of the area shows increases of about a week. There is a wide spread warming to be found.

The rather smooth spatial distribution of the near future changes towards the end of the century. Large parts in the remote future show increases of almost five weeks. This widespread area is intersected by lower increases in higher elevated regions. Over the European Alps, the Harz, Thüringer Wald, Erzgebirge and in northern most parts increases in summer days are just two to three weeks. Low laying areas as along the Rhine River Valley are characterized by maximum increases of over six weeks. In general, there is an increase from the North German Lowlands to the more elevated regions in the South, which decreases towards higher elevated areas along the summits. So, there is an overall increase of summer days that shows acceleration with height except for the highest elevated regions. This overall picture is rather interesting as future increases tend to be large over areas experiencing already now largest numbers of summer days in the observation period. The Rhine River Valley for instance or the region north-east of the Bavarian Alps had seven to eight weeks of summer days in the past (1961−1990). Within these areas increases in summer days are about three weeks. This means that in total over ten weeks of summer days per year can be expected as the climatological mean for the near future, which results in: (i) almost every day in summer (JJA) is a summer day or (ii) the period exhibiting summer days will expand towards spring and autumn. This picture changes in the far future. Low laying areas catch up and increases are almost the same throughout the whole area besides highest elevated regions, which depict somewhat reduced increases of summer days. This appears to be related to the low temperatures of high laying sites. In most areas increases in summer days are substantially accelerated towards the end of the century.

For the second analysis method (**“Multivariate pattern approach”** – **Figure 1**), which is not based on RCMs output, we have selected an European region, whose transport corridors are likely to be harmed by high atmospheric temperatures. This is not likely in Fennoscandia but it is for transport networks, for instance, in the Iberian Peninsula, which is representative for many regions in south Europe. We investigated the summers between 1948 and 2012, isolated a large scale atmospheric pattern over the North Atlantic and Europe that shows large positive values when hot summers are on record and negative values in case of cool summers. Then we took GCM projections for the A1B and the A2 socio-economic scenarios and investigated the appearance of this atmospheric pattern in the near and remote future.

Figure 11 shows the distribution of the intensities with which the atmospheric pattern related to warm and cool summers in the Iberian Peninsula appears. The line colors correspond exactly to those of **Figure 9**. The observed distribution shows little variability compared to the winter distribution in **Figure 9**, which is in accordance with experience. Summer temperatures in Europa tend to have lesser variability than winter temperatures. However, the rate of change is larger than the one seen in **Figure 9**. Already in the near future many states standing for cool summers do not appear in 2021−2050 and the states showing maximum likelihood are the hottest summers of the past. In the remote future (2071−2100) the distributions have nearly no intersection. Coldest summers in the remote future are somewhat warmer than the hottest observed so far. The hottest summers of the remote future are two times the observed total range of variability away from the hottest past summers. A2 scenarios are more extreme than those based on the A1B social-economic scenarios. The variances of all projections increase compared to the past.

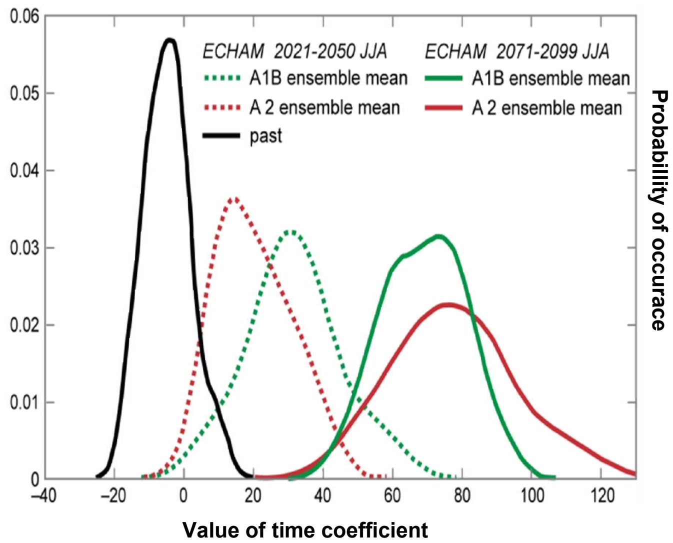


__Figure 11:__ *Probability distributions of the first EOF's appearances throughout the past (black, solid line) the near future (colored, dashed lines) and the remote future (solid, colored lines). Red lines refer to the A2, green lines to the A1B scenario (e.g. CliPDaR3.1 for a more detailed description).* 3.1

- **The simulated changes in summer are larger than those found for the cold season. The states of the remote future have not been observed so far. Hottest states in the remote future are two times the observed range of states away from the hottest observed summers;**
- **The distribution characterizing the near future still contains observed states, but do not model cold summers of the observation period (1948−2012) anymore. The most likely states are the hottest summers of the past;**
- **In both cases, the near and the remote future, the variability grows compared to the observed past – the remote A2 future (2071−2100) shows a variability almost twice as large as the observed one;**
- **In the near future and the 85th percentile panel increases in summer days are smallest relatively close to the ocean and in low laying areas. Largest increases are to be found in regions that show largest numbers of summer days in the past 1961−1990;**
- **In the farther future, low laying areas catch up. So that most of the region features more than four weeks of increasing summer days. Smaller increases are to be found in high elevated regions (European Alps, the Harz, Thüringer Wald, Erzgebirge).**

Q13. Some hints on future possible landslides?

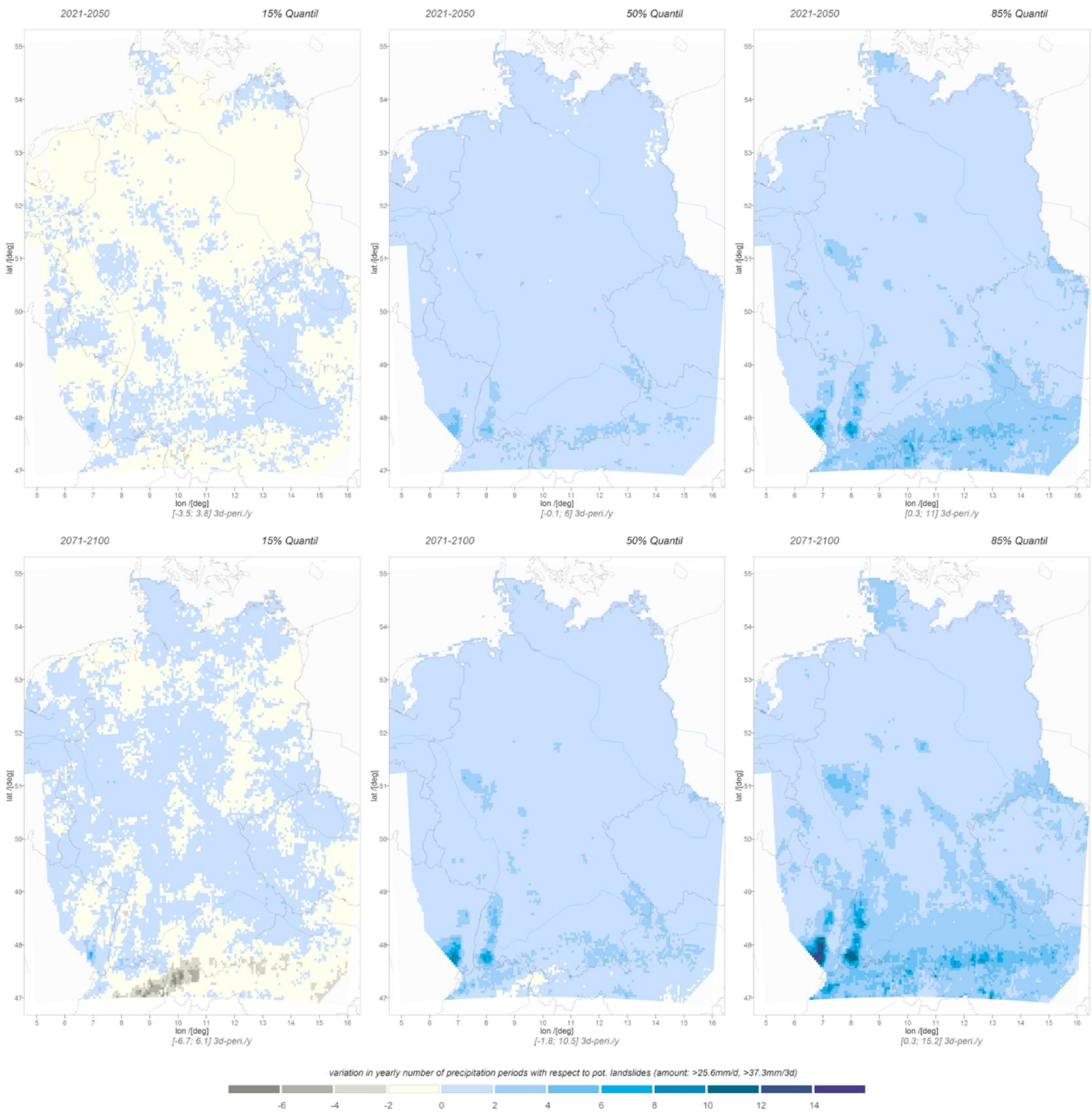


Figure 12: *Changes in the CI that is related to landslides. At some places (steep hillsides, high groundwater levels, human alterations modifying the discharge, etc.) the CI - one day of rain minimum 25.6 mm and in 3 days over 37mm may under or overestimate the risk depending on the specific location. So, this is a very first guess. In contrary to the other KLIWAS17 based Figures the remote future is displayed in the second row. The rest of the figure is organized just as Figures 8 and 10.*

Referring to landslides there are regions showing no change and other areas with substantial increases, which predominantly occur close to topographic complex terrain. Such regions are characterized by precipitation induced by orographic lifting. Increases can be caused by the more frequent advection of moist air masses carrying more water vapor than observed so far. The findings rely on the so called KLIWAS17 ensemble used already by Matulla et al. (2014) in related cases and generated by Imbery et al. (2013). Findings are depicted by the 15th 50th and 85th percentiles which allow covering ranges of possible changes (**Figure 12**). This way proper measures handy for decision making regarding the planning of transport networks and the reinforcement of existing assets may be developed.

In the near future we do not see much alteration in the number of occurrences of the landslide CI (at least one day of minimum total of 25.6 mm and in three days more than 37mm). In the remote future Germanys shows, along the Rhine River Valley and in complex, elevated topography ten times higher occurrences of this CI compared to 1961−1990. This may be related to warmer air that can carry larger amounts of moisture than cold air and therefore produce larger amounts of precipitation. This can be seen in the near future too, especially in the right panel standing for the 85th percentile. Additional results e.g. on rutting can be found in our paper (Figure 6) Matulla et al. (2014). 3.1

Q14. Are there other questions to be addressed regarding the planning & design, the reinforcement and the Maintenance of the transport network in the context of climate change? - A conclusion.

"The adaption of road networks to a changing climate is one of the central issues that road authorities have addressed in the past and that needs to be carried further in the near future. So, the overall aim of climate researchers (that are active in this field) is to provide road owners with adaption technologies and the models and tools to support decision making concerning adaption measures for the road infrastructure." This statement is taken from a talk given by Gordana Petkovic, Senior Principal Engineer at NRA at the TRA in Paris, 2014. I think this really tells a lot about the cooperation between research and application management as well as the objectives both are in charge to address. Making ideas and solutions happen in the transport sector requires creativeness on both sides of the medal.

Assessments of people's future demand for transport capacity indicate tremendous challenges. The reason is that we all want to increase the quality of our own life and (hopefully) the quality of the life of others. This is reputable, but difficult to reach as presently it is thought that the only way towards this goal is through growth. Anyway, it is expected that the demand in transport assets will double within the next three decades. Meaning that the full scale transport volume that has evolved over the past several centuries is going to be doubled within the next thirty years. This is massive. On top of this enormous technical challenge comes climate change, which is expected to hurt the infrastructure harder, than ever before. From this perspective it is necessary to expand the transport network in a sustainable way, meaning all infrastructure built now and in the future have to accomplish their lifetimes. We cannot afford to scrap a railway station for instance that is designed to last 100 years after 20 years because the close by river floods the station almost every year since climate change turned a 50 year flooding event of the past into an event, which will have a return period of three years in twenty years. So, climate researchers have to work closely together with the engineers in charge of building the infrastructure needed to meet the future demand of society. The lesson here is that climate change is a serious issue for the infrastructure since the lifetime of many assets exceeds thirty years by far. Often transport assets are planned to last much longer (bridges, tunnels, railway stations, airports, etc.).

We think that within this project a state of the art approach was shown. Based (i) on the CIs that define physical processes potentially harming all sorts of infrastructure and (ii) on current climate change projections we have probability based tools on hand that delivers highly resolved, infrastructure related tools and scenarios. This way engineers road authorities in charge and owners are able to make their decisions on the best basis possibly available. These tools can be enhanced by blending the information given by the CIs and the ensembles of climate change projections with (i) exact topographic information (exposition, slope, etc.), (ii) vegetation and soil data (helping to tailor down the information e.g. regarding landslides, etc.) and (iii) land use change data caused by human activities. Aside from these enhancements, fundamental improvements are: (i) the formulation of the CIs (the cause-effect tensor) as functions of space and time (which is clearly highly challenging), (ii) the assessment of the uncertainty along the production chain of the regional climate change projections, which are to be grouped in ensembles and (iii) improvements regarding the climate change projection themselves.

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The ZAMG CliPDaR team, beginning with the third row from left to right: Petra Mayer, Julia Gringinger, Brigitta Hollósi, (second row) Christoph Matulla, Barbara Chimani, Nathalie Nosek, Christine Hagen, (first row) Konrad Andre.

Joachim Namyslo from the DWD managed CliPDaR and supported the correspondence to the CEDR.

[4] Several figures displayed in the headers are extracted from the internet.