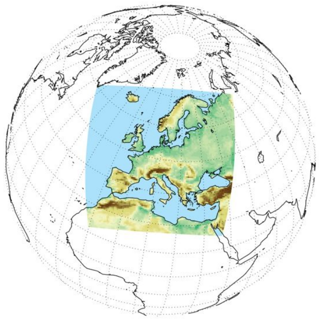
Guidance for EURO-CORDEX climate projections data use



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The *Guidance for EURO-CORDEX climate projections data use* is intended to provide background information, best practices and links to further information for users of regional climate model data. The main target audiences are researchers in impacts communities, engineers in industry and the public sector, or small and medium enterprises. For each topic, a short summary of the most important aspects is given, followed by references for further and more detailed information. It is important to note that this document represents the current state-of-the-art from the EURO-CORDEX community. However, it is a living document and will be updated as our understanding of regional climate and regional climate change as well as regional climate modelling improves.

In order to provide feedback, please send an email to feedback@euro-cordex.net.

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General information on the climate system

General Remarks

The output of climate simulations are data sets of relevant atmospheric and surface variables. Using these data for various purposes, e.g., for analysis of processes, as input for impact models or for estimating projected changes in order to define adaptation pathways, requires comprehensive analysis and understanding of the data, their validity and representativeness. Some issues are explained in the *CORDEX terms of use* (see also http://www.data.euro-cordex.net), others are described in the Chapter **Interpreting regional climate projections**.

Helpful advice on how to use climate model output can also be found in Kreienkamp et al. (2012), where the guidelines ('Leitlinien') are elaborated from a German federal state expert discussion (http://klimawandel.hlug.de/?id=448). The discussion paper is available in both German and English.

Further reading

- Kreienkamp et al., 2012: Good practice for the usage of climate model simulation results - a discussion paper, Environmental Systems Research, 2012, 1:9. https://doi.org/10.1186/2193-2697-1-9

What is climate?

The World Meteorological Organization states that climate *can be defined as the statistical description in terms of the mean and variability of relevant quantities over a period of time.* This period of time has typically been defined as 30 years. (http://www.wmo.int/pages/prog/wcp/ccl/faqs.php#q1). Therefore, climate is the statistical description of weather at a location and describes the likelihoods for a range of states and phenomena. Examples for statistical quantities related to climate are *mean* or *standard deviation*, but also *return-periods* and *intensity-duration-frequency* are frequently used to provide a picture of extreme events.

What is climate change?

According to the WMO, *climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer)* (http://www.wmo.int/pages/prog/wcp/ccl/faqs.html).

The IPCC relates their definition to the one of the UNFCCC in the following way: *Climate change in IPCC usage refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global* *atmosphere and that is in addition to natural climate variability observed over comparable time periods.* (http://www.ipcc.ch/publications_and_data/ar4/syr/en/mains1.html).

What is climate variability?

Climate variability is defined as variations of climate on all temporal and spatial scales, beyond individual weather events. Variability is mainly due to natural internal processes within the climate system (internal variability) or variations in natural or anthropogenic external factors (external variability) (http://www.wmo.int/pages/prog/wcp/ccl/faqs.php).

Internal variability arises from chaotic processes in the climate system and nonlinear interactions between its components, i.e., atmosphere, hydrosphere including cryosphere, biosphere and pedosphere. It is typically most pronounced on small spatial and short temporal scales, but is also relevant over multi-decadal time scales for regional and global climate projections (e.g. Hawkins & Sutton, 2011).

External variability involves factors external to the climate system. These include natural factors such as solar variability, orbital variations or volcanic eruptions, but also anthropogenic forcings like emissions of greenhouse gases and aerosols into the atmosphere and land use changes.

Further reading

- Hawkins, E. & Sutton, R., 2011: The potential to narrow uncertainty in projections of regional precipitation change. Clim. Dynam. 37, 407–418, https://doi.org/10.1007/s00382-010-0810-6

What is the difference between climate variability and climate change?

Whether we observe or simulate climate change trends or climate variability can be tested with suitable statistical tools. The results may be different for different meteorological parameters, phenomena and derived extreme events. Any attribution of already observed or projected changes to human influences must be investigated with care as individual events cannot be directly attributed to human-induced climate change and even sequences of anomalous events might be within the bounds of natural variability (see http://www.wmo.int/pages/prog/wcp/ccl/faqs.html). Only when persistent series of anomalous events - with respect to the context of broader changes in regional climate parameters - is observed may a human-induced climate change be suggested. One special case is a sequence of record-breaking events, as variables that are independent and identically distributed (iid; i.e. a null-distribution for a stationary series) have well-defined probabilities for the recurrence of record-events (see http://onlinelibrary.wiley.com/doi/10.1029/2008EO410002/pdf). For examples on the attribution of past changes to human-induced climate change refer to, e.g., IPCC AR5 (Chapter 10).

Further reading

- IPCC WG I FAQS: http://www.wmo.int/pages/prog/wcp/ccl/faqs.html

- http://www.climatechange2013.org
- http://climate4impact.eu/impactportal/documentation.jsp?q=internal_variability1
- IPCC WG I, AR5, Chapter 10, https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter10_FINAL.pdf

What are climate scenarios?

Climate scenarios (or climate projections) are representations of various possible future states of the climate system, based on numerical model simulations. These models describe the complex processes and interactions affecting the climate system, but also use information about anthropogenic climate forcing. Different factors of anthropogenic activity like socio-economic, technological, demographic and environmental development are characterized in climate models as equivalent changes in greenhouse gas concentrations as well as changes in land use and land cover (However, land use and land cover changes are mainly incorporated in global models and therefore we focus here on greenhouse gas concentrations). Since the future evolution of anthropogenic factors cannot be known in advance, their potential effects are explored through different scenarios describing several possible emission (and thus greenhouse gas concentration) pathways.

When performing a climate simulation, the chosen emission scenario provides forcing data for the climate model, resulting in the physical reaction of the climate system to that particular future anthropogenic forcing. Due to this forcing-dependent character, climate model outcomes are not interpreted as *forecasts* (known as an initial value problem in mathematics), but as *projections* based on a specific emission scenario (a boundary value problem in mathematics). The importance of the emission scenario choice can be evaluated using an ensemble of climate projections (see also **How should an ensemble of climate projections be used?**) - a set of parallel simulations with slight variations in the experimental setup (e.g. slightly different starting point or different model).

Two sets of emission scenarios were used in the general circulation model (GCM) simulations that provided the basis for the last three assessment reports of the IPCC (2001, 2007, 2014). These are the so-called SRES (Special Report on Emissions Scenarios; Nakicenovic et al., 2000; AR3 & AR4) and RCP (Representative Concentration Pathways; Moss et al., 2008; AR5) scenarios. The EURO-CORDEX ensemble is based on the RCP scenarios, only. For more details on the differences between RCP and SRES scenarios see the Appendix of this document or the publication *Climate change, impacts and vulnerability in Europe 2016 (EEA, 2016,* http://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016).

Further reading

- IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate

Change (eds.: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.
- IPCC 2007: Climate Change 2007: The Scientific Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds.: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L.). Cambridge University Press, Cambridge, United Kingdom, 946 pp.
- IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds.: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
- is-enes, *Background & topics - Scenarios* (http://climate4impact.eu/impactportal/documentation/backgroundandtopics.jsp?q=Scenarios)
- *Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies*, Technical summary, IPCC expert meeting report, 2007 (http://www.ipcc.ch/pdf/supporting-material/expert-meeting-ts-scenarios.pdf)

What are climate models (global and regional)?

Numerical climate models are used to project the possible future evolution of the climate system as well as to understand the climate system itself. They are built on mathematical descriptions of the governing physical processes of the climate system (e.g., momentum, mass and energy conservation, etc.). Numerical solutions of the underlying equations are then obtained based on numerical algorithms.

General circulation models (GCMs) are global numerical climate models which are used to study climate change on a global scale. They describe various components of the Earth system and the nonlinear interactions and feedbacks between them. In order to simulate the past climate, measured values are used as forcing data, whereas for future projections values from particular emission scenarios are employed (see also What are climate scenarios?).

Due to the large number of data points and the high complexity of GCMs, their integration requires a large amount of computational resources. The resolution of their horizontal mesh currently ranges from 100-500 km and they provide output with a 6-hour temporal frequency. Due to this relatively coarse horizontal and temporal scale, GCMs are insufficient for many aspects of regional and local scale estimates of climate variability and change. Therefore, downscaling is needed to describe the local consequences of the global change, which can be done using empirical-statistical downscaling (ESD) or dynamical downscaling by means of regional climate models (RCMs), also referred to as limited area models (LAMs).

LAMs have been widely and successfully used in weather forecasting since the 1970s. Their application for climate purposes started in the 1990s. RCMs are used to downscale GCM simulations using the GCM output data as lateral boundary conditions. RCM integrations are typically run at 10-50 km horizontal resolution over a specific region of interest (e.g., over Europe in case of EURO-CORDEX). Through a combination of explicitly resolving important processes (e.g., mountain circulations, land-ocean contrasts) and parameterization schemes adapted to higher resolutions, RCMs are able to provide more detailed characteristics of regional to local climate. Another method to derive regional to local climate information from GCMs is *Empirical Statistical Downscaling* (ESD). ESD exploits the dependency between large and small scales of different climate variables such as temperature and precipitation.

Further reading

- is-enes, *Background & topics - Climate models - Global models,* http://climate4impact.eu/impactportal/documentation/backgroundandtopics.jsp?q=global_models
- Rasmus Benestad, 2016: Downscaling Climate Information, https://doi.org/10.1093/acrefore/9780190228620.013.27
- is-enes, *Background & topics - Climate models - Regional models*, http://climate4impact.eu/impactportal/documentation/backgroundandtopics.jsp?q=regional_models

What is the added value of regional climate models?

The application of RCMs requires high-level expertise and a considerable investment in human and computing resources. As such, the use of RCMs has to be well motivated in terms of their added value (AV) with respect to the driving global model, scientific questions and intended downstream applications. The same is true for costly high-resolution RCM integrations (e.g., EUR-11 or higher resolved) that should provide AV compared to their low-resolution counterparts (e.g. EUR-44). We focus here on the first aspect (RCM versus GCM) and also explicitly leave out the question to what extent RCM-based applications could be replaced or complemented by computationally cheaper statistical downscaling methods.

AV of RCMs can be verified in two different aspects, which are partly dependent on each other but do not necessarily coincide: (1) A better representation of the present-day climate, and (2) a more accurate projection of future climate change. As GCMs and RCMs mostly share similar computational codes, AV basically arises from the fact that RCMs employ a much finer grid spacing. However, depending on the metric employed and on the specific type of comparison AV will not always be found. This is in particular true for mean features over large spatio-temporal scales (such as seasonal mean values averaged over larger domains) that can in principle also be well represented by coarse-resolution models. AV can primarily be expected for meso-scale atmospheric phenomena (e.g., Feser et al., 2011), for regional-scale spatial climate variability and its future changes, especially in regions of complex surface forcing (topography, land use, land-sea contrast etc.; e.g., Di Luca et al., 2012; Giorgi et al., 2016; Kotlarski et al., 2015; Torma et al., 2015) and for the tails of frequency distributions at high temporal resolution (e.g., for daily extremes; Jacob et al., 2014). In general, AV is more likely to occur for precipitation than for temperature (Di Luca et al., 2013). As resolutions are pushed towards scales where critical processes are explicitly resolved, additional benefits are seen. For example, convection-resolving RCM simulations at kilometer-resolution have shown additional AV in terms of the daily cycle of summer precipitation and sub-daily precipitation extremes (Ban et al., 2014; Prein et al., 2013). Besides benefits at high temporal and spatial scales, there are also strong indications that RCMs can improve on their driving GCMs for aggregated large-scale mean values that are, in principle, also resolved by GCMs themselves (Kerkhoff et al., 2014; Torma et al., 2015). Whether this translates into a better representation of present and future climate is, however, not necessarily clear. Despite obvious advantages of RCMs for many aspects of present-day climate and climate change patterns, it should be noted that any RCM-based climate scenario depends to some extend on its driving GCM. The quality and accuracy of a regional climate change scenario then is determined by both the RCM and the driving GCM. Considering only one RCM-GCM combination represents only one of very many potential outcomes. To sample the range of potential outcomes, and uncertainty associated with particular RCMs and/or GCMs, it is necessary to provide ensemble simulations combining different RCMs with different GCMs, as it is done within the CORDEX framework.

Further reading

- Ban, N., J. Schmidli and C. Schär, 2014: Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. Journal of Geophysical Research: Atmospheres 119, https://doi.org/10.1002/2014JD021478
- Di Luca, A., R. de Elía and R. Laprise, 2012: Potential for added value in precipitation simulated by high resolution nested Regional Climate Models and observations. Climate Dynamics 38, 12291247, https://doi.org/10.1007/s00382-011-1068-3
- Di Luca, A., R. de Elía and R. Laprise, 2013: Potential for added value in temperature simulated by high-resolution nested RCMs in present climate and in the climate change signal. Climate Dynamics 40, 443-464, https://doi.org/10.1007/s00382-012-1384-2
- Feser, F., B. Rockel, H. von Storch, J. Winterfeldt and M. Zahn, 2011: Regional Climate Models Add Value to Global Model Data - A Review and Selected Examples. Bulletin of the American Meteorological Society 92: 1181-1192, https://doi.org/10.1175/2011BAMS3061.1
- Giorgi, F., C. Torma, E. Coppola, N. Ban, C. Schär and S. Somot, 2016: Enhanced summer convective rainfall at Alpine high elevations in response to climate warming. Nature Geoscience, https://doi.org/10.1038/NGEO2761

- Jacob, D. et al., 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environmental Change 14: 563-578, https://doi.org/10.1007/s10113-013-0499-2
- Kerkhoff, C., H. R. Künsch amd C. Schär, 2014: Assessment of Bias Assumptions for Climate Models. Journal of Climate 27: 6799-6818, https://doi.org/10.1175/JCLI-D-13-00716.1
- Kotlarski, S., D. Lüthi and C. Schär, 2015: The elevation dependency of 21st century European climate change: an RCM ensemble perspective. International Journal of Climatology 35: 3902-3920, https://doi.org/10.1002/joc.4254
- Prein, A. F., A. Gobiet, M. Suklitsch, H. Truhetz, N. K. Awan, K. Keuler and G. Georgievski, 2013: Added value of convection permitting seasonal simulations. Climate Dynamics 41: 2655-2677, https://doi.org/10.1007/s00382-013-1744-6
- Torma, C., F. Giorgi and E. Coppola, 2015: Added value of regional climate modeling over areas characterized by complex terrain - Precipitation over the Alps. Journal of Geophysical Research: Atmospheres 120, https://doi.org/10.1002/2014JD022781

What are limits of climate modelling?

Each climate model realization is an incomplete representation of reality. The reason for this is that not all temporal and spatial scales can be resolved and not all processes within the Earth system can be simulated. Processes in the climate system occur on time scales that range from centuries to sub-daily and spatial scales from tens of thousands kilometres to below 1 kilometer. It is impossible to capture them all. Furthermore, several processes and interactions like turbulent exchanges under stable conditions or aerosol life cycles are not yet fully understood and therefore not directly quantifiable in explicit terms (If there is enough data describing these processes, however, it is possible to make use of statistical techniques to quantify some of their aspects). EURO-CORDEX models are operated on the same spatial scales of approximately 12km or 50km but have implemented slightly varying parameterizations of small-scale processes and therefore the results differ. Also the model configuration influences the results. Examples are the implementation of surface characteristics (e.g. land-use information), the number of vertical levels and the numerical scheme used to solve the equations. Other inherent limitations of climate projections are scenario uncertainty because the RCP-scenarios are based on certain assumptions for the future, and internal climate variability, which may be in the range of the analysed time scale of 30 years (Deser et al., 2012). ESD, on the other hand, requires much less computational resources than RCMs and can be applied to large multi-model ensembles and different emission scenarios (Benestad et al., 2016).

These limitations and the resulting uncertainty influence the reliability of the results, but since ESD and RCMs make use of different sources of information, combining the results from these strategies can improve confidence. Model results nevertheless have to be used and interpreted carefully and in a manner consistent with their intended purpose. In general it can be stated that climate models are good at simulating the state and trends of the climate system for larger time slices and regions. Special care has to be taken in order to assess whether RCMs can be used to study events occurring on small temporal and spatial scales, e.g., when analysing the state of the climate system for a particular location (i.e., a single grid box) or a special date or a short time period (e.g. single storm events).

Further reading

- Deser, C., Knutti, R., Solomon, S. & Phillips, A. S., 2012: Communication of the Role of Natural Variability in Future North American Climate. Nature Climate Change, 2, 775–779, https://doi.org/10.1038/nclimate1562

How can climate model simulations be evaluated?

The evaluation of the model results aims at analysing the strengths and weaknesses of the global and regional climate models through different statistical (and physical) measures over long periods. Moreover, in case of regional models, their added value can be assessed with respect to the global climate models (see also What is the added value of regional climate models?). In order to evaluate climate model simulations, they have to be integrated for several past decades to be compared against suitable reference climatological data sets (e.g., observations and/or re-analyses data).

It has to be noted that the available reference data sets also have shortcomings and should only be applied for purposes they have been intended for. For instance, E-OBS (Klok and Klein-Tank, 2009) is a commonly used gridded dataset for Europe, but since it contains some precipitation gaps, more often homogenized national data sets are taken instead.

In case of regional climate models, two types of simulations are conducted for simulating the recent past each serving different purposes:

Hindcast simulations: For hindcast simulations, the initial and lateral boundary conditions are provided by a re-analysis product. With these simulations the quality of the regional climate model itself can be evaluated. As explained above the re-analyses are three-dimensional data sets for the whole globe (recently also available for limited domains) based on the blend of a numerical short-term weather forecasts and many kinds of observations. Since the boundary conditions in the hindcast experiment are based on measurements that are a reasonable representation of the true atmospheric state, the evaluation results mainly reflect the weaknesses and strengths of the regional climate model. In addition, shorter time periods can be analysed since the observed year-to-year correlation is preserved. The results of such an evaluation are also used to improve RCMs (e.g., an overestimation of heavy precipitation, indicates the necessity to research on convection parameterization).

Historical simulations: For historical simulations, initial and lateral boundary conditions are provided by a GCM. Therefore, the evaluation gives some hints on the GCM-RCM chain behaviour. Long time periods (usually 30 years) should be investigated since this type of experiment is not synchronised with the observed climate. Additionally, the GCM simulation should be investigated to assess whether a bias stems from the GCM or from deficiencies that are attributable to the RCM. This kind of evaluation experiment has great importance, as lateral boundary conditions for future projections are provided by GCMs.

Physical consistency test. There are few evaluations of the consistency between the GCM/reanalysis and the embedded RCM which answer some critical statements about their physical consistency. The RCMs and GCMs may for instance employ different choices in the 'model physics' (parameterisation schemes) which result in different model solutions. Changes in the precipitation climate, cloudiness and convection will imply a change in the vertical energy flow from the surface to the top of the atmosphere. The question is whether this matters. Closure tests can be used to assess how the RCM and the GCM performed together, e.g., by comparing the aggregated energy and mass fluxes through the top and lateral boundaries of the RCM and corresponding surfaces in the GCM. The question that needs to be answered is whether there is a mismatch in the energy and mass fluxes in the two stages and if so are they related to the biases in a systematic way, or if they can introduce artificial trends.

ESD evaluation. The evaluation of ESD needs to make use of different strategies than for RCMs. One is the use of cross-validation (Wilks, 1995), where the data is split into two batches: one for calibrating the statistical models and the other for independent validation. The models' ability to reproduce the long-term trends is tested by calibrating the models with de-trended data, and then use the original data with any trend embedded to reproduce the original observations. This stage can be combined with the cross-validation for a more stringent test. It is also possible to stratify the data and use the low values to train the model and then use predictions for the high values for validation. The validation of both ESD and RCMs were discussed in the European COST-action VALUE (Maraun et al., 2015)

Model outputs are inevitably imperfect, mainly due to the complex nature of the climate system, model shortcomings (i.e. errors) and model approximations (i.e. parameterizations), resulting in biases when compared to reference data sets. For more information on how to deal with such biases see How to interpret and adjust model biases?

Further reading

- Klok, E.J. and A.M.G. Klein Tank, 2009: Updated and extended European dataset of daily climate observations. Int. J. Climatol., 29, 1182, https://doi.org/10.1002/joc.1779
- Maraun, D., Widmann, M., Gutiérrez, J. M., Kotlarski, S., Chandler, R. E., Hertig, E., Wibig, J., Huth, R. and Wilcke, R. A.I. (2015), VALUE: A framework to validate

downscaling approaches for climate change studies. Earth's Future, 3: 1–14., https://doi.org/10.1002/2014EF000259

Why are ensemble climate projections needed?

Climate models are employed to generate projections of the future climate at multi-decadal to centennial time scales. The simulated temporal evolution of future climate is subject to uncertainties which are tackled by different ensemble simulation strategies. The uncertainties can be grouped into three major categories: (i) scenario uncertainty, (ii) internal climate variability and (iii) model uncertainty (Hawkins and Sutton, 2009, 2011). In the following subsections, these sources of uncertainties and the respective ensemble simulation strategies are shortly described.

(i) Scenario uncertainty: External anthropogenic forcings are derived from emission scenarios (see above). The latest generation of climate projections for the 21st century build on Representative Concentration Pathways (RCPs) (Moss et al., 2010). RCPs are defined by different radiative forcing levels at the end of the 21st century. The related temporal evolution of atmospheric greenhouse gas and aerosol concentrations (in some cases emissions) are prescribed in global climate models, which then simulate the response of the climate system to the forcing. By prescribing different forcings according to different pathways, a range of potential future climate evolutions can be projected. A subset of currently four RCPs are used to create a multi-scenario ensemble to cover a large bandwidth of future climate evolutions. For the historical simulations of the 20th century, observed concentrations of atmospheric substances are prescribed in the models. The simulated climate projections are then compared to the historical climate simulations in order to derive projected climate change signals.

(ii) **Internal climate variability** (see above) is simulated by models of the climate system (Deser et al., 2012). Its temporal evolution strongly depends on the initialisation of each model component. To consider different potential evolutions of climate variability, a set of simulations with the same external forcing can be performed, but with slightly different initialisation states. The results of such an initial-condition ensemble lie within a range of equally probable climate evolutions.

(iii) Model uncertainty: Models are always simplified representations of the earth's climate system. Different models apply different physical parameterisations and also different numerical approaches. Those structural differences lead to a range of simulated climate responses to external forcing. They are addressed with multi-model-ensemble simulations (see below). Multi-model ensemble simulations based on a certain scenario, sample modelling uncertainties, but also different initial conditions of the climate system (see *Internal climate variability* above), as each global model is initialised at a different climate state. Also included under model uncertainty is the fact that different classes of models (e.g. dynamical vs. statistical downscaling) might give different results.

Within the EURO-CORDEX initiative, a coordinated multi-model, multi-method, multi-scenario, multi-initial-condition ensemble of downscaled experiments for Europe on 0.11° horizontal resolution has been established (Jacob et al. 2013).

Further reading

- Jacob, D.; Petersen, J.; Eggert, B.; Alias, A.; Christensen, O. B.; Bouwer, L. M.; Braun, A.; Colette, A.; Déqué, M.; Georgievski, G.; Georgopoulou, E.; Gobiet, A.; Menut, L.; Nikulin, G.; Haensler, A.; Hempelmann, N.; Jones, C.; Keuler, K.; Kovats, S.; Kröner, N.; Kotlarski, S.; Kriegsmann, A.; Martin, E.; van Meijgaard, E.; Moseley, C.; Pfeifer, S.; Preuschmann, S.; Radermacher, C.; Radtke, K.; Rechid, D.; Rounsevell, M.; Samuelsson, P.; Somot, S.; Soussana, J.-F.; Teichmann, C.; Valentini, R.; Vautard, R.; Weber, B. & Yiou, P. EURO-CORDEX (2014): new high-resolution climate change projections for European impact research Regional Environmental Changes. Vol. 14, Issue 2, pp. 563-578., https://doi.org/10.1007/s10113-013-0499-2
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- Deser, C., Knutti, R., Solomon, S. & Phillips, A. S., 2012: Communication of the Role of Natural Variability in Future North American Climate. Nature Climate Change, 2, 775–779, https://doi.org/10.1038/nclimate1562

How should an ensemble of climate projections be used?

For climate service purposes, it is recommended to use the largest possible model ensemble for evaluation and application of climate model results in order to achieve robust results. Only an ensemble analysis enables to make sensible use of the model-inherent uncertainties for assessing the results. *An ensemble of model simulations may consist of different models but only one scenario (multi-model-ensemble), one model and different scenarios (multi-scenario-ensemble), one model and different physical parameterization schemes (multi-physics-ensemble), or one model, one parameterization scheme and different realisations (multi-member-ensemble).* There exist several approaches to estimate the uncertainty of an ensemble by defining the bandwidth of the results (see e.g. Déqué et al., 2007). Analysing mean and standard deviation of ensemble members is the simplest method, but possible outliers often have a too large influence. This can be avoided by calculating median and suitable lower and upper percentiles. The percentile analysis can then be translated into likelihood terminology by an exceedance probability after Solomon et al. (Eds., 2007). Methods are described by Knutti et al. (2010).

For specific cases and applications it might be useful to reduce the size of the available ensemble by means of subsampling. There are different criteria how such a subsampling can be performed. One criteria could be that based on the evaluation results better model simulations are weighted higher than ones with less quality (see, e.g., Christensen et al., 2010). Another criteria for subsampling could be that the smaller ensemble represents the same range of projected climate change signals as the full ensemble (e.g., refer to IMPACT2C).

Further reading

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- Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), 2007: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

How to identify a “robust expected change” among the mass of information?

The robustness of projected climate changes based on an ensemble of climate simulations is defined in the IPCC Third Assessment Report - Climate Change 2001: Synthesis Report, Question 9: '... a robust finding for climate change is defined as one that holds under a variety of approaches, methods, models, and assumptions and one that is expected to be relatively unaffected by uncertainties.'

The verification of robustness is often based on satisfying different conditions. For example, the method applied in the ‘Klimasignalkarten’ (http://www.gerics.de/products_and_publications/maps_visualisation/csm_regional/index.php.en) identifies a projected change as beeing robust if, at least 66 % of all simulations agree in the direction of change and at least 66 % of the simulations pass a suitable statistical significance test (e.g., U-Test or Mann-Whitney-Wilcoxon Test).

Other authors define climate change robustness differently. Seaby et al. (2013) apply robustness tests to two different bias-correction methods and length of reference and change periods and do not include the significance tests. Knutti and Sedláček (2013) define the climate change robustness parameter, 'inspired by the ranked probability skill score used in weather prediction, and by the ratio of model spread to the predicted change (noise to signal).'

Further reading

- IPCC Third Assessment Report - Climate Change 2001: Synthesis Report, Question 9
- GERICS Climate Signal Maps regional (http://www.climate-service-center.de/products_and_publications/maps_visualisation/csm_regional/index.php.en), described in Hennemuth, B., Bender, S., Bülow, K., Dreier, N., Keup-Thiel, E., Krüger, O., Mudersbach, C., Radermacher, C., Schoetter, R. (2013): Statistical methods for the analysis of simulated and observed climate data, applied in projects and institutions dealing with climate change impact and adaptation. CSC Report 13, Climate Service Center, Germany, http://www.climate-service-center.de/products_and_publications/publications/detail/062667/index.php.en
- Seaby, L.P., J.C. Refsgaard, T.O. Sonnenborg, S. Stisen, J.H. Christensen, K.H. Jensen, 2013: Assessment of robustness and significance of climate change signals for an ensemble of distribution-based scaled climate projections. Journal of Hydrology 486 (2013) 479–493, https://doi.org/10.1016/j.jhydrol.2013.02.015
- Knutti, R. and J. Sedláček, 2013: Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change,Vol. 3, https://doi.org/10.1038/nclimate1716

Interpreting regional climate projections

General remarks

In this section we highlight a few topics that are important to keep in mind when using climate change projections for practical applications. It might be necessary that the reader briefly reviews previous sections.

- Be aware of limitations of climate modelling (see What are limits of climate modelling?)
- Understand how climate models work and which processes are parameterized (see among others What are climate models (global and regional)?)
- Use an ensemble of models (all available relevant models). This offers more meaningful results because statistical information can be provided. (see among others Why are climate ensemble projections needed?)
- Analyse plausibility and robustness of each climate model and scenario (see How to identify a “robust expected change” among the mass of information?)

- Analyse at least 30 years and several grid boxes. Be aware that the climate signal may be different for different reference periods (e.g., 2021-2050 - 1961-1990 vs. 2021-2050 - 1981-2010). Results of climate projections for one season or one decade might not be meaningful because of the climate variability and their time scale (see among others What is climate variability?).
- Do not use present day observation data as reference for future climate signals (see among others How should an ensemble of climate projections be used?).
- Exercise caution when analysing extreme events. Extreme events are rare and often require application of special statistical tools to be evaluated properly. Collaboration with experts in statistics is strongly advised (see among others What are limits of climate modelling?).

How to interpret small-scale structures?

There is still a debate to what extent small-scale structures at the spatial scale of individual climate model grid cells can and should be interpreted (e.g. Grasso 2000). On the one hand, several grid cells (typically more than four) are required to resolve atmospheric structures. Smaller scale variations are partly removed by the numerical filters of climate models in order to ensure numerical stability. Spatial smoothing is also frequently applied to the surface forcing fields of a climate model, in particular to orography in order to avoid steep topographic gradients and corresponding numerical instabilities. On the other hand, the surface forcing is grid cell specific and directly influences the simulation results over the individual grid cells. This is true for forcings such as topography, land use and soil type. Neighbouring grid cells, for instance, are typically located at different elevations which directly leads to differences in near-surface air temperature and to differences in the presence or absence of cryospheric features at the grid cell scale.

The most appropriate manner to analyse small-scale structures probably lies somewhere in-between the above described cases - i.e., interpretation of simulated atmospheric features at the grid cell scale should be avoided unless a direct and consistent influence of specific surface forcings can be expected.

Further reading

- Grasso L. D. (2000), The differentiation between grid spacing and resolution and their application to numerical modeling. Bull. Amer. Meteorol. Soc. 81.3, pp. 579-580

How to interpret divergence between models?

Climate models differ in their model details as well as in the respective model setup (see chapter What are limits of climate modelling?). This explains differences in the output of different models even if the initialisation or the lateral boundary conditions of the model are the same. Further, differences in the results of regional models can be attributed to different regionalisation methods (e.g. dynamical vs. statistical downscaling).

It has to be noted that there is *a priori* no criteria for which chain of global to regional model is the *best* one. Therefore, the first recommendation is to treat all model combinations as equal. Only after an in-depth evaluation of all regional model results (see chapter How can climate model simulations be evaluated?) there may be clear indications to sort out particular models. This must be done consistently for all ensemble analyses.

How to interpret time and space variability?

Individual components of the climate system (including their interactions and feedbacks) operate on very different time scales. Variability of the climate system is observed at time scales ranging from intra-seasonal to inter-decadal (or even centennial and millennial) scale. Furthermore, local physical processes may induce large spatial variability of the climate characteristics, that typically appear more robustly over complex surfaces, e.g., mountainous or coastal regions.

The climate system is vastly complex, there is a number of governing processes that we have deficient knowledge about (e.g., turbulence, cloud microphysics, surface fluxes, aerosols). Due to this fact and the limited computational capacity, a certain level of simplification in climate models is inevitable. It means that climate models are able to provide information about climate variability only on limited spatial and time scale, depending on their resolution, described physical processes, and on their domain-size in case of regional simulations.

Global climate models currently have 100-500 km horizontal resolution. These models are dedicated to project the future climate change and its variability on larger time and spatial scale (e.g., large scale atmospheric or ocean internal modes of variability like NAO and ENSO, respectively). Due to such long-memory phenomena existing in the atmosphere and ocean, to distinguish climate change from climate variability, statistics of the meteorological conditions should be considered over at least a 30-year long period. Local processes may significantly alter the general large scale signals, as a result changes on smaller scale may be amplified or lessened, or even be in contrast with the global tendencies.

Detailed information about climate change and its variability for a smaller area (e.g., a country) can be obtained from regional climate models, which are applying 10-50 km resolution nowadays and are therefore describing dynamical processes in the atmosphere in more detail. However, it must be considered that the effective model resolution is at least 2-3 times coarser than the grid spacing, i.e., only phenomena with a characteristic size bigger than this effective resolution should be examined. Intra-annual or intra-seasonal variability, with special emphasis on climate extremes can be adequately estimated with the use of fine resolution regional climate models. However, it should be taken into account that going towards finer time and spatial scale of specific investigations, the model results tend to become noisy. Consequently, the ensemble approach for evaluation of the climate models is especially important as much as it is important to have the ensemble approach for projections about future climate characteristics.

In climate projections, main sources of uncertainties are (i) the internal variability, (ii) the scenario uncertainty and (iii) the model uncertainty. Based on Hawkins and Sutton (2009, 2011), it is concluded that model uncertainty is of great importance both for temperature and precipitation projections at all time scales. The choice of emission scenarios is relevant rather in temperature projections and on multi-decadal time scales. In precipitation projections, total uncertainty is basically composed of the internal variability and model uncertainty, especially when focusing on smaller regions.

Further reading

- Hawkins, E., Sutton, R., 2009: The potential to narrow uncertainty in regional climate predictions. Bull. of Amer. Meteor. Soc. 90, 1095–1107, https://doi.org/10.1175/2009BAMS2607.1
- Hawkins, E., Sutton, R., 2011: The potential to narrow uncertainty in projections of regional precipitation change. Climate Dynamics 37, 407–418, https://doi.org/10.1007/s00382-010-0810-6
- Deque, M.; Somot, S.; Sanchez-Gomez, E.; Goodess, C. M.; Jacob, D.; Lenderink, G. & Christensen, O. B. The spread amongst ENSEMBLES regional scenarios: regional climate models, driving general circulation models and interannual variability Climate Dynamics, 2012, 38, 951-964, https://doi.org/10.1007/s00382-011-1053-x

How to interpret and adjust model biases?

There is a growing demand for regional climate change information for use in impact modelling, which in turn provides downstream inputs for decision-making. Such information generated by climate models has a number of uncertainties and these affect the ability of climate models to accurately simulate changes in the complex climate system. All models are only an approximation of the real climate system and have different simplifications resulting in biases of the simulated climate when compared to the observed one. It has been widely recognised that raw climate model output cannot always be used directly as input to, e.g., impact models. As a result an adjustment (also referred to as “bias correction”) towards the observed climatology is necessary. Alternatively, one may use results from ESD, which are calibrated against observations, provided its assumptions are justified and observation density is sufficient.

Nowadays, bias adjustment has become an integral part of the pre-processing of climate simulations for the use in impact modelling studies. However, bias adjustment is generally a statistical approach missing physical arguments, and applying bias adjustment to climate model simulations introduces a new often unexplored level of uncertainty. Moreover, often bias-adjusted simulations are ‘blindly’ used, even though their limitations are very well documented. In short, bias adjustment should be considered only as a statistical post-processing approach, while the reduction of model biases can only be done by continuous model development.

The two main questions regarding bias adjustment are: i) What in general can be bias adjusted and what not and ii) How can bias adjustment modify future climate projections? Most bias adjustment methods are based on the quantile mapping approach (e.g., Piani et. al. 2010) which generally provides very good results in terms of seasonal means and percentiles but does not take directly into account time-dependent statistics as for example consecutive dry/wet days (Addor and Seibert, 2014). Additionally it has to be noted that such a point wise approach is not supposed to correct spatial displacements of atmospheric phenomena such as the positioning of the simulated rain belt associated with the Inter Tropical Convergence Zone (ITCZ).

With respect to the second question it was also found that bias-adjusted climate simulations alter the projected climate change signals when compared to non-adjusted ones (Maurer and Pierce, 2014). A number of different approaches (modifications) are used to deal with this issue as for example the ISI-MIP method, which tries to preserve monthly mean trends (Hempel et al. 2013). However, future climate change can be expected to not only affect monthly means but also the different higher-order statistics (trends in extremes etc.).

Despite these very well known problems and fragmented recommendations, there are no systematic assessments of bias-adjustment-related uncertainties and no general guidance on the use of bias-adjusted climate simulations.

Bias-adjusted CORDEX simulations should be used carefully with full understanding of all potential limitations of the bias adjustment approach. It’s strongly recommended to read following report describing for what applications bias adjusted climate simulations can be used and for what not:

- Breakout Group 3bis: Bias Correction (pp. 21-23) in IPCC, 2015: Workshop Report of the Intergovernmental Panel on Climate Change Workshop on Regional Climate Projections and their Use in Impacts and Risk Analysis Studies [Stocker, T.F., D. Qin, G. -K. Plattner, and M. Tignor (eds.)]. IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland, pp. 171. (https://www.ipcc.ch/pdf/supporting-material/RPW_WorkshopReport.pdf)

Further reading

- Addor, N. and J. Seibert, 2014. Bias-correction for hydrological impact studies – beyond the daily perspective. Hydrol. Process., 28, 4823-4828, https://doi.org/10.1002/hyp.10238
- Hempel, S., Frieler, K., Warszawski, L., Schewe, J. and F. Piontek, 2013 A trend-preserving bias correction – the ISI-MIP approach, Earth Syst. Dynam., 4, 219-236, https://doi.org/10.5194/esd-4-219-2013

- Maurer, E. P. and D: W. Pierce, 2014. Bias correction can modify climate model simulated precipitation changes without adverse effect on the ensemble mean, Hydrol. Earth Syst. Sci., 18, 915-925, https://doi.org/10.5194/hess-18-915-2014
- Piani, C., Haerter, J., and E. Coppola, 2010. Statistical bias correction for daily precipitation in regional climate models over Europe, Theor. Appl. Climatol., 99, 187–192, https://doi.org/10.1007/s00704-009-0134-9

How can climate change results be communicated?

Climate change results are in most cases communicated to persons who are not familiar with climate modelling. Therefore, it is necessary not only to deliver the results but explain what the results are based on and what the processing methods are. All results - text, tables, figures - must contain the full information. The necessary points are listed below.

- Always give the full result information (scenario, global and regional models, time slice, region, spatial resolution...), in the case of climate change information the reference and the future period must be given. The user should be able to reproduce the steps taken based on the methods and data description.
- Always communicate climate change result *and* uncertainty range
- Differentiate scenarios - e.g. in case of low radiative forcing scenario point out that this can be used to highlight mitigation effects.
- Make clear that the result is not a forecast but a projection.
- Statements concerning trends, robustness and exceeding probability must be based on state-of-the-art analysis and statistical methods.
- Climate change signals can be communicated as absolute differences or as relative differences. It depends on the meteorological parameter which value is suitable, e.g. relative changes are not sensible for temperature. For parameters like precipitation or wind speed it may depend on the context whether the climate changes is communicated as absolute or relative value, e.g. for low-wind regions an increase of 10 % in wind speed still may be a negligible change.
- Interpretation of climate change results must take into account the information in the chapters above, particularly limits of modelling, suitability of the used data in time and space scales, bandwidth or probability statements.
- Visualisation of results is an essential tool in communication, therefore the figures must be clear and not suggest wrong conclusions. Helpful hints are given in Kreienkamp et al., 2012. Some examples of visualisation of ensemble results are documented in Hennemuth et al., 2013, based on "How to read a climate-fact-sheet" http://www.climate-service-center.de/imperia/md/images/csc/projekte/climatefactsheets/manual_cfs-update_march2016.pdf

Further reading

- Deser, C., Knutti, R., Solomon, S. & Phillips, A. S., 2012: Communication of the Role of Natural Variability in Future North American Climate. Nature Climate Change, 2, 775–779, https://doi.org/10.1038/nclimate1562
- Kreienkamp, F., H. Huebener, C. Linke and A. Spekat (2012): Good practice for the usage of climate model simulation results - a discussion paper. Environmental Systems Research 2012, 1:9, https://doi.org/10.1186/2193-2697-1-9
- Hennemuth, B., Bender, S., Bülow, K., Dreier, N., Keup-Thiel, E., Krüger, O., Mudersbach, C., Radermacher, C., Schoetter, R. (2013): Statistical methods for the analysis of simulated and observed climate data, applied in projects and institutions dealing with climate change impact and adaptation. CSC Report 13, Climate Service Center, Germany, http://www.climate-service-center.de/products_and_publications/publications/detail/062667/index.php.en

- Also, see a pedagogic video concerning the sources of climate change uncertainty in future projections: https://vimeo.com/85531490

Model data formats and structures

What kind of data do models generally produce?

Regional climate model simulations produce 3-dimensional fields of climate variables like temperature, humidity, wind velocity etc. and in addition 2-dimensional fields of surface precipitation, radiation, etc. ESD, on the other hand, may produce time series for a point (1D), a group of points (2D) or derived quantities such as storm tracks, and follow the format of the observations. ESD can also be gridded like observations to provide 2D data objects. In several portals EURO-CORDEX data are used to explore climate model data and to calculate climate impact indicators. Below some links to websites of interest are listed:

- is-enes project: exploring climate model data: https://climate4impact.eu/impactportal/general/index.jsp
- CLIPC – Climate Information Platform for Copernicus: http://www.clipc.eu/
- IMPACT2C - Quantifying projected impacts under 2°C warming: https://www.atlas.impact2c.eu/en/

How to download EURO-CORDEX projections?

EURO-CORDEX simulations for Europe have been performed for two different horizontal resolutions:

- 0.44 degree (EUR-44, ~50 km)
- 0.11 degree (EUR-11, ~12.5km)

The EURO-CORDEX simulations (EUR-44 and EUR-11) are openly available through the Earth System Grid Federation (ESGF) under the CORDEX project.

Steps towards the data download:

- **Accessing and registering at the ESGF Portal**:
  - Access the Earth System Grid Federation (ESGF) Search Portal via one of the available data nodes (Select nodes from: http://www.data.euro-cordex.net)
  - Look for the hyperlink “Create Account” to be granted an ESGF OpenID and corresponding password. This account is needed to be able to download data.
- **Searching for data**:
  - After registration, go back to the Search Portal and look for the hyperlink allowing to access the CORDEX Data Search (this may differ depending on the portal you chose)
  - You may specify the data you are looking for by ticking the respective selection options on the left (e.g. Project: “Cordex”, Domain: “EUR-11”, Variable Long Name: “Air Temperature”, etc.)
  - Clicking on “Search” generates a list with all available data that match your specifications.
  - Clicking on the interrogation mark next to the “Search” button provides you with additional search information
- **Choosing the desired data:**
  - If you are unsure which item from the list you are looking for, press “show metadata” below each result of the data search to check for additional information or refine your search criteria.
- **Downloading a certain set of data:**
  - By opening “Show Files”, you may access a list of files that contains the requested data. Depending on the temporal resolution of the data, this can be several data files.
  - You may either download each of these files individually, by clicking on “HTTPServer OPENDAP” located right of the file…
  - ...or you download a shell script by clicking on “WGET Script”, which manually downloads all data files if run.
  - The download of multiple files could be easier via 'datacart' option. You can create a wget-script over all selected files to download them at once.
- **Data Access Login:**
  - Enter your ESGF OpenID and corresponding password to download the data

More details on how to access CORDEX data are provided in Data Access section on the CORDEX website (http://www.cordex.org/index.php?option=com_content&view=article&id=228&Itemid=537).

A subset of the Euro-CORDEX simulations (both EUR-11 and EUR-44), bias-adjusted by a few different methods, are also openly available on ESGF under the CORDEX-Adjust project (http://www.cordex.org/index.php?option=com_content&view=article&id=275&Itemid=785). Currently the bias-adjusted daily data for mean/max/min temperature and precipitation is available. This subset of bias-adjusted Euro-CORDEX simulations is a first step. At moment not all Euro-CORDEX simulations are bias-adjusted but work on expanding and filling the bias-adjusted Euro-CORDEX matrix is ongoing.

How to change netcdf into other formats?

The conversion of NetCDF-data into other formats can be carried out with the Climate Data Operator (CDO), which is available at https://code.zmaw.de/projects/cdo. The CDO is a collection of command line operators to manipulate and analyse climate and numerical weather prediction model Data. Supported data formats are GRIB, NetCDF, SERVICE, EXTRA and IEG. There are more than 600 operators available
With this tool, data can be converted into the following data formats: grb, grb2, nc2, nc4, nc4c, srv, ext, ieg.
To convert a NetCDF-file into a GRIB-file:

```
cdo -f grb copy input_file.nc output_file.grb
```

Furthermore, there is also an option to write NetCDF-data as a customised table into an ASCII-file. However, a NetCDF-file containing two or three dimensional data may not appropriate to write into an ASCII-file without modifications since the data will be written line by line according grid-cells and timesteps orders. Therefore, it can be helpful to calculate a fieldmean of the data or extract one grid-cell before writing into the ASCII-file first:
To calculate a fieldmean:

```
cdo fldmean input_file.nc output_file.nc
```

To extract a longitude/latitude point using the *nearest-neighbour mapping*:

```
cdo remapnn,lon=XX/lat=yy input_file.nc output_file.nc
```

Notice: When you are using single grid-cells from climate model data, it may appropriate to calculate the weighted average of each grid point plus the 8 surrounding points to avoid strange values:

```
cdo smooth9 input_file.nc output_file.nc
```

To write data as a customised table into an ASCII-file:

```
cdo outputtab,name,year,month,day,lon,lat,value input_file.nc
>output_file.txt
```

How to read EURO-CORDEX data into analysis tools?

The free data analysis tool R (http://cran.r-project.org) can read netCDF files (CF conventions) and allows a large universe of statistical analysis, tests, and visualisation (e.g. regression and extreme value analysis). There is a wide range of R-packages which can be installed on top of R that have been designed for specific uses and purposes. One such package has been especially designed for general climate data analysis and ESD, and is freely available from a GitHub repository (http://github.com/metno/esd). It has also been written to process RCM results.

How to extract a specific region?

There are two proven methods how you can select a region: the software 'Climate Data Operators' (CDO) for your downloaded files on your computer or a web-based method (https://climate4impact.eu) in order to download data that contain only the region of interest.

Once you have downloaded the EURO-CORDEX simulation (see How to download EURO-CORDEX projections?), you can select a region by using the command 'cdo sellonlatbox' by giving the longitude and latitude coordinates of the edges of the region of interest. For further information or if you have not installed the software CDO, please follow the introductions of this website: https://code.zmaw.de/projects/cdo.

When you prefer to download data only for a specific region, use this web-based method. Login at https://climate4impact.eu with your ESGF account, go to Account -> Processing, select 'convert and subset.' Under 'select a file', a window opens where you can access via the 'search function' the ESGF data. After choosing your file of interest, select your file for processing by clicking on the 'basket'-icon. Back in the main window, you can either select a region by specifying the longitude and latitude coordinates of the edges of the region. Or you can select the region with your mouse by changing the size of the box which is presented on the map on the right.

After choosing a file name at the bottom of the page, you can press the 'Start processing' button and a file in netcdf format with your selected region will be automatically produced and ready for download.

Examples of EURO-CORDEX data use

In the following, some examples of practical use cases of the EURO-CORDEX data are listed, e.g., national diagnostics on climate change. The list is nonexhaustive and growing with time.

- EURO-CORDEX climate change simulations have already been used in the frame of national climate services such as in France through the DRIAS web portal (www.drias-climat.fr).
- Climate change scenarios retrieved from EURO-CORDEX have provided the basis to assess impacts on solar photovoltaic (Jerez et al., 2015) and wind power (Tobin et al., 2016) production across Europe along the 21st century.
- EURO-CORDEX simulations will be used in preparing the Climate Change Adaptation Strategy for Republic of Croatia (2016-2017; http://prilagodba-klimi.hr)
- EURO-CORDEX simulations form the basis for the Norwegian Climate Service Center's climate projections visualization web service: https://klimaservicesenter.no/faces/desktop/scenarios.xhtml?org.apache.catalina.filters.CSRF_NONCE=D73DBECDCC6FA4A727931C4A6E2A8BE6

Further Reading

- Jerez, S.; Tobin, I.; Vautard, R.; Montavez, J. P.; Lopez-Romero, J. M.; Thais, F.; Bartok, B.; Christensen, O. B.; Colette, A.; Deque, M.; Nikulin, G.; Kotlarski, S.; van Meijgaard, E.; Teichmann, C. & Wild, M., 2015: The impact of climate change on photovoltaic power generation in Europe, Nature Communications, 6, https://doi.org/doi:10.1038/ncomms10014
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Existing Guidelines

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- World Meteorological Organization, 2011: Guide to Climatological Practices, WMO-No. 100, World Meteorological Organization, Geneva, ISBN 978-92-63-10100-6
- Bund- Länder- Fachgespräch "Interpretation regionaler Klimamodelldaten", 2014: Leitlinien zur Interpretation regionaler Klimamodelldaten, http://klimawandel.hlug.de/?id=448
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Appendix

Further details on RCP and SRES scenarios:

- **SRES** (Special Report on Emissions Scenarios; Nakicenovic et al., 2000) scenarios quantify anthropogenic emissions of greenhouse gases (and some other pollutants), land-use and other factors for the 21st century by giving a wide range of possible alternatives, based on modelling (socio-economical, bio-geochemical modelling) and research. The scenarios are grouped in 4 major families: A1, A2, B1, B2, each consisting of several scenarios. The A families are characterized by rapid economic development, while B scenarios represent environmental sustainability. A1 and B1 versions show population decrease after few decades and global solutions for the world challenges, whereas A2 and B2 scenarios indicate continuous population growth with local socio-economic solutions. A1 scenario have three groups describing alternative directions of technological change in the energy system: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). By the end of the 21st century, the highest concentration levels are reached in A1FI and A2; more "optimistic" future paths are resulted by B1 and A1T; and A1B is a medium scenario.

- **RCP** (Representative Concentration Pathways; Moss et al., 2008) scenarios are the most recent, developed for the last IPCC Assessment Report (AR5) using integrated assessment modelling, climate modelling and impact modelling. The basic concept of RCP is different from the SRES: instead of socio-economic scenarios, these scenarios define pathways of the additional radiative forcing caused by anthropogenic activity till the end of the 21st century (the value in 1750 is considered as reference). The reason behind the conceptual change is the fact that a single radiative forcing pathway can result from a range of socio-economic and technological development scenarios. Four basic sets of scenarios were created, named after their total radiative forcing (in W/m^2) in year 2100 relative to 1750: RCP8.5, RCP6.0, RCP4.5 and RCP2.6. RCP 8.5 represents very high greenhouse gas emission leading to 8.5 W/m^2 radiative forcing, which continues to rise even after 2100; RCP4.5 and RCP6.0 are stabilization scenarios, meaning that the forcings stabilize at their given value around the end of the century; and RCP2.6 represents an aggressive mitigation scenario with a considerable negative future emission. According to the AR5 report, global surface temperature change by the end of the 21st century is likely to remain below 2°C, relative to the 1850-1900 period (i.e., the important 2°C target can be kept), for RCP2.6 and RCP4.5, but it is likely to exceed this threshold for RCP6.0 and RCP8.5.

Further reading

- Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Rogner, H. H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., 2000: IPCC special report on emissions scenarios. Cambridge University Press, Cambridge.
- Richard Moss, Mustafa Babiker, Sander Brinkman, Eduardo Calvo, Tim Carter, Jae Edmonds, Ismail Elgizouli, Seita Emori, Lin Erda, Kathy Hibbard, Roger Jones, Mikiko Kainuma, Jessica Kelleher, Jean Francois Lamarque, Martin Manning, Ben Matthews, Jerry Meehl, Leo Meyer, John Mitchell, Nebojsa Nakicenovic, Brian O'Neill, Ramon Pichs, Keywan Riahi, Steven Rose, Paul Runci, Ron Stouffer, Detlef van Vuuren, John Weyant, Tom Wilbanks, Jean Pascal van Ypersele, and Monika Zurek, 2008. Towards New Scenarios for Analysis of Emissions, Climate Change,

Impacts, and Response Strategies. Technical Summary. Intergovernmental Panel on Climate Change, Geneva, 25 pp.

- http://climate4impact.eu/impactportal/documentation/backgroundandtopics.jsp?q=Scenarios
- http://www.ipcc.ch/pdf/supporting-material/expert-meeting-ts-scenarios.pdf

Glossary

A glossary will be included in future releases of the guidelines.