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# **CEDR Transnational Road Research Programme Call 2012: Road owners adapting to Climate Change**

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***Climate projection data base for roads: CliPDaR***

## **Guidelines for the use of Statistical and Dynamical Downscaling results as input for impact models**

Deliverable D1.3

The **CliPDaR** Consortium:



## **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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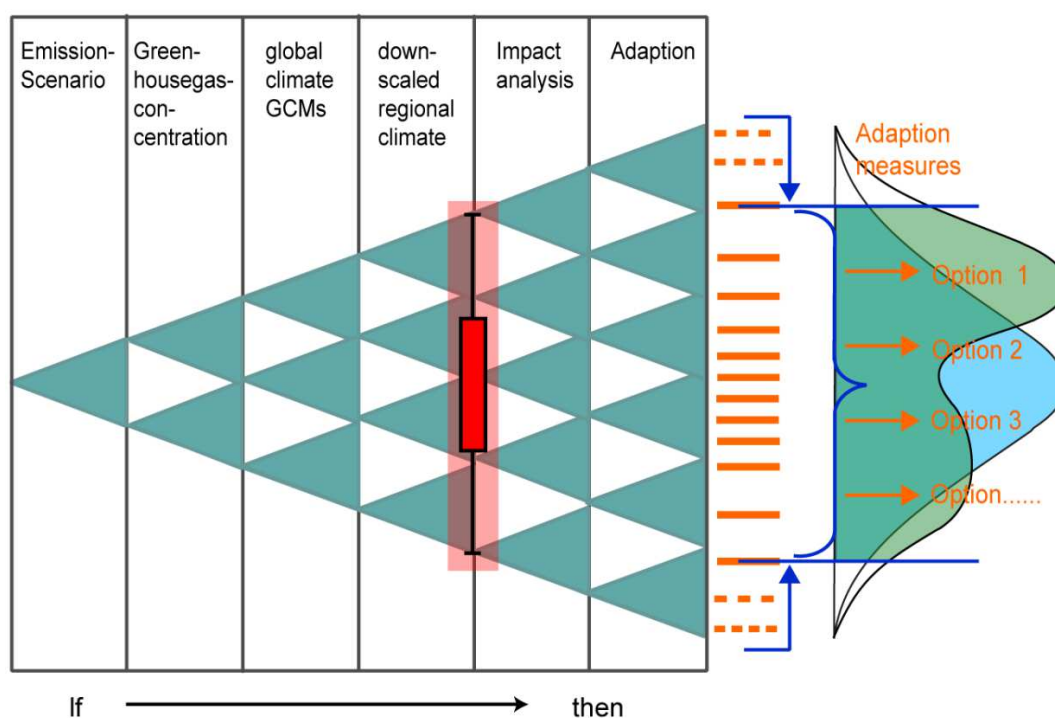
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## Executive summary

Climate change is an important topic within the context of designing, maintaining and operating traffic networks. Most transport infrastructure is intended to be of service to the public for several decades. Bridges and tunnels are designed to be of use for a century or so. Some bridges, for instance, built under Emperor Franz Joseph are still in service. In some cases the problem is that the bearing capacity is unknown since the design drawings and construction plans have been lost during WWI. The point is that the life cycles of assets in transport are long enough to take the full strain coming with climate change. Climate impact is experienced on the small scale. Crops are destroyed by flooding events; forest timber is felled by heavy storm events and infrastructure is devastated by various kinds of extreme events. *Hence, transport infrastructure is on the spatial and temporal scale heavily impacted by climate change.*

CliPDaR aims at enabling the reader to make informed and efficient decisions on whether a proposed climate change scenario is suitable to derive particular adaptation measures or not. Moreover the information given here should enable you to establish yourself climate change scenarios helping to answer particular problems regarding future transport infrastructure. This is accomplished by a guideline helping decision makers through the whole process (depicted in Figure 1) from the socio-economic scenarios to the adaptation measures to be put into effect. This report especially focuses on the downscaling step (fourth column in Figure 1).



**Figure 1:** This "cascade-process" is involved when deriving adaptation measures to handle climate change.

Depending on the problem different local scale climate variables are needed to derive proper adaptation measures. Combinations of such variables or functions of them, which are of importance regarding assets, are called Climate Indices (CIs) henceforth (Matulla et al. 2013).

The following sketch of a specific problem may serve as a motivation for this report. Often climate change is not the only reason for changing risks of damages to infrastructure. In general problems like "rutting" result from the combination of several factors. Next to global warming new regulations are of importance too. The new EU regulation to harmonize lorry weights across Europe certainly constitutes a problem in this regard. The new vehicles are weighing 60 tonnes and are over 25 m long. The trend to longer and larger super-size lorries is a development towards higher standards in ecology (since there is a potential of saving up to four fifths of the fuel required by vehicles of 7.5 tonnes and the need for roads can be reduced by a factor of seven). However, the increased load is a challenge for roads. The risk of financial losses and downtime as a result of rutting is going to increase with load. This EU regulation is also a challenge for old bridges (mentioned above) as collapses might cause injuries and fatalities.

To develop an understanding how e.g. the *risk of damages* to north German roads (perhaps at some spots) *caused by rutting may change* in the future, it is necessary to know the rate of future warming there. From experience of some national road agencies it is known that rutting occurs if road surface temperatures exceed a threshold value of about 55° C and in case heavy lorries are running right then over it. This surface temperature is reached if daily maximum temperatures at 2 m height are at least 30° C or higher (called a "Hot day"). Significant cooling during the night is prevented, if the nights are "tropical" (minimum air temperature not lower than 20°C). So, the appendant CI under investigation is: *consecutive days and nights complying with these temperature conditions*. In order to assess changes in the risk of rutting at some traffic spots in northern Germany it is necessary to derive local scale temperature changes at these spots. Hence, at least two plausible but different future pathways of development of mankind (socio-economic scenarios) together with the corresponding large scale climate change projections (i.e. the reaction of the climate system to the socio-economic scenarios) should be selected.

Since we are interested in the transport network in Europe a downscaling technique is required that transforms the large scale information to the road infrastructure. The changing risk of damages depends on day and night temperatures. In case there are temperature observations close to the spots on hand, it is reasonable to use the Analog Method (an Empirical Downscaling technique, see Section 'Empirical Downscaling') to generate local scale climate change scenarios there. These scenarios have to be evaluated with regard to the CI. Changes of CI between the past and the future can be now translated into changing

risks of damages to roads. Based on these findings decisions regarding the adaptation measures can be made.

The above example illustrates the aim of our report. In order to enable the reader to evaluate a proposed approach (whether is qualified for answering a problem regarding adaptation measures or not), it is necessary to discuss Downscaling strategies (fourth column of Figure 1). The setup of this report (see the next section) should help to ensure this.

## 1 Preliminary remark

Concerning the CEDR Call 2012 "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 return periods of e.g. cold winters or hot summers.

Because of the given short time line 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 and KLIWAS, to contribute to a paper of recommendations for the involved national road agencies.

The mission of CliPDaR is creating a design guideline setting standards for the handling with climate change data and downscaling methods used in pan-European traffic infrastructure risk assessment.

## 2 Introduction, main target and setup of the report

This report focuses on the downscaling step, which is necessary to derive local scale climate change scenarios from GCM projections. The idea and the purpose of Downscaling is motivated in **Figure 1**. Downscaling covers all techniques that derive regional or local scale climate from the continental scale (large scale) evolution of the state of the atmosphere over several decades.

The recently published IPCC report, the fifth assessment report 2013, highlights again and with higher confidence that the warming of the climate system is unequivocal. Many of the observed changes, especially from the 1950s on, haven't been experienced during the past millennia. Highest confidence is attached to statements on temperature controlled processes and quantities. The atmosphere and the ocean, for instance, have warmed while the sea ice content decreased and glaciers have shrunk almost all over the planet. Sea levels have risen etc. The second important message to the public is that mankind is dominantly causing these changes by the release of greenhouse gases into the atmosphere. As such it is crucially important to develop an understanding of the consequences coming along with different pathways of mankind. To answer such 'if - then' questions it is necessary to run lots of experiments using Global Climate Models (GCMs) simulating the climate system of the Earth.

The impact of climate change is mostly experienced at the regional or local scale (e.g. perhaps increased bridge scour due to altered precipitation regimes). To derive proper adaptation measures necessary to prepare road infrastructure to climate change it is necessary to have local scale climate change projections on hand. Therefore, calculating regional climate projections the GCM are followed often by Regional Climate Models (RCMs) to downscale to higher spatial and temporal resolutions using the GCM results.

### 2.1 Structure of the report

Once (Chapter 3) the physical cause requiring the performance of Downscaling is elucidated (Chapter 4) dynamical and (Chapter 5) empirical Downscaling are explained. First, each Downscaling variant is considered on its own and then compared to each other (Chapter 6). The comparison includes a discussion on the pros and cons of the techniques. Conceptual differences are exemplified (e.g. understanding the different ways the observations are made use of) as well as (Chapter 7) appendant compensation and correction procedures are discussed (bias correction, etc.). Two specific examples are given (Chapter 8); the first one dealing with temperature changes in the complex terrain of the Alps; the second example describes the changes in the risk of damages to transport infrastructure in terms of rutting. A lookup Table is presented (Chapter 9) that is of help for a quick

assessment of a proposed solution-finding path. In Chapter 10 concluding remarks are discussed.

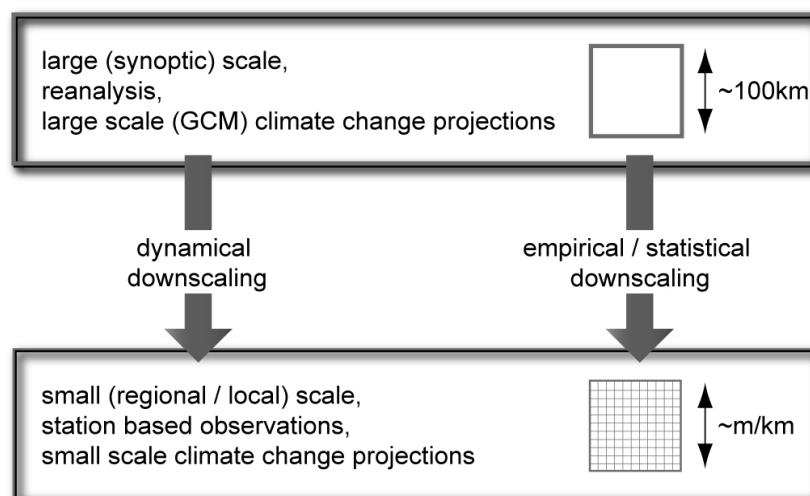
## **2.2 Historical note**

The term "downscaling" was first used in the MPI Report No. 64, preprint of the article of Hans von Storch et al. (1993). This approach was developed out of a request for elaborating the utility of GCM output, asked by a group of German hydrologists - the details of the meeting are by now forgotten. Inspired by Kim et al. (1984) Hans von Storch and Eduardo Zorita applied Canonical Correlation Analysis to derive Iberian Peninsula seasonal rainfall change in winter from global GCM scenarios.

The method and analysis was finally published first in Spain (Zorita and von Storch, 1991) and then in the Journal of Climate (von Storch et al. 1993).

### 3 Physical Background

It is crucially important to understand that a higher resolution cannot be realized by applying an interpolation routine to GCM output at a few grid points. In general it often makes perfect sense to enhance the spatio-temporal resolution of fields by interpolation strategies. This is particularly the case if there is knowledge on the features (e.g. continuity, differentiability) of the considered fields available. These features must be maintained at the newly introduced grid points contouring the distribution. In case of GCM fields, however, a simple interpolation is of no help. This stems from the way to tackle the so called primitive equations in atmospheric research. The physical equations governing the motion of the atmosphere and describing its thermodynamic state are differential equations that cannot be solved analytically. Depending on the extent of the atmospheric phenomena of interest the equations are 'filtered' by estimating the magnitudes and comparing terms ('scale theory', e.g. Holton 2004). GCMs calculate processes taking place on the synoptic scale, meaning smaller scale processes (e.g. on the meso scale or even below on the convective scale) are not explicitly solved by construction. The *effects* of so called sub-grid scale processes that are (in an accumulated way) visible on the large scale are considered in the GCM equations by parameterization (see for example the convection scheme of Tiedtke (1989)).



**Figure 2:** A sketch of how highly resolved local scale data are generated from coarse scale GCM simulations.

As GCMs focus on the continental scale the appendant output has to be interpreted on this scale too, with the consequence that data on just a few grid points comprise on information. Local scale information cannot be derived by simply interpolating GCM output since it is not contained in GCM projections. GCM output is meaningful at a continental scale but not on scales below.

As a consequence GCM output is not sufficient for climate-impact-research investigating e.g. how ecosystems are affected by climate change. Impact research

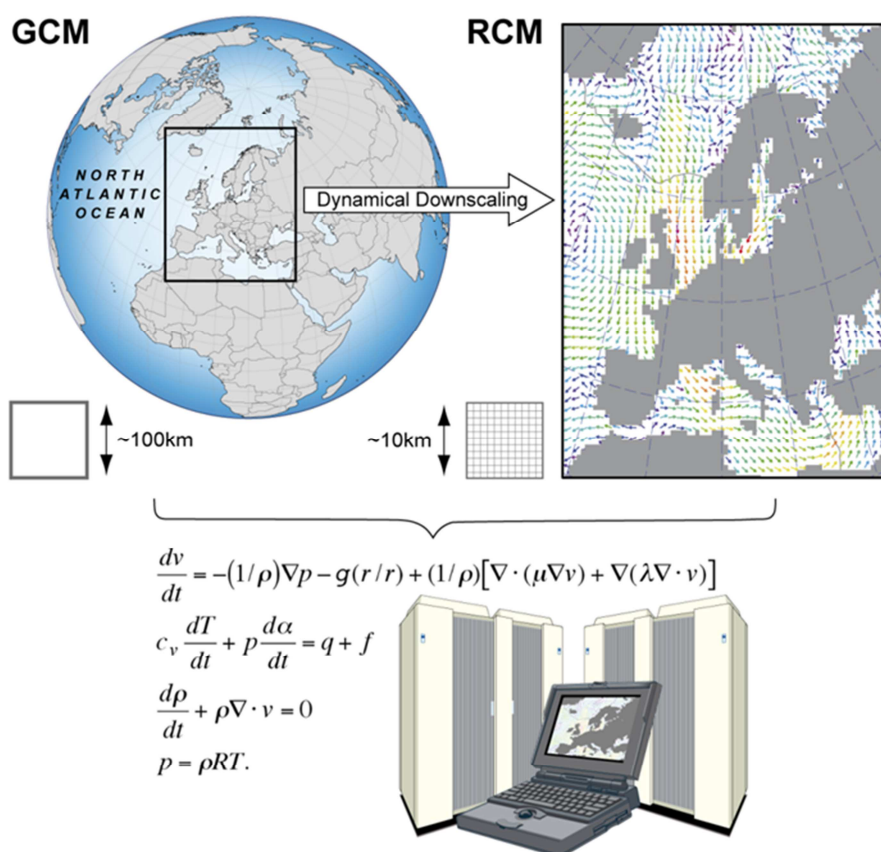
typically requires climate change data on small (regional or local) scales (e.g. Lexer et al. 2002). So there is additional information required which has to be added to the GCM output in order to derive local scale data capable to drive local scale impact assessment. This information has to be brought in from an 'outside source'. This is done by 'Downscaling'. Downscaling introduces knowledge of the behaviour between the large and the small scale. This additional knowledge is a necessary prerequisite for consistently deriving regional scale information from the large scale GCM atmospheric evolution. In brief, Downscaling sets the link necessary to derive small scale climate change projections from large scale GCM simulations, which in turn are capable to drive local scale impact assessment.

There are two basic downscaling strategies (see **Figure 2**). The first one (called 'empirical or statistical downscaling' (often abbreviated with 'SD')) uses observations on both scales to estimate the link and the second one ('dynamical downscaling' (often abbreviated with 'DD')) makes use of the physics of the atmosphere applied within thermodynamically Regional Climate Models (RCMs).

Both approaches critically depend on two main assumptions which are: (i) the large scale state of the atmosphere and its evolution affect the local scale weather development, (ii) the GCMs description of the reaction of the climate system to altered boundary conditions (so called 'projections') is complete and accurate. We are introducing both approaches, starting with dynamical downscaling.

## 4 Dynamical Downscaling

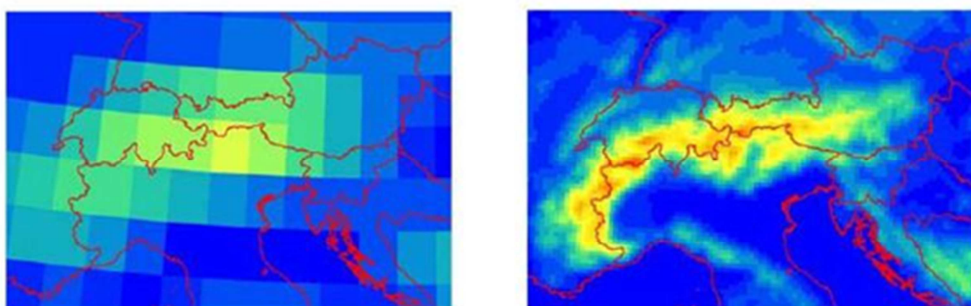
Dynamical Downscaling (DS) makes use of Regional Climate Models (RCMs) solving the primitive equations on a fine computing lattice (fine compared to GCM grids) for a small part of the globe (e.g. Europe, see **Figure 3**). In RCMs the spatial grid scale is approximately up to 10 times smaller than in GCMs. Due to this higher spatial resolution RCMs explicitly calculate small scale processes unrecognized by GCMs. At the boundaries of the considered geographical region RCMs are driven by GCM data. Inside, RCMs generate physically consistent states of the atmosphere that account also for features of the region (e.g. its topography and surface categories) in high resolution (e.g. Giorgi et al., 1991). Processes that are still too small to be captured by the RCM grid are again introduced by ‘parameterization’ (e.g. Pielke, 2002). The propagation of the solar radiation through the atmosphere, for instance, or interaction (exchange processes) between the spheres (e.g. between the biosphere and the atmosphere), atmospheric convection and phase transitions of water are parameterized. In total there are quite some RCMs available. REMO (Jacob and Podzun, 1997) and COSMO-CLM (Böhm et al. 2006) for example are used in the IPCC AR5 (IPCC 2013), which was recently released.



**Figure 3:** Sketch of the ‘dynamical downscaling’ approach. The interdependency of the atmospheric processes on different scales is given by physical equations, which are numerically solved by computers.

Since August 2013, the CLM-Community coordinating office is based at the Deutscher Wetterdienst (DWD) in the climate modelling section. The main intention of the CLM-Community is the coordinated model development of COSMO-CLM, the climate mode of the COSMO model (a weather prediction model for the regional scale), in close cooperation with the COSMO community. Hence, the climate modelling section of the DWD is not only involved in maintaining the good communication in the CLM-community through the coordinator, but also in model development itself and the management of several project groups.

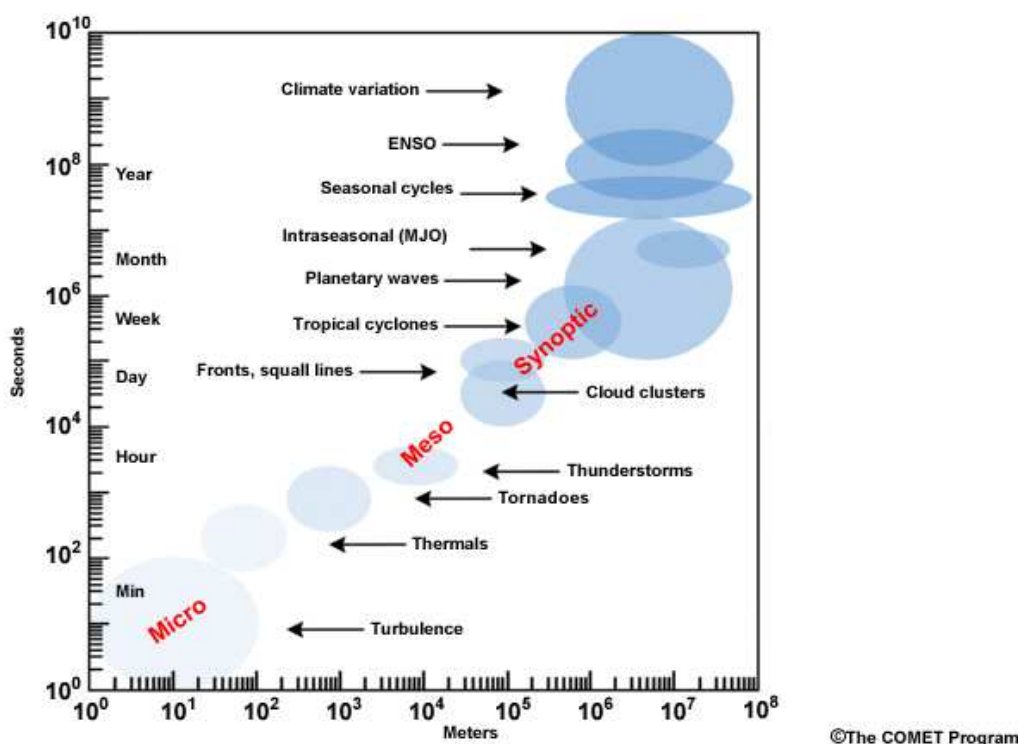
RCMs are based on the physics of the climate system and hence their numerical core is quite similar to the one used in GCMs. Differences are coming from the parameterizations and the numerical solution processes. Depending on the target-processes and regions, RCMs are tuned differently to simulate aspects of interest best. HIRLAM (Dethloff et al. 1996), for instance, is tuned to reasonably picture the climate of the high latitudes and the Arctic. COSMO-CLM and REMO have often been applied to the mid-latitudes and tropical areas. In this sense the literature gives a helpful hint which RCM projections may be best suited for setting up an ensemble of regional scale simulation to answer a particular problem (as for instance how the frequency and intensity of severe winters in Scandinavia may change in the future). **Table 3** in Chapter 9 contains a rather comprehensive literature review connecting geographical regions with empirical downscaling approaches. This is a valuable guideline (i) to group an ensemble of regional scale climate change projections according to own individual requirements and (ii) to check the usability of a given ensemble to address particular research questions. The benefit of the high RCM resolution (compared to GCMs) is achieved at the expense of computer resources (processing power and storage capacity) and time. This kind of small scale climate change depiction is possible because of the restriction of the calculations to a limited geographical sector.



**Figure 4:** Topography of the European Alps at a resolution of 100 km (left) and a resolution of 10 km.

**Figure 4** displays the European Alps at a 100 km and a 10 km grid. The 100 km grid is finer and the attendant topography closer to reality than the grids used by most GCMs. The 10 km grid displayed in **Figure 4** is quite representative for those currently used to produce RCM output. RCMs can be used to generate output on even finer scales. This is achieved by a process called ‘nesting’. For a small region

inside the area selected for the first downscaling (e.g. the Greater Alpine Region inside Europe) the RCM is driven with the data from the first downscaling run and sufficiently high resolution images of the orography and further surface properties. The quality of the simulations in terms of proximity to reality depends on the accuracy of the split into explicitly solved and parameterized processes and on the quality of the numerical algorithms. This approach is called 'one way nesting'. Another possibility whereby the enclosed atmospheric feeds back on the larger volume is called 'two way nesting' (Smolarkiewicz and Grell, 1992). A problem coming along is related to discontinuities introduced at the boundaries of the regions.



**Figure 5:** Classification of atmospheric phenomena in terms of their extent. With every downscaling step towards higher resolution more processes have to be simulated.

**Figure 5** gives an overview of the new processes that have to be simulated by the RCMs with every downscaling step introducing smaller spatio-temporal meshes. It is important to be aware of the errors associated with the modelling of regional scale climate change projections. They result from several sources including the incomplete understanding of the forces and the atmospheric processes. Parameterizations, numerical schemes, imprecise data describing the orography, surface features are introducing further features.

The overall effect of these error sources can be estimated by driving RCMs with observations assembled on a GCM like grid (so called 'reanalysis data'). ERA40 (Uppala et al. 2004) from the ECMWF (the European Centre for Medium range Weather Forecasts) and the NCEP/NCAR dataset (Kalnay et al. 1996) from the National Centre for Atmospheric Research in Boulder, Colorado are such databases.

They are entered into RCMs and the output for a climatological period (e.g. 1961-1990) is compared to local scale observations. This is no rigorous performance evaluation in a strict sense as the local scale observations (to which the RCM output is compared to) enter the process at its beginning. However, the results give at least a meaningful estimate of model capabilities. It has been shown that CLM underestimates temperatures in the Greater Alpine Region up to 4°C (Suklitsch et al. 2008), which is in the same order of magnitude as the expected warming throughout the 21st century. Deviations increase with altitude (Haslinger et al. 2012). Potential causes are the incorrect determination of clouds and wrong energy exchange processes at the Earth's surface. Processes participating in cloud formation have not yet been finally understood. The IPCC has devoted a separate chapter to that issue (IPCC 2013). Precipitation sums are largely underestimated (up to -20% south of the Alpine ridge) and overestimated (up to 40% North of the ridge). Differences are most pronounced within the complex terrain of the Alps where overestimations of 70% and more are to be found. Similar evaluations have been performed for heat waves (length and timing, Vautard et al. 2013). Based on EURO-CORDEX it turns out that the days in heat waves are underestimated while the timing fits rather well. Truhetz et al. (2007) investigated wind speed and found for six stations in the Alps (located in the 'Hohe Tauern' region) that low speeds are overestimated and high speeds underestimated, meaning that up to a wind speed of about 3 m/s occurrences are simulated with higher speeds as observed, while from 3 m/s the opposite happens.

When considering the amount of uncertainty inherent in climate change projections it is important to know which share is contributed by which factor. These factors are, for instance, natural climate variability, the emission scenario, the considered GCM or the applied RCM.

The simulated change and the associated uncertainty (the span of the findings) of the local scale projections, which are the output of a modeling chain (including socio-economic scenarios, emission scenarios, developments of greenhouse gas concentration in the atmosphere, GCMs, RCMs and perhaps a nesting sequence, see **Figure 1**), can be attributed to the different modeling steps. For the first half of the 21st century the range of different outcomes mainly depend on (up to 85%) the selected GCM and is influenced to only about 10% by the chosen emission scenario; a share which increases to 35% during the second half of the century (Prein et al. 2011). Aside from the uncertainties coming with summer precipitation totals GCMs create larger amounts of variability than RCMs (Deque 2007 and Deque et al. 2012). This distribution of the result-range between GCMs and RCMs changes in the Alps for spring and summer precipitation. Heinrich and Gobiet (2011) point out that RCMs are responsible for 50 to 65% of the uncertainties there.

Knowledge about the shared contribution to the uncertainties associated with the different modeling steps is of important help. It can support an informed choice of one or two local scale climate change projections from an ensemble in case the

derivation of a set of adaptation measures (e.g. a climate change resilient bridge foundation) is too expensive in terms of computer resources or time. This subject of making an informed choice is discussed in later parts.

## 5 Empirical Downscaling

Climate change impact is mainly felt on the regional scale, meaning damaged infrastructure or devastated harvests, for instance, happen on rather small spatial scales. Flood events or forest fires can affect larger areas too. In most cases, these regions are still below the continental scale, which is required to capture the large scale processes. The fact that the impact of climate change is felt on small scales is perhaps obvious, but worth mentioning in the context of empirical downscaling since the small scale observations are valued significantly different in Empirical Downscaling than in Dynamical Downscaling.

Empirical Downscaling refers to all techniques correlating processes, which are acting on different scales, in a mathematically consistent way. That requires records, which help constructing the missing link needed to derive local scale climate change projections from large scale GCM realizations (see the explanatory notes in 'Physical background' Chapter 3 above and in **Figure 6**). The idea consists thus in establishing a statistical model formulating the local scale variable of interest as a function of the large scale process. This approach reminds of the work carried out by a weather forecaster who tells from his experience the local scale weather from large scale distributions of meteorological fields. In this picture the use of the weather forecaster's experience would be the statistical function. Compared to Dynamical Downscaling Empirical Downscaling relies on one more prerequisite, which refers to the functional relationship derived from the observations. It is preconditioned that the functional relationship remains in effect under climate change.

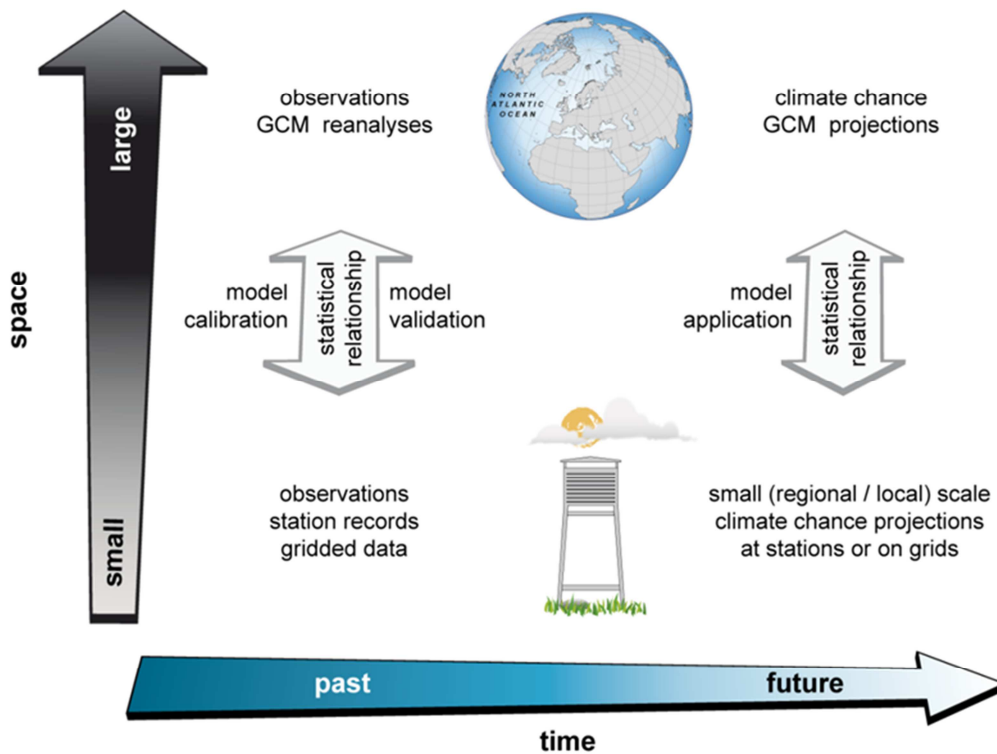
Below a brief overview of the three strategic approaches used in Empirical Downscaling is given (**Table 1** lists briefly their pro and cons). *This should help developing a sense whether a proposed course of procedures is suitable to address a particular task (e.g. risk assessment) or not.* As Empirical Downscaling is of central importance to climate change impact-research numerous papers on it and reviews can be found in the literature (e.g. von Storch et al. 2000 or Wilby and Wigley 1997). Presently there is an EU-COST project called 'VALUE' running, which focuses on Downscaling. For further information, readers are referred to von Storch and Zwiers (1999), who derive the techniques in a mathematically consistent framework and discuss them on the basis of examples taken from the literature.

### 5.1 Transfer functions

Transfer functions are used rather frequently for downscaling purposes. Depending on the way information is passed on between the scales the transfer functions are separated into linear and non-linear. Linear methods are Multiple Linear

Regressions (MLR), for instance, or pattern based techniques maximizing a constraint, leading to an eigenvalue problem. MLR based methods often use time coefficients of Empirical Orthogonal Functions (EOFs) of atmospheric fields (Hewitson and Crane 1992; Matulla et al. 2002) as predictors. The use of EOFs and the appendant time coefficients reduces the amount of independent variables and makes the equation system solvable.

Other linear approaches identify pairs of patterns (one on the large, synoptic scale and the other on the small scale), which are in a certain sense optimally coupled. The Canonical Correlation Analysis (CCA), the Singular Value Decomposition (SVD) and the Redundancy Analysis (RA) are examples (see e.g. von Storch and Zwiers 1999). CCA constructs patterns whose time coefficients are maximally correlated; SVD does the same for the covariance. In contrast to CCA and SVD the Redundancy Analysis is not symmetric between the scales. RA is set up to maximize the simulated variance of the local scale observations. On a seasonal timescale CCA was often used to link small scale precipitation to the large scale atmosphere. Von Storch et al. (1993) focused on the Iberian Peninsula, Busuioc et al. (1999) on Romania and Gyalistras et al. (1994) on the Alpine region. SVD was applied by Widmann and Bretherton (2000) to simulate precipitation in the Northwestern US and Huth (1999) used it to model European temperatures. WASA (1998) showed that RA is suitable to model significant wave height at the oil field Brent north of Scotland during winter.



**Figure 6:** Layout of Empirical Downscaling, which splits the temporal and the spatial scale into parts within which the method is calibrated and applied.

An example for a non-linear transfer functions has been given by Auer et al. (2005). They applied a hyperbolic Tangens to estimate the change of frost and ice days within a part of the European Alps if present temperatures are increased by one degree.

## 5.2 Classification Techniques

This strategy defines a suite of *weather types* (see e.g. Hess and Brezowsky 1969, Lauscher 1972, Werner and Gerstengarbe 2011) that span the space wherein atmospheric states take place. Local scale climate changes are described by weighting the local scale realizations with the changes in the frequency of the large scale weather types. This approach is straight forward and the relationship between the scales is physically a priori consistent since the large and the local scale states of the atmosphere have been observed at the same date.

Kidson and Watterson (1995) used objectively defined weather patterns (that are orthogonal but not necessarily physically meaningful) and analyzed changes in local scale precipitation, wind, temperature and sunshine. Conway and Jones (1998) applied the Lamb weather classes and the rotation of the wind field to model statistical features of daily precipitation over England.

Statistical-dynamical downscaling (Frey-Buness et al. 1995, Fuentes and Heimann 1996, 2000) defines weather types first, which are then dynamically downscaled. The dynamical downscaling exercise is carried out just once at the beginning. Future large scale states of the atmosphere are described by a weighted sum of the weather types and the associated local scale realizations are given by the assigned sum of the dynamically downscaled local scale states.

The Analog Method was introduced into Downscaling by Zorita et al. (1995). The observed large scale states of the atmosphere are split into their components with regard to the leading EOFs, which are derived from all states of the observation period. This equals a vector representation of the large scale states with the EOFs as their basis. The GCM projected states of the atmosphere are also depicted by the EOFs (from the observation period). For each time step the vector representation of the projected large scale state is compared to those of the observation period and the most similar (the analogue) is singled out. The local scale climate change projection of the large scale GCM projection is given by the observed local scale states of the analogues.

## 5.3 Weather generators

Weather generators are tools often used to simulate statistical features of variables characterizing local scale climate variability. This way local scale time series of any length can be easily produced. Two categories of weather generators are customarily applied. The first one uses so called Markov chains to model

sequences of consecutive states (Richardson 1981; Hughes et al. 1999; Charles et al. 1999). The second setup is based on dwelling times (Racksko et al. 1991; Wilks 1999b). A comparison of weather generators is contained in Semenov et al. (1998). One possible application of weather generators for Statistical Downscaling purposes is to formulate the weather generator's parameters as a function of the large scale GCM projections. This way the large scale climate change signal is translated down to the local scale (Wilby et al. 1998, Matulla et al. 2004).

**Table 1:** A comprehensive summary of empirical techniques together with their pros and cons (see Wilby et al. 2004).

Method	Strengths	Weaknesses
Classification techniques (e.g. analogue method, hybrid approaches, fuzzy classification, self-organizing maps, Monte Carlo methods).	<ul style="list-style-type: none"> <li>• Yields physically interpretable linkages to surface climate</li> <li>• Versatile (e.g., can be applied to surface climate, air quality, flooding, erosion, etc.)</li> <li>• Compositing for analysis of extreme events</li> </ul>	<ul style="list-style-type: none"> <li>• Requires additional task of weather classification</li> <li>• Circulation-based schemes can be insensitive to future climate forcing</li> <li>• May not capture intra-type variations in surface climate</li> </ul>
Weather generators (e.g. Markov chains, stochastic models, spell length methods, storm arrival times, mixture modelling).	<ul style="list-style-type: none"> <li>• Production of large ensembles for uncertainty analysis or long simulations for extremes</li> <li>• Spatial interpolation of model parameters using landscape</li> <li>• Can generate sub-daily information</li> </ul>	<ul style="list-style-type: none"> <li>• Arbitrary adjustment of parameters for future climate</li> <li>• Unanticipated effects to secondary variables of changing precipitation parameters</li> </ul>
Transfer techniques (e.g. linear regression, neural networks, canonical correlation analysis, kriging).	<ul style="list-style-type: none"> <li>• Relatively straightforward to apply</li> <li>• Employs full range of available predictor variables</li> <li>• 'Off-the-shelf' solutions and software available</li> </ul>	<ul style="list-style-type: none"> <li>• Poor representation of observed variance</li> <li>• May assume linearity and/or normality of data</li> <li>• Poor representation of extreme events</li> </ul>

## 6 Comparison of Empirical and Dynamical Downscaling techniques

The downscaling techniques introduced in the sections above have their specific pros and cons. The capability of classification based approaches (empirical downscaling) for instance, depends on how comprehensive the large scale atmospheric states of the GCM projections are described by the large scale patterns derived from the observations. This means, broadly speaking, as long as climate change does not force the projected large scale states of the atmosphere outside the space spanned by a basis derived from the observations (e.g. EOFs), the empirical technique shall work sufficiently well. With other words: even substantial changes of the probability density function can be modelled as long as they can be composed of what has been experienced so far. This corresponds to the assumption that the relationship obtained from the observations holds for the projections as well. An advantage of empirical methods is that the production of local scale climate change projections is rather cheap in terms of processing power and storage capacity. So it is feasible to generate large ensembles of climate change projections.

The performance of a dynamical downscaling setup depends on e.g. how well a particular parameterization scheme (e.g. Tiedtke's convection scheme) represents processes over the region under investigation or how closely the model topography matches the actual topography of the region under investigation. If the assumptions for the parameterizations do not apply or if the surface conditions of the considered regions do not match reality the downscaling lacks quality.

From a physical point of view dynamical downscaling is satisfying since all processes within and between the components of the climate system are governed by physical laws. In fact, however, the physical equations are simplified, parameterizations are introduced and numerical procedures are applied to approximate the solutions. All this may add up to very large biases (e.g. Suklitsch et al. 2008, Haslinger et al. 2012), which have to be corrected by so called 'bias correction' approaches. Bias correction (Chapter 7) methods are conceptual flaws as empirical methods are used to achieve reasonable results. Puristically seen a bias correction runs counter the concept of using the physical laws to generate local scale climate change projections instead of statistical techniques based on observations (i.e. empirical downscaling). Aside from that bias correction methods destroy the consistency between the downscaled model variables which is in principle guaranteed by the use of physical laws. However, presently dynamical downscaling is partly not able to reproduce the observed regional scale climate. As such bias corrections are necessary. Consequently this technique is used in the production of projections. As long as dynamical downscaling yields no better results bias correction a legitimate way to improve the results significantly.

It is presently state-of-the-art to use ensembles of climate change projections in impact research. These ensembles, normally based on a single emission scenario (e.g. SRES-A1B), are accounting for the variability of climate projections generated from different climate model approaches and different GCM-RCM combinations. Based on such a "composed" ensemble with its "specific" uncertainty of the projected climate input data, the range of impact model results could be used to give a first indication of the amount of uncertainty in developing adaptation measures.

Because empirical downscaling relies on the assumption that the relationship between the scales (the large, synoptic scale on which GCMs generate output and the regional to local scale where the observations are available) stays relatively unaltered in the future. So, empirically downscaled scenarios are more trustworthy for the decades ahead than for far away periods.

Weather generators take more or less the unstationarity of the ruling climate trends into account (e.g. Spekat et al. 2010, Kreienkamp et al. 2013). Dynamical downscaled climate projection data are normally used for a further statistical downscaling and/or impact studies for time slices up to the end of the century ("far future"). We would recommend for future studies ensembles made up by both downscaling techniques.

Hence, for developing an understanding of the possible ranges of uncertainty of the given local scale climate change projections, both approaches (empirical and dynamical downscaling) shall be used to provide large numbers of local scale projections.

## 7 Bias correction

Most part of impact models are not applicable to climate change signals, because these models are developed for the input of meteorologically and spatial-temporally consistent absolute values. Furthermore, climate models produce a reduced representation of natural processes such that a systematic error (bias) arises. When using climate model simulation results for impact models, these internal errors must be quantified and corrected. In case one or even more input parameters show a strong model bias, it might be impossible to run those models on the basis of climate projection data. The same problem can occur, when projection data do not simulate the spatial-temporal distribution of the observations sufficiently well. A statistical postprocessing that corrects for systematic errors is one way to solve this issue.

The basis for postprocessing is an observational data set. This observational data set has to be transferred to the grid of the climate projections. The data set should cover at least 30 years of observations. Before bias-correcting the data, gridded observations and model data should be compared.

The simplest way of bias-correction, applicable when a linear relation between model data and observations is evident, is the multiplication by a constant factor and/or the additive correction of a constant offset. This procedure is often adequate for yearly means. Other methods for bias-correction reduce the distance between the distribution of the observations and the error-prone distribution of the projection data by means of an average transfer function. Although more sophisticated than a linear correction, this way of postprocessing has still certain drawbacks. The individual bias-correction of one or more meteorological parameters interferes seriously with their physical consistency, an undesired side effect especially when dealing with complex multi-parameter impact models. Moreover, some typical model deficits are not possible to correct satisfyingly even by bias-correction procedures.

Another adverse effect of bias-correction is the possible change of climate signals, which occurs for instance in Quantile-mapping in case the correction coefficients for different ranges of the distribution diverge considerably.

Hence, for studies based on climate model output it is important to be aware of possible disadvantages using bias-corrected model data. While corrected RCM datasets are required as input for impact investigations in most cases, studies on climate change signals can also be carried out with uncorrected RCM data.

Therefore, the implementation of bias-correction procedures always requires a careful examination of both the quality of the resulting data series and the sensitivity of the impact model towards inconsistencies between the input variables.

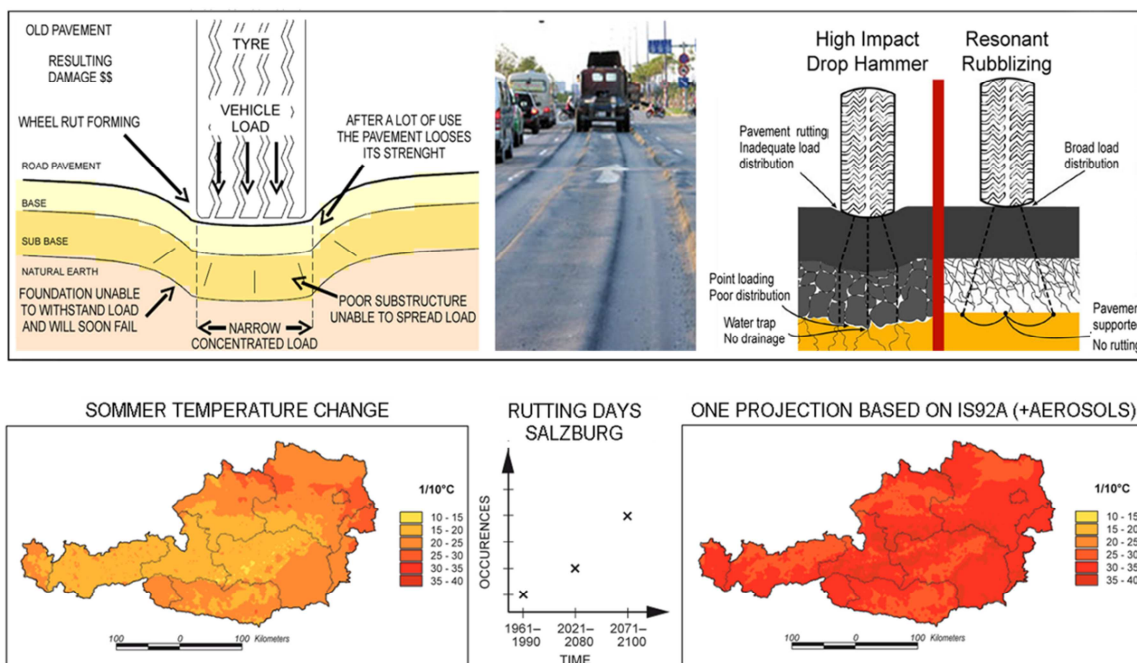
## 8 Examples

Global Climate Models (GCMs) used for climate studies and climate projections are run at coarse spatial resolution (typically of the order of 50 kilometres in 2012) and are unable to resolve important sub-grid scale features such as clouds and topography. As a result GCM output cannot be used directly for local impact studies.

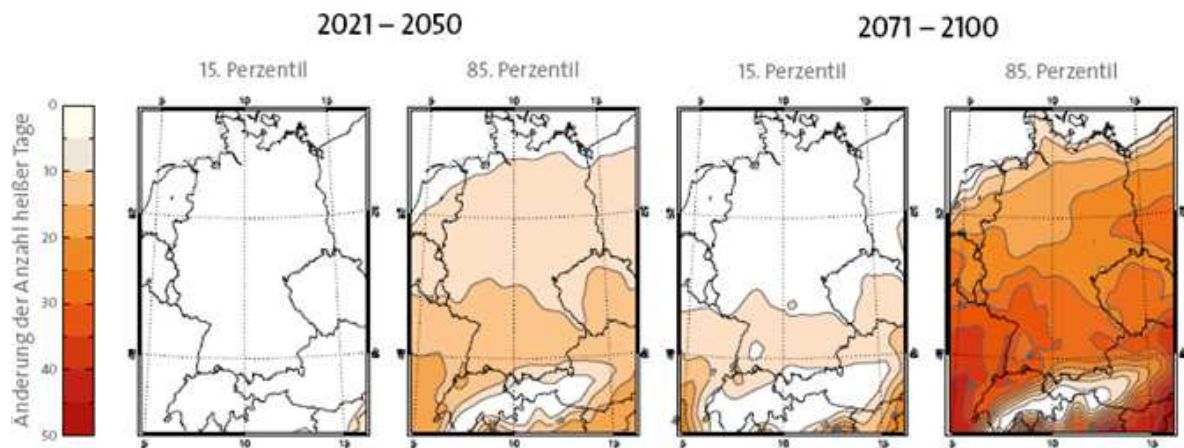
To overcome this problem downscaling methods are developed to obtain local-scale surface climatology from regional-scale atmospheric variables that are provided by GCMs. Two main forms of downscaling technique exist (see Chapters 4, 5 and 6).

Wilby and Wigley (1997) divided downscaling into four categories: regression methods, weather pattern-based approaches, stochastic weather generators, which are all statistical downscaling methods, and dynamical downscaling. Among these approaches regression methods are often preferred because of its ease of implementation and low computation requirements.

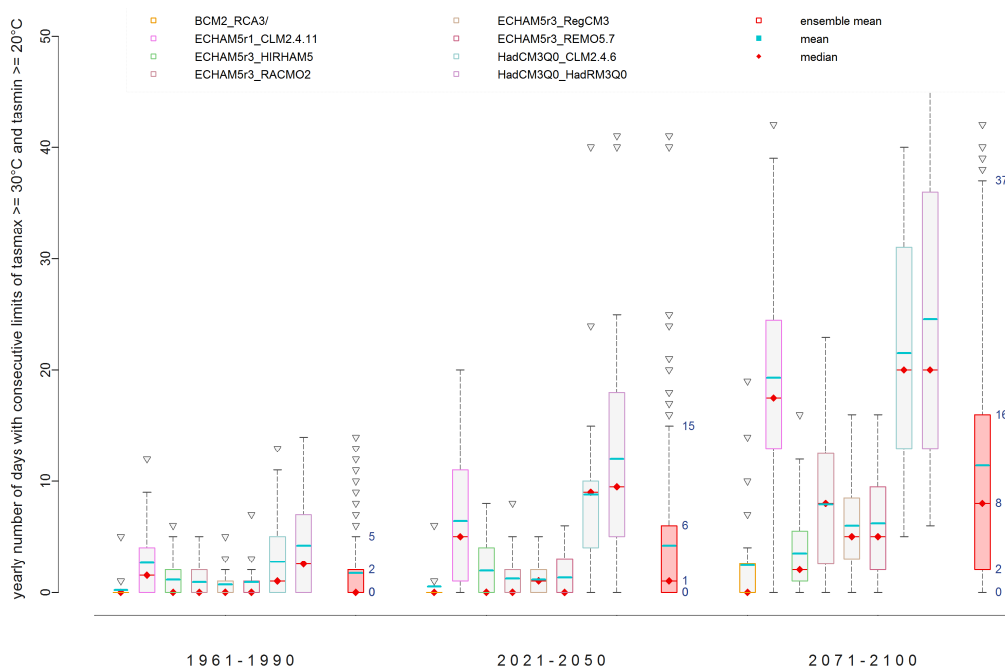
Two specific examples are given: The first one dealing with temperature changes in the complex terrain of the Alps; the second example describes the changes in the risk of damages to transport infrastructure in terms of rutting (**Figure 7**). In addition a 'Lookup Table' (**Table 3**) is presented that is of help for a quick assessment of a proposed solution-finding path.



**Figure 7:** An example-sketch that motivates the link of rutting and increased temperatures. The scenarios shown (Matulla et al. 2002) are not explicitly used in CliPDaR to link rutting to increased temperature projections, but are still of help to illustrate the problem, pointing out the changed risk of rutting with increased temperatures in an European region not entirely covered by the ensemble applied in CliPDaR.

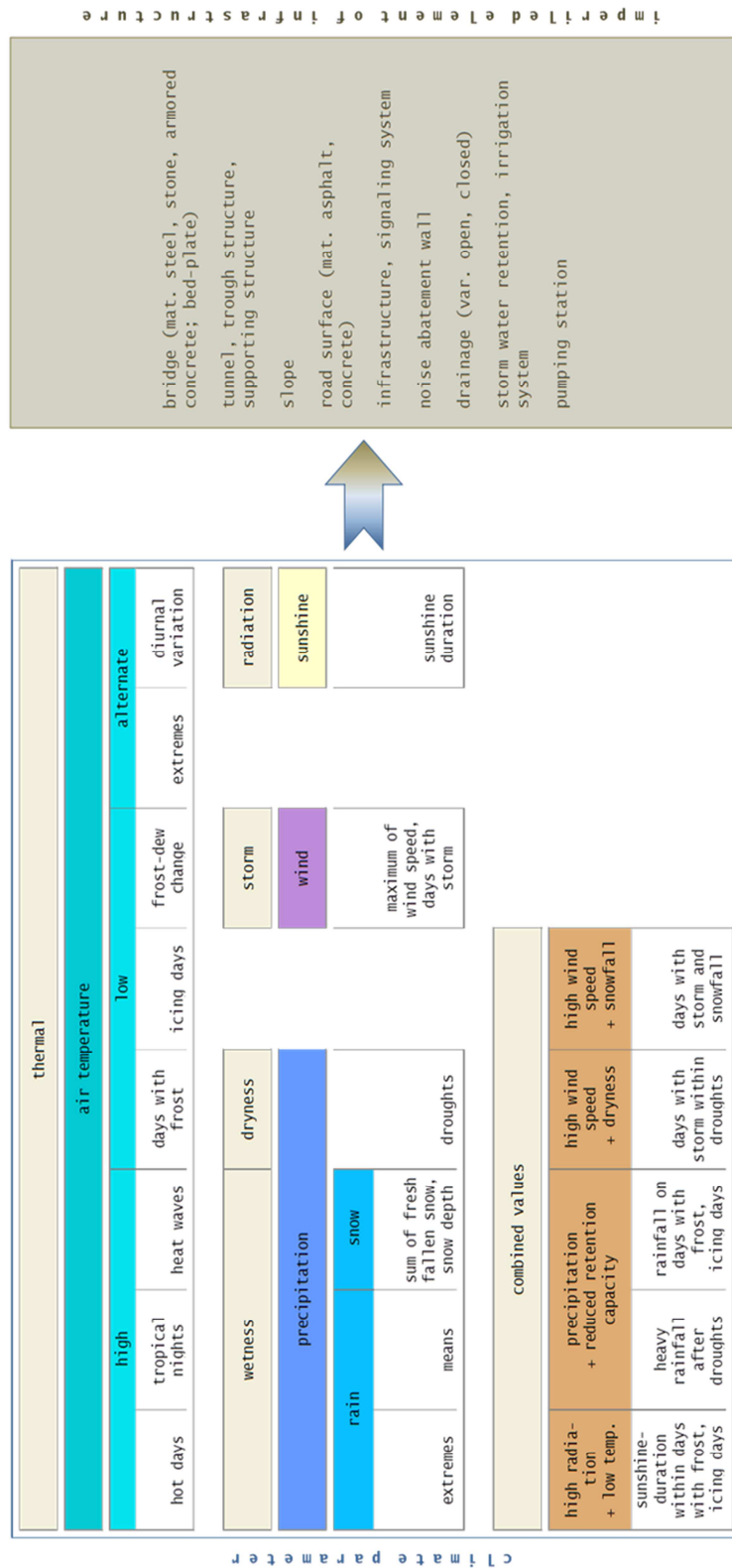


**Figure 8:** One possibility to illustrate the findings from an ensemble of projections (a multi model ensemble for A1B used here). The panels show the increase in the number of hot days per year. The left two panels refer to the 15th and 85th percentile for the near future (2021-2050), the right two the same and the farther future (2071-2100). Source: DWD (Klimaatlas).



**Figure 9:** Boxplots for the yearly number of potential 'rutting days' ( $T_{max} >= 30 \text{ °C}$  and  $T_{min} >= 20 \text{ °C}$ ) for Frankfurt am Main (a detailed explanation of the plot is given in Matulla et al. (2013) or CliPdaR\_D3.1). Low occurrences appear near the zero-level, which is mainly in high elevated regions).

Temperature related CIs cover a large proportion of the CET2 (Cause-Effect-Tensor of 2nd stage, see **Figure 10** and Matulla et al. 2013) and are responsible for a multitude of damages to transport infrastructure. Here we focus on a CI (henceforth called TRUT) that is characterized by high daily temperatures ( $\geq 30 \text{ °C}$ ) together with nights having  $T_{min} \geq 20 \text{ °C}$  (Tropical Nights). Such series of days and nights bear the potential of harming road surfaces via rutting **Figure 7** or blow ups.



**Figure 10:** Some infrastructure elements and climatological indices (CIs) causing financial and other loss. This is part of the CET2 - the Cause-Effect-Tensor of 2<sup>nd</sup> stage (see e.g. ClIPdaR\_D2.1)

Presently such days are rather rare throughout the considered parts of Europe (**Figure 9**). Taking the average over the median at all transport spots of KLIWAS 8 (KLIWAS 8 is made up of 8 regional climate change projections generated by combinations of GCMs and RCMs driven by the SRES-A1B scenario, see **Table 2**), less than one event per year is to be expected. Frankfurt am Main shows the highest frequency (1.6 occurrences per year). This number is increasing to 7.4 days/year in 2071-2100 (**Figure 9**). This time slice, however, exhibits pronounced differences within KLIWAS 8 projections. This behavior is particularly apparent for the two HadCM runs and the CLM run driven by ECHAM5 (see **Table 2**). While these three projections point to 14 occurrences per year, the other five projections give two days per year (**Figure 9**). This time slice, however, exhibits pronounced differences within KLIWAS 8 projections. This difference is to be seen at most sites, slightly more pronounced in the South than in the North of the domain and already detectable (albeit less obvious) in the near future (2021-2050). The variance of KLIWAS 8 changes significantly between 1961-1990 and 2071-2100, meaning, that the uncertainties increase towards the end of the century.

**Table 2:** Overview of climate simulations of (i) the years 1961-2000 for the control run (C20), (ii) projection runs for the years 2001-2100 based on the scenario A1B. 17-member ensemble, bias-corrected and regionalized on a 5 km grid. KLIWAS 8-member ensemble is signed by crosses (after Imbery et al. 2013, modified).

Control run/ SRES scenario/ reanalysis driven run	GCM	RCM	KLIWAS 8	
<b>C20/A1B</b>	ARPEGE	HIRHAM5 RM5.1		
	BCM2	HIRHAM5 RCA3	X	
	ECHAM5r1	CLM2.4.11	X	
	ECHAM5r2	CLM2.4.11		
	ECHAM5r3		HIRHAM5	X
			RACMO2	X
			RCA3	
			RegCM3	X
	HadCM3Q0		REMO5.7	X
CLM2.4.6 HadRM3Q0			X X	
HadCM3Q3		RCA3 HadRM3Q3		
HadCM3Q16		RCA3 HadRM3Q16		

## 9 Using the lookup Table

Here we present a lookup Table that shall help to construct the necessary steps to solve a given problem regarding the planning, reinforcement and maintenance of transport infrastructure in the context of a changing climate.

We will give some hands-on-advice to the reader how to use the gained knowledge (summarized in the CliPDaR deliverables) to achieve meaningful solutions to practical problems. Thereby we will make use of examples e.g. given in the preceding paragraph. Suppose you are planning a new part of the European transport network in heat exposed parts of Europe that is going to be in place in five years. This, together with the time the roads shall be open to the traffic adds up to e.g. 50 years before the first complete overhaul is to take place, which affects the appendant drainage systems and lots of other components. Another example relates to prestressed concrete bridges which are susceptible to heat expansions. So for both examples heat is perhaps the main problem. Depending on their surfaces roads are prone to rutting in case the surface is made up by asphalt and to 'blow ups' if it's concrete. Bridges have to handle heat expansion, which is in the mentioned case an issue.

So, in our example we would search for a Climate Index (CI) that describes such critical situations. One possibility (perhaps not the only and best one) is to regard some days that are rather hot, possibly so called 'hot days' exceeding 30°C together with nights that do not allow the surfaces to cool off. Such nights are called 'tropical nights' (temperatures of 20°C or larger). These conditions even cause increased mortality rates in human populations as the human body cannot recover during tropical nights.

Presently the problem is identified (i) the assets are roads and bridges; (ii) we have singled out a CI picturing the meteorological situation potentially harming the assets. Now (iii) we have to determine the CI's present occurrence frequency and the probable future occurrence frequencies. In case of the roads we can focus on the near future (2021-2050), but in case of bridges we will have to take the far future (2071-2100) into account as well, because bridges shall have life cycles of a century or longer. In Croatia, for instance, several bridges built under the Austrian-Hungarian monarchy are still under heavy use. The next step is to select a downscaling approach that works well for temperature extremes in Europe. The below 'Look up table' (**Table 3**) taken from the IPCC third assessment report focuses on three ways of downscaling (transfer functions, weather typing and weather generators). Bias corrected dynamically produced projections are always a possible alternative and we have already mentioned that a sound ensemble should include empirical generated as well as dynamically produced regional to local scale climate change projections. Anyway, let us consider **Table 3**. It tells that, if local scale records covering the past

are given on hand (e.g. from weather stations), regional to local scale temperature can be downscaled by the application of Transfer Functions (e.g. Murphy, 2000 and Benestad, 1999), which can be used in case of  $T_{\min}$  and  $T_{\max}$  as well (Trigo and Palutikof, 1999 Palutikof et al., 1997 Winkler et al., 1997). However, weather generators (Semenov and Barrow, 1997) and classification methods (e.g. Heimann and Sept, 1999) can be applied too. **Table 3** comprises many combinations of methods and local parameters to be generated for future periods together with the preferred time resolution (e.g. months or days). So, aside from dynamical processed regional scenarios empirically produced projections can be constructed. Ideally the applied ensembles to address the problem should contain many projections generated by empirical and dynamical techniques. This helps to derive robust statements.

These examples show how to construct a meaningful approach to handle given problems coming along with the planning, reconstructing or maintaining roads having to withstand climate conditions in 50 to 100 years from now. Based on such an approach telling the probable future climate conditions that transport assets may experience, educated decisions regarding the material, adaption measures depending where the transport network runs and further important options may be taken.

**Table 3:** The ‘look up Table’ helping to judge which downscaling method was successfully applied to generate regional to local scale projections characterizing the possible future behaviour of the target parameter under investigation. The table focuses on empirical techniques and the European continent.

Region	Technique	Predictor	Predictand	Time	Author(s)
Europe	WG	VOR, W			Conoway et al., 1996
Europe	WG, TF	C, Tmax, Tmin, O	T, P	D	Semenov and Barrow, 1996
Europe	TF	C, W, VOR, T, Q, O	T, P	M	Murphy, 1998a, b
Europe	TF	C	T,P vapour pressure	D	Weichert and Bürger, 1998
Germany	TF	T	Phenological event		Maak and van Storch, 1997
Germany	TF	C	Storm surge	M	Von Storch and Reichardt, 1997
Germany	TF		Salinity		Heyen and Dippner, 1998
Germany	WT		Thunderstorms	D	Sept, 1998
Germany	TF		Ecological variables		Krönke et al., 1998
Iberian Peninsula	WG	C	P	D	Cubash et al., 1996
Iberian Peninsula	TF	C	Tmax, Tmin	D	Trigo and Palutikof, 1998
Iberian Peninsula	TF		T,P		Boren et al., 1999
Iberian Peninsula	TF		T,P		Ribalaygua et al., 1999
Spain (and USA)	TF	C	Tmax, Tmin	D	Palutikof et al., 1997

Spain (and USA)	TF	C	Tmax, Tmin	D	Winkler et al., 1997
Spain	WT			D	Goodess and Palutikof, 1998
Portugal	TF	C	P	M	Corte-Real et al., 1995
Portugal	WT	C		D	Corte-Real et al., 1999
The Netherlands	WT	C, VOR, W	T, P	D,M	Buishand and Brandsma, 1997
Norway	TF	C, O	T, P and others	M	Benestad, 1999a, b
Norway (glaciers)	TF	C, O	Local weather	D	Reichert et al., 1999
Romania	TF	C	P	M	Busuioac and von Storch, 1996
Romania	TF	C	P	M	Busuioac et al., 1999
Switzerland	TF		P		Buishand and Klein Tank, 1996
Switzerland	TF		P		Brandsma and Buishand, 1997
Switzerland	TF			D	Widmann and Schär, 1997
Switzerland	WG	C	Local Weather	H	Gyalistras et al., 1997
Switzerland	TF		P		Buishand and Brandsma, 1999
Poland	TF	C	T, sea level, wave height, salinity, wind, run-off	D,M	Mietus, 1999
Alps	WT				Fuentes and Heimann, 1996
Alps	TF	C, T	T, P	M	Fischlin and Gyalistras, 1997
Alps	WT	C	Snow		Martin et al., 1997
Alps	WT				Fuentes et al., 1998
Alps	TF	C, T	T, P		Gyalistras et al., 1998
Alps	TF	C, T	Snow cover		Hantel et al., 1998
Alps	WT	C, T	Landslide activity		Dehn, 1999a, b
Alps	WT		T, P	D	Heimann and Sept, 1999
Alps	WT		P	D	Fuentes and Heimann, 1999
Alps	TF, WG	C, T	Weather statistics	M	Riedo et al., 1999
Alps	TF	C	P	M	Burkhardt, 1999
Mediterranean	TF	C, P	T		Palutikof and Wigley, 1995
Mediterranean	TF	C	P	S	Jacobeit, 1996
North Atlantic	TF	C	Pressure tendencies	M	Kaas et al., 1996
North Atlantic	TF	C	Wave height	M	WASA, 1998
North Sea	TF		Ecological variables		Dippner, 1997a, b
North Sea coast	TF	C	Sea level	M	Langenberg et al., 1999
Baltic Sea	TF	SLP	Sea level	M	Heyen et al., 1996

**Technique** (utilised in the above categories):

- WG = weather generators (e.g.: Markov-type procedures, conditional probability).
- TF = transfer functions (e.g.: Regression, canonical correlation analysis, and artificial neural networks).
- WT = weather typing (e.g.: cluster analysis, self-organising map, and extreme value distribution).

**Predictor variables:** C = circulation based (e.g.: sea level pressure fields and geopotential height fields).

T = temperature (at surface or on one or more atmospheric levels). TH = thickness between pressure levels.

VOR = vorticity. W = wind related. Q = specific humidity (at surface or on one or more atmospheric levels).

RH = relative humidity (at surface or on one or more atmospheric levels). Cld = cloud cover.

ZG = spatial gradients of the predictors. O = other.

**Predictands:** T (temperature); Tmax (maximum temperature); Tmin (minimum temperature); P (precipitation).

**Region** is the geographic domain.

**Time** is the time-scale of the predictor and predictand: H (hourly), D (daily), M (monthly), S (seasonal), and A (annual).

The predictor variables are addressed here as potential input parameters for the three statistical approaches mentioned above.

## 10 Concluding remarks

CliPDaR will establish a design guideline treating climate change scenarios, downscaling techniques and statistical methods necessary for the generation of regional scale scenarios across Europe. This sets the basis for consistent, Europe wide risk assessments of road infrastructure regarding climate change.

As such it is important to identify climate indices (e.g. long term rain events, heat spells) harming road assets. This is to be done in cooperation with the road administrations, people in charge and constructional engineers. The Austrian - German Workshop in Vienna (6<sup>th</sup> to 8<sup>th</sup> May 2013) has been devoted to that. Additionally, interviews with road experts have been arranged (see Deliverable CliPDaR\_D2.1). Thus CliPDaR has been addressed to this with workshops, interviews and participation in international meetings (e.g. FEHRL FIRM13 in Brussels). Next to that, KLIWAS and VALUE as well as the German Adaptation Strategy (DAS), the Austrian Adaptation Strategy and the IPCC Recommendations (IPCC 2007) regarding adaptation measures will be taken into account.

These sources will be completed by the German Federal expert discussions on "Climate impacts" and on "guidelines dealing with climate projection data". All these documents will be considered when preparing the CliPDaR guidelines.

## 11 Acknowledgements

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