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Inter-comparison matrix for CMIP and CORDEX data used in climate service

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Table of Contents

Executive summary

The establishment of an ensemble of global climate model (GCM) results was initiated in 1995 with the Coupled Model Intercomparison Project (CMIP) to serve scientists with a database of coupled GCM simulations under standardized boundary conditions. Since 1995 lots of progress have been made regarding the scientific motivation, the covered time horizon, the details of the described physical processes, and the number of applied models. Today the planning of CMIP6 (6th Phase of CMIP) is ongoing. To obtain information about the regional climate change aspects, high-resolution regional climate models (RCMs) are used. Regional models are focusing on a selected area with fine horizontal resolution, and the large-scale processes are taken into account in the forcings provided by the global results. The first climate simulation with a regional climate model was carried out in 1989. PRUDENCE (Predicting of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects) and ENSEMBLES were the first international collaborations, providing climate projections for Europe with high resolution using basically different IPCC SRES emission scenarios. The participating regional climate modelling institutions successfully coordinated the definitions of the simulation domains and created a database of directly intercomparable model simulations. In the CORDEX (COordinated Regional Downscaling Experiment) initiative, this procedure is extended to the entire world, increasing the number of global and regional models, and using the modern RCP scenarios (Representative Concentration Pathways).

CMIP outputs serve as input to the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), GCM data provide information about the large-scale features of climate change for regional downscaling, while RCM outputs gives information about the regional climate change for local impact assessments. Copernicus C3S gather all the available and scientifically sound information into the Climate Data Store (CDS) to serve as a primary database for various users. Regarding climate projections, its main basis will be the CMIP5 and CORDEX datasets. The objective of this data inventory is to provide a compact guideline for the potential users of CDS on applying the climate model outputs and later the CDS data. Five CORDEX-domains are investigated which cover Europe partly or entirely: EURO-CORDEX, MED-CORDEX, MENA-CORDEX, Central Asia CORDEX and Arctic-CORDEX. Besides CMIP5, our main focus is on the EURO-CORDEX database, as it is the most comprehensive and well documented dataset utilizing the recent scenario family and its domain covers the entire continent. Evaluation is based on the following aspects: data accessibility, involved RCM-GCM combinations, spatial resolution of the outputs, time horizon of the model experiments, applied emission scenarios, available meteorological variables, the frequency of the outputs stored in the archive, the uncertainty range covered by the ensemble and existence of bias-adjusted data. Assessment of the quality of the different models and their results is beyond the scope of the data inventory.

There are 6 different nodes operating for browsing and downloading CMIP5 simulation outputs. Taking all the available CMIP5 projection results, the investigation was started with 47 GCMs. The horizontal resolution of the model outputs varies from 0.56° to 5.6°. Most models have a 1°–2° (approximately 100-250 km) or a 2°–3° (approximately 200-350 km) resolution. Upper level atmospheric data are given on predefined pressure levels ranging from 1000 to 10 hPa. 42 models have simulations until the end of the century and 13 GCMs go beyond 2100 (up to 2300). Data are archived with a monthly, daily, 6-hourly and 3-hourly frequency. Atmospheric parameters given at sub-daily resolution are the near-surface temperature, the wind components, the sea level and surface pressure, the near-surface specific humidity, the precipitation, the pressure level variables and some radiation components. An 8-member ensemble can be designed, providing climate projections for all RCP (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) scenarios at daily level for the surface, pressure-level and radiation variables: BCC-CSM1.1(m), CSIRO-Mk3.6.0, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-MR, MIROC, MRI-CGCM3, NorESM1-M. Since our last investigation (in April 2017) further data are uploaded to ESGF due to the gap evaluation carried out by different C3S Lots; for instance, CMIP5 was extended with 6-hourly model level data for temperature, wind components and specific humidity for 26 GCMs. These data are especially important for dynamical downscaling of global fields.

There are 4 European data nodes available for browsing in CORDEX data for various regions. Lateral boundary conditions for 11 RCMs used in EURO-CORDEX were provided by 10 different GCMs in the projections. On the 0.44-degree resolution (EUR-44) grid, altogether 8 RCMs were driven by 10 GCMs resulting in 18 simulations. A somewhat smaller amount (15) of experiments was conducted on the 0.11-degree resolution (EUR-11) grid with combination of 7 RCMs and 5 GCMs. Control parts of the projections start between the years 1951 and 1971 and continue until 2005. Most scenario runs cover the 21st century, apart from the HadGEM2-ES driven experiment (running only until 2099). Three RCP scenarios are applied: RCP2.6, RCP4.5 and RCP8.5. RCP8.5 and RCP4.5 are uniformly utilized in the projections, while RCP2.6 is the least used scenario, employed in 7 EUR-44 and 5 EUR-11 simulations. The dataset chiefly consists of surface data, but most simulations provide horizontal wind components, temperature and geopotential heights on 850 hPa, 500 hPa, 200 hPa pressure levels, as well. Model level variables are not stored. Data are archived mainly with monthly and daily output frequency. Bias adjustment brings new component of uncertainty into the projections originating from the choices regarding the method, the reference dataset and the calibration period. In EURO-CORDEX 6 methods (mostly based on quantile mapping) are applied with 3 different observational datasets. The bias adjustment was employed primarily for daily precipitation and daily minimum, maximum and mean temperature values. In a few EUR-11 simulations, some methods were applied for the 3-hourly radiation and surface wind. Evaluating the occurrence of daily surface, pressure-level and radiation variables from climate projections conducted with all the 3 RCP scenarios, 7-member and 4-member ensembles can be designed on 0.44- and 0.11-degree resolutions. If bias adjusted data are also requested, the ensemble size further decreases to 2 members consisting of RACMO22E and RCA4, both driven by HadGEM2-ES on EUR-44, and to 1 member of REMO2009 driven by MPI-ESM-LR on EUR-11. Not requiring the RCP2.6 scenario (nor the bias adjusted data), 5 and 7 extra RCM simulations are added to the selections, resulting in 14- and 9-member ensembles per RCPs over EUR-44 and EUR-11, respectively.

In EURO-CORDEX, RCA4 is the only regional model coupled to at least 5 GCMs; while among the GCMs, CNRM-CM5, EC-EARTH, MPI-ESM-LR, HadGEM2-ES provide forcings broadly. It has to be noted that from them solely HadGEM2-ES outputs are stored in CMIP5 dataset on the ESGF with sufficient details (daily outputs, all scenarios etc.). It renders, that much more GCM data are available than it was resulted by the browsing the ESGF. All this makes difficult to provide a consistent set of GCM and RCM simulations with detailed data availability based on the existing CMIP5 and CORDEX results. Furthermore, these selections do not represent any qualitative assessment of the model outputs and do not give any information on model skills. Nevertheless, to judge the independency of the simulations in the resulted ensembles, evaluation of the applied RCMs and GCMs as well as of their outputs are needed. In order to improve the homogeneity, a new CORDEX-CORE framework is envisioned to achieve a standard core set of RCMs downscaling a core set of GCMs over all or at least most CORDEX domains for a minimum set of (high and low end) scenarios.

During the evaluation of the CMIP5 and CORDEX datasets, several technical difficulties and gaps were found:

- An extended selection method using also logical (AND, OR etc.) functions would help to select the appropriate realization, time horizon and variables of the projections to spare the users from digging in the metadata information.
- Provision of the geographical information (e.g., orography, land-sea mask) is highly desirable to perform further interpolation on the model outputs.
- Some RCP scenarios are currently inadequately represented within the models. RCP4.5 and RCP8.5 are the most intensively used scenarios, covering only a part of the whole uncertainty spectrum. This gap should be filled with an accomplishment of new GCM simulations.
- The applicability of CMIP5 model outputs as boundary forcings for dynamical downscaling is limited due to the lack of model level data. Driving data can be used more widely in those regional climate models which are able to utilize pressure level data instead of model level data.
- Summary should be provided regarding the main differences between different model versions of the same model family, with recommendations describing which version to take for different purposes.
- Some GCMs are over- or underrepresented as driving in the EURO-CORDEX ensembles. Overrepresentation can be concluded also for some RCMs. Therefore, a deep assessment is needed regarding the independency of the available RCM simulations and every choice has to be done considering the user objective.
- Sub-daily outputs are basically not stored on ESGF. Access to these data has to be organized bilaterally between data user and data provider.
- In EURO-CORDEX, the vertical resolution of atmospheric data is quite coarse, containing only 3 pressure levels: 850 hPa, 500 hPa and 200 hPa. To fulfil further requests, future extension of ESGF storage capacity should be considered.
- Bias adjusted data are available only for EURO-CORDEX data on ESGF.
- MED-CORDEX data are not stored on ESGF, but in a different database with a very simple browsing possibility. Metadata are sometimes incomplete in this portal.
- Territory of Turkey is located in the vicinity of the border in all the available CORDEX domains. This issue can be handled with definition of a new domain.

The scope and diversity of topics as well as the data volume involved in CMIPs have grown tremendously in the last 20 years. A thorough investigation at the end of CMIP5 resulted in a structural change of CMIP. For the first time in a CMIP phase, a vulnerability, impacts, adaptation and climate services advisory board is included to improve the communication between the climate modelling and the user community. CORDEX archive is continuously extended with new model simulations. In the recent CORDEX 2 framework, focus has shifted towards more science-based questions through “Flagship Pilot Studies” (FPS) concentrating on sub-continental-scale regions. Focusing on the European territory, 4 flagship pilot studies are endorsed: (i) convective phenomena at high resolution over Europe and the Mediterranean; (ii) impact of land use changes on climate in Europe across spatial and temporal scales; (iii) role of the natural and anthropogenic aerosols in the Mediterranean region; (iv) role of the air-sea coupling and small scale ocean processes on regional climate.

1. Introduction and motivation

1.1 Motivation: content, giving the focus of the data inventory

The establishment of an ensemble of global climate model (GCM) results was initiated in the mid-1990s: the Working Group on Coupled Modelling (WGCM) of WCRP (World Climate Research Programme) elaborated the Coupled Model Intercomparison Project (CMIP) in 1995 with the aim of serving scientists with a database of coupled GCM simulations under standardized boundary conditions. Since 1995, lots of progress have been taken place regarding the scientific motivation, the covered time horizon, the details of the described physical processes, and the nature of the applied models. Due to the rapid evolution of the models and the available enhanced computer power, the horizontal resolution of the global general circulation models reaches nowadays the 100 km range. These models are continuously improving, providing solid basis and realistic projections for the synoptic scale characteristics of the climate, however, they are not sufficient for detailed regional scale estimations. To obtain information about the regional climate change aspects, high-resolution regional climate models (RCMs) are used to focus on a limited area (e.g., on Europe) with finer horizontal resolution, and the large-scale processes are taken into account by the forcings provided by the global results since 1989 (Giorgi and Bates).

In spite of the advantages of RCMs, their simulation results still suffer from multiple deficiencies varying usually from one model to other one. Therefore, at the design of projections, it is crucial to consider several simulations of various models, because only the ensemble approach provides appropriate tool to specify the uncertain aspects in the projections. PRUDENCE (Predicting of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects; Christensen et al., 2007) was the first international collaboration providing climate projections over Europe with high resolution. Numerous simulations were carried out with a range of global and regional climate models using two basically different IPCC SRES (Nakicenovic et al., 2000) emission scenarios. It was followed by the ENSEMBLES EU FP6 (Sixth Framework Programme of the European Union; van der Linden and Mitchell, 2009) project in 2004. In ENSEMBLES, the participating regional climate modelling institutions successfully coordinated the definitions of integration domains and created a database of directly intercomparable model simulations following a SRES scenario. In the CORDEX (the Coordinated Regional Downscaling Experiment) initiative, this is extended to the entire world, simultaneously increasing the number of global and regional models, and using the modern RCP scenarios (Representative Concentration Pathways; Moss et al., 2010).

The user needs have also evolved and extended in the last decades. CMIP outputs are applied in several areas: they serve as input to the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), which support the high-level decision making with up-to-date information, global climate model data provides information about the large-scale features of climate change for regional downscaling and also for impact assessments. RCM data provides information about the regional climate change features for local impact assessments and they will also serve as input to the next IPCC assessment report. Copernicus C3S will gather all the available and scientifically sound information into the Climate Data Store (CDS) to serve as a primary database for various users. Regarding climate projections its basis will be the already existing datasets.

The objective of this data inventory is to provide an overview for the potential users of CDS on applying the CMIP and CORDEX outputs and later the CDS data. Among different CMIPs, our focus is on the CMIP5 database, as it is the most recent finalized CMIP utilizing the recent scenario family.

Within CORDEX, five CORDEX-domains are investigated in detail which cover Europe partly or entirely. Main emphasis is on the EURO-CORDEX database as the most comprehensive and well documented dataset utilizing the recent scenario family and its domain covers the entire continent. The report is dedicated to long-term global climate projections and the datasets are evaluated based on the following aspects: data accessibility, spatial resolution of the outputs, time horizon of the model experiments, applied emission scenarios, available meteorological variables, the frequency of the outputs stored in the archive, the uncertainty range covered by the ensemble and existence of bias-adjusted data. Assessment of the quality of the different model simulations (i.e., model validation) is beyond the scope of the data assessment (nevertheless, we already provided some hints on this issue in the deliverables 2.1 and 2.2).

The deliverable is structured as follows: motivation is followed by a brief description of the CMIP and CORDEX programmes. Section 2 is dedicated to the inter-comparison matrix for CMIP and CORDEX data: we give an overview about the evaluation aspects, afterwards the outcomes of the assessment of the CMIP5 and the selected CORDEX database are presented in detail. Possible selections of ensembles composed of CMIP5 and EURO-CORDEX models are discussed for Copernicus C3S Climate Data Store together with the identified gaps. The report is closed by summary of the main conclusions and an outlook.

1.2 Available climate model datasets

The first phase of CMIP, CMIP1 focused on collecting output from control simulations in which external climate forcing was held constant at pre-industrial or present-day levels (Covey et al., 2000; Lambert and Boer, 2001). In the next phase, CMIP2, an idealized global warming scenario was included as well, and at the same time, more extensive model output was collected (Covey et al., 2003). For the later phases more extensive series of climate change simulations have been conducted, forced by realistic emission scenarios, taking into account also the anthropogenic activity for both the historical and the future periods. In CMIP3 (Meehl et al., 2007), simulations focused on three SRES emission scenarios (A2, A1B and B1; Figure 1), each of them representing a substantially different future pathway of anthropogenic activity (with approximately 850, 700, 550 ppm CO_2 concentration by 2100, respectively). Results are freely available in the CMIP3 database and the simulations were used as the input to the IPCC Fourth Assessment Report (AR4; Solomon et al., 2007). CMIP3 was followed directly by CMIP5 (Taylor et al., 2012b) in 2010. CMIP5 model simulations already applied the RCP scenarios for prescribing future anthropogenic forcings. The RCP scenarios were constructed following a new methodology and are referred to their radiative forcing values for the year 2100 compared to the pre-industrial value, which can be resulted along several socio-economic development paths. RCPs have four representative versions: RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Figure 1), with 2.6, 4.5, 6.0, and 8.5 Wm^{-2} subsequent radiative forcing in 2100. Results served as the input to the IPCC AR5 (Stocker et al., 2013). The simulation results are freely accessible through the cloud-based interface of ESGF (Earth System Grid Federation).

Climate impact assessments and the development of regional to local-scale adaptation strategies require high-resolution climate change scenarios, including an assessment of their robustness and their inherent uncertainties. The CORDEX initiative provides a framework to improve regional climate scenarios with harmonisation of model evaluation activities in the individual modelling centres (Jones et al., 2011). Important objectives were to better understand relevant regional and local climate phenomena and to generate ensembles of regional climate projections worldwide, but especially for the regions not covered with high-resolution climate change scenarios. Special effort was dedicated to the communication and knowledge exchange with users of regional climate information.

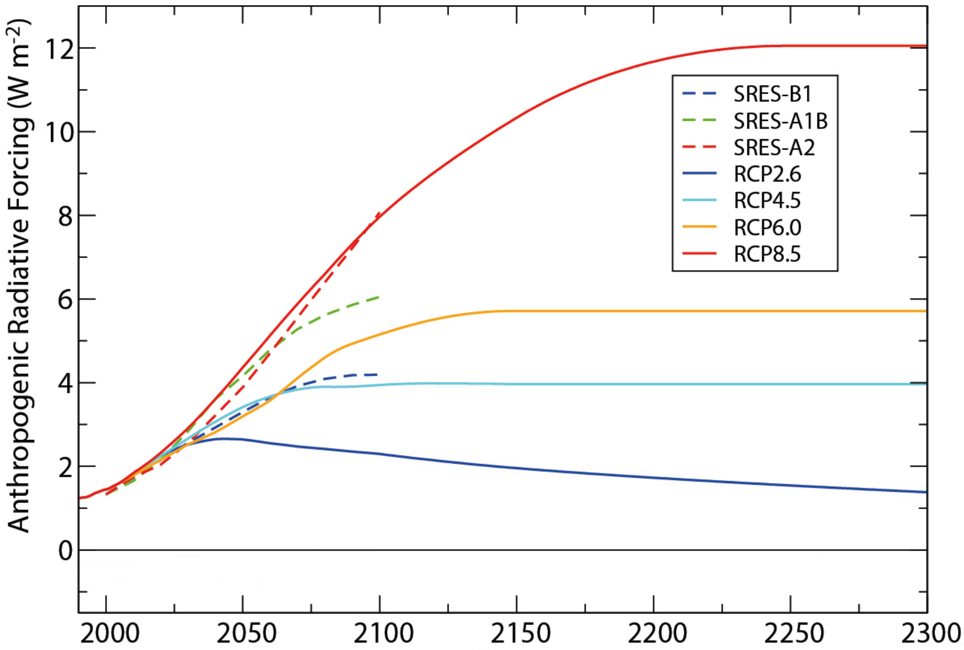

Figure 1: Time evolution of the total anthropogenic radiative forcing relative to the pre-industrial (about year 1765) level between 2000 and 2300 for the RCP scenarios, and for the SRES scenarios until 2100, as computed by the Integrated Assessment Modelling Consortium (IAMC). Source: Stocker et al., 2013.

Currently, 14 domains are designed in CORDEX. Due to the objectives of the DECM project, the present assessment is limited to areas covering partly or entirely the European continent resulting in the following 5 domains (Figure 2):

1. EURO-CORDEX covering the entire European continent and the Northern coast of Africa;
2. MED-CORDEX including Southern and Central Europe even up North till Denmark;
3. MENA-CORDEX designed to include the Arabian Peninsula and North Africa, but it covers also Southern Europe reaching North until the Alps;
4. Central Asia CORDEX covering large parts of Russia, Turkey and the Arabic Peninsula and stretching almost to the Asian Pacific coast;
5. Arctic-CORDEX domain covering the Northern Arctic region including Greenland and the northern parts of the American and Eurasian continents.

In general the resolutions of CORDEX areas are of the order of 50 km. For Europe, where particularly the EURO-CORDEX collaboration is very active, an integration area of about 12 km resolution has also been used (Jacob et al., 2014). A common set of output fields and sampling frequencies were defined along with a detailed data file format protocol based on NetCDF and the CF convention (Christensen et al., 2014). The simulations, which have been voluntarily provided by many groups across the world, are usually freely accessible through the ESGF. Currently data from 23 different RCM model versions and 13 different GCM model versions plus the ECMWF ERA-Interim re-analysis are accessible in the ESGF archive.

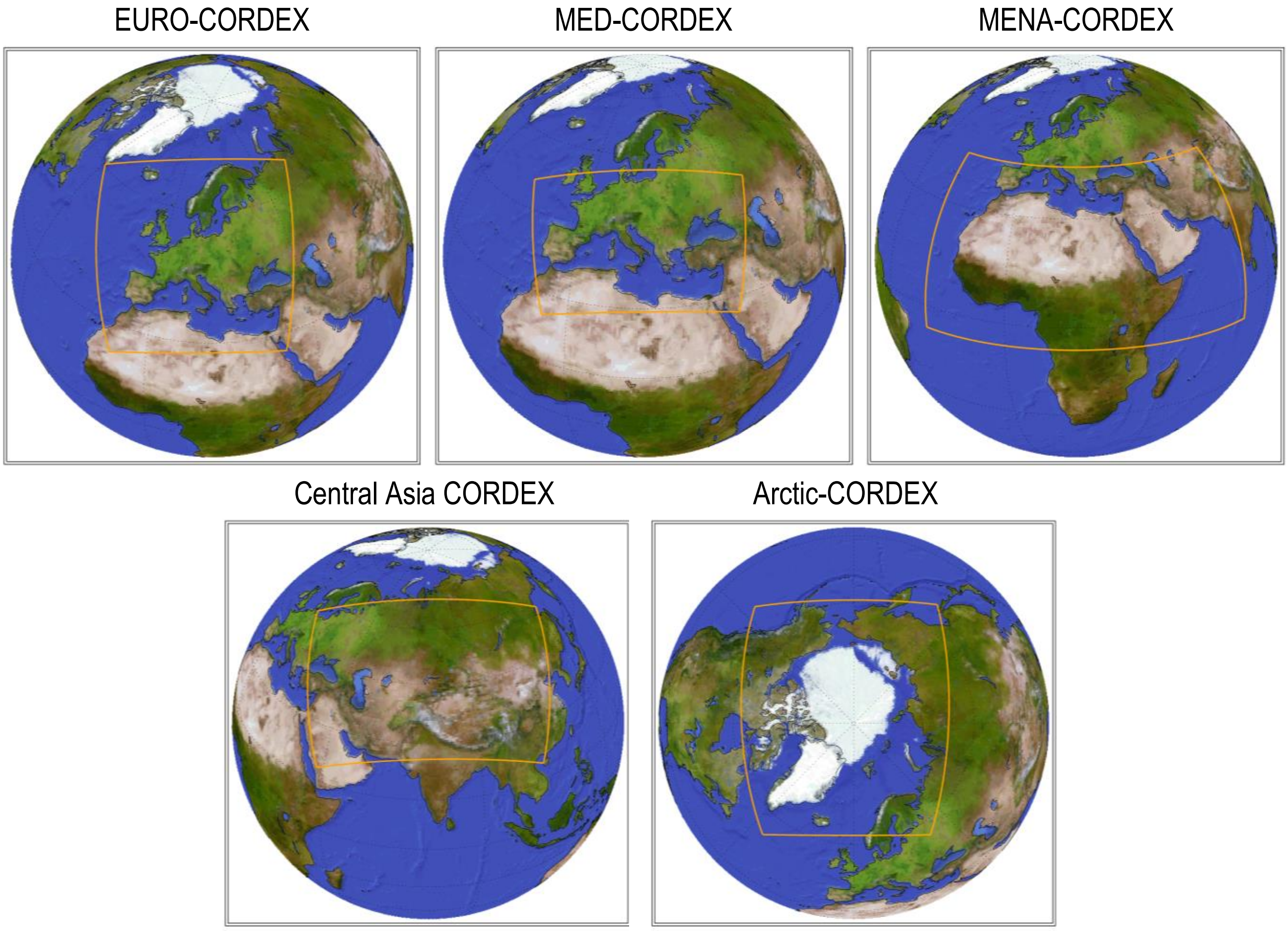

Figure 2: Domains of the investigated CORDEX branches.

2. Inter-comparison matrix for CMIP and CORDEX data

2.1 Investigation aspects

Data are analysed and sorted according to their relevance, usability, accessibility and limitations with respect to their current and future level of usage. This evaluation is focusing on the aspects below:

- Accessibility: Most data are stored on ESGF, in the NetCDF format, while metadata is available in a text format. Several difficulties make the work with data complicated: e.g., there are some nodes where no CMIP5 data is officially available; there are some nodes linking to another one (i.e., there is not a real node behind); it is difficult and challenging to narrow the data search, especially in case of MED-CORDEX, data of which are archived on different system (not on ESGF) with a very simple browsing method; in some cases no openID account is provided for download. In the present data inventory, we are collecting the errors and the drawbacks of the search engine of ESGF.
- Experiment types: CMIP5 and CORDEX provide a large set of global climate model simulations with the purpose of improving our understanding on climate, climate change and its possible consequences. This knowledge can be achieved by evaluating how accurate are the models in simulating the climate of the past few decades, by evaluating the future projections on different time scales, and by running targeted experiments focussing on certain aspects or processes of the climate system.
- RCM-GCM combinations: The performance of RCMs are strongly influenced by the lateral conditions, coming from the driving GCMs in practice. Consequently, uncertainty range covered by the RCM projections partly depend on the applied global models. In the inventory, we assess how wide the range of the driving GCMs is and how many RCMs are used in the ensemble.
- Spatial grid and resolution: The horizontal resolution – defined as the horizontal distance between two adjacent grid points – is a key parameter that determines the level of spatial details in model results. The resolution varies strongly among the global climate models, ranging from the quite sparse resolution of several degrees to the finest resolution of a few tenths of a degree. Horizontal resolution can also be a limiting factor in the applicability of model results, since some impact assessment methods require a certain minimal resolution for climate data to be used as input. Climate models provide information not only at the surface but also on the whole three-dimensional atmosphere, and thus the availability of pressure level and model level data is evaluated, as well. On ESGF, the atmospheric information is either given on pre-defined pressure levels. Some applications require the model orography and the land area fraction (ratio of land to ocean areas within a grid cell) paired with the climate data, and therefore, the availability of these two time-independent fields is also inspected for each CMIP5 model. Additionally, it is also examined if there is any European country which is not covered well by any of the CORDEX domains.
- Time horizon: In the data inventory, the focus is put on the user needs, therefore, we are categorizing the CMIP5 ensemble mostly under historical runs from 1850 and RCP-scenario runs from 2006 until 2100 and beyond, while the CORDEX ensemble under control runs until 2005 and RCP-scenario runs from 2006 (as it was also concluded based on personal

communication with the Copernicus C3S representatives in the project kick-off meeting). Within CORDEX, the ERA-Interim driven evaluation experiments uniformly cover the period of 1989–2008.

- Scenario uncertainty: Scenario runs produce information to investigate the effects of anthropogenic climate change. The chosen emission scenario is a key source of projection uncertainty, so the availability of model runs with different scenarios is crucial to fully cover the uncertainty cascade of the future model results. It is essential to use as many data as logically possible and scientifically solid. There are four RCP scenarios used within the CMIP5 model runs: RCP4.5 (“optimistic”) and RCP8.5 (“pessimistic”) scenarios, additionally, there are a medium path (RCP6.0) and a highly idealistic scenario (RCP2.6). In CORDEX, RCP6.0 scenario is not applied in the simulations. To quantify scenario uncertainty at different levels, we are selecting several sets of the available runs.
- Temporal resolution: The highest accessible temporal resolution of the CMIP5 model outputs is sub-hourly data, but the availability of variables at this frequency seems not controlled within the models. It is followed by 3-hourly and 6-hourly data, this sub-daily data is mostly applied in further downscaling methods. For CORDEX, the highest accessible temporal resolution of RCM model outputs is daily data, sub-daily data are archived on ESGF only for a limited number of simulations. For most user needs and for investigating future tendencies of extremes, daily resolution might be sufficient. Furthermore, the monthly outputs and seasonal climatological means are based on daily sums and averages. User requirements concerning the model output frequency are related to the meteorological variables, consequently, we handle this issue together with the aspects of available variables. In the evaluation we are dealing also with basic variables with no time-dependency (like orography).
- Available variables: Due to the large number of available variables in the data base, some classification and filtering are necessary to help the potential users in navigating through the abundant possible options. In the current work, atmospheric and land surface variables are analysed. The subject of the investigation was simply the availability or absence of the most frequently-used and most important variables, providing also their (monthly, daily, etc.) archive frequencies. Numerous applications require more than one meteorological variables from the same model simulation (e.g., near-surface temperature, precipitation and wind speed). For this reason, “variable packages” were defined and their availability was also evaluated for each model simulation.
- Bias adjusted data: Impact researchers prefer climate model data without systematic errors. Coarse resolution global climate model outputs provide primary inputs for statistical and dynamical downscaling methods requiring physically consistent driving fields. Bias adjustment methods violate this physical consistency, therefore, raw GCM outputs are used in dynamical downscaling and correction is usually applied on the results of downscaling (although there are some efforts to apply prior statistical correction of global forcings; Colette et al., 2012). On the ESGF nodes there is a single CMIP5 model with 4 corrected variables, obtainable on a monthly basis and within decadal predictions only. Nevertheless, several bias adjustment methods are applied for the regional climate model data. On the ESGF under the project name CORDEX-Adjust, there are adjusted simulations for EURO-CORDEX available. The bias adjustment will be extended to other CORDEX regions and probably published at ESGF.

2.2 Joint assessment of the CMIP and CORDEX datasets

CMIP5 data are resulted from various experiment types, e.g., hindcasts and predictions, pre-industrial control runs, time-slice experiments, historical ensemble simulations, atmosphere-only model simulations, future projections, and paleo-climate runs. In the CMIP data inventory (deliverable 2.1), we were focussing on two experiment types: (i) historical simulations and (ii) future projections. Historical simulations cover the period 1850–2005, including the observed anthropogenic (lived gas species and aerosols) as well as the natural effects (volcanic solar forcing variations) on climate change. They give the basis for model validation against the observed climate of the past decades, and allow to research and detect the human impact on the climate system. Future projections begin from the year 2006 and span the whole 21st century (some simulations continue even beyond 2100). The initial conditions are provided by the historical experiments. The atmospheric concentrations of greenhouse gases follow the observed values until the end of 2005 and from 2006 the concentrations are prescribed as in the RCP scenarios.

The RCM outputs are derived from two kinds of simulations. Evaluation experiments were carried for the past to validate the performance of RCMs for a multi-decadal period covered by observations. Lateral boundary conditions were provided by ERA-Interim re-analysis data (Berrisford et al., 2011), so the integrations started in 1979. Due to the measurement-based drivings, validation of these experiments shows the deficiencies mainly originating from the regional climate models and serves valuable information to their further improvements. In the projection experiments, the large-scale constraints were ensured by global climate models instead of re-analyses. These experiments consist of two parts: (i) control runs are carried out for the past lasting until 2005 and their validation produces combined information about both the global and regional model deficiencies; (ii) scenario experiments cover the 21st century starting in 2006. All projections use the RCP scenario family as anthropogenic forcing.

2.2.1 Accessibility

There are 10 different nodes available for browsing and downloading the CMIP5 simulation outputs and 6 nodes operate correctly for search:

1. CEDA: https://esgf-index1.ceda.ac.uk/search/cmip5-ceda, in the United Kingdom;
2. DKRZ: https://esgf-data.dkrz.de/search/cmip5-dkrz, in Germany;
3. LLNL: https://pcmdi.llnl.gov/search/cmip5, in the United States;
4. IPSL: https://esgf-node.ipsl.upmc.fr/search/cmip5-ipsl, in France;
5. ESRL: https://esgf.esrl.noaa.gov/search/esgf-esrl, in the United States;
6. LIU: https://esg-dn1.nsc.liu.se/search/cmip5; in Sweden.

Even though CEDA, DKRZ, LLNL are the most common nodes for physical data storage and DKRZ seems to have the fullest data collection, due to the absence of metadata information about time horizons on this node, we recommend using CEDA node for Europe.

There are six European data nodes available hosting CORDEX data for various regions: CEDA, DKRZ, DMI, IPSL, CNRM, NSC/LIU. Four of them also act as index nodes, i.e., the web portal where search can be carried out. The direct links to them are the following:

1. CEDA: https://esgf-index1.ceda.ac.uk/search/cordex-ceda, in the United Kingdom;
2. DKRZ: https://esgf-data.dkrz.de/search/cordex-dkrz, in Germany;

3. IPSL: https://esgf-node.ipsl.upmc.fr/search/cordex-ipsl, in France;
4. LIU: https://esg-dn1.nsc.liu.se/search/cordex, in Sweden.

All nodes contain identical lists of all available data and offer a uniform interface for facetted search and download. Thus, no recommendation is given on the site of the 4 nodes as best one.

Tailoring the search is very straightforward for most cases, but here is an example on a node how to find data on heatwaves change. After entering CEDA search page, select "CMIP5" under "Project" option for GCM data or for RCM data choose "CORDEX" and "EUR-11" options under "Project" and "Domain" menu points, respectively and then select "Show all replicas" (Figure 3 for CMIP5). Supposed that the impact of different anthropogenic scenarios is of interest, one must click under the "Experiment" option "historical", "rcp45" and "rcp85". Heatwaves are presented on a daily basis that can be set at the option of "Time Frequency" and it is based on a near-surface air temperature, so "Atmospheric variable" is set and "Near-surface air temperature" under the option of "Variable long name". Since institutions usually made lots of parallel runs, one could select "r1i1p1" (the most commonly used basic) member of the model runs to access to the most available models. If a user prefers to concentrate on a single model, the model has to be chosen. After this, the desired variables ("tas" in our case) must be selected under the results of the historical and RCP experiment group of files by using the "Show Files" option, and then to click on "Add to Data Cart" or simply use the "HTTPServer" link for direct download. Some institutions split their runs into time slices, therefore, all of them must be gathered to fully cover the requested time horizon.

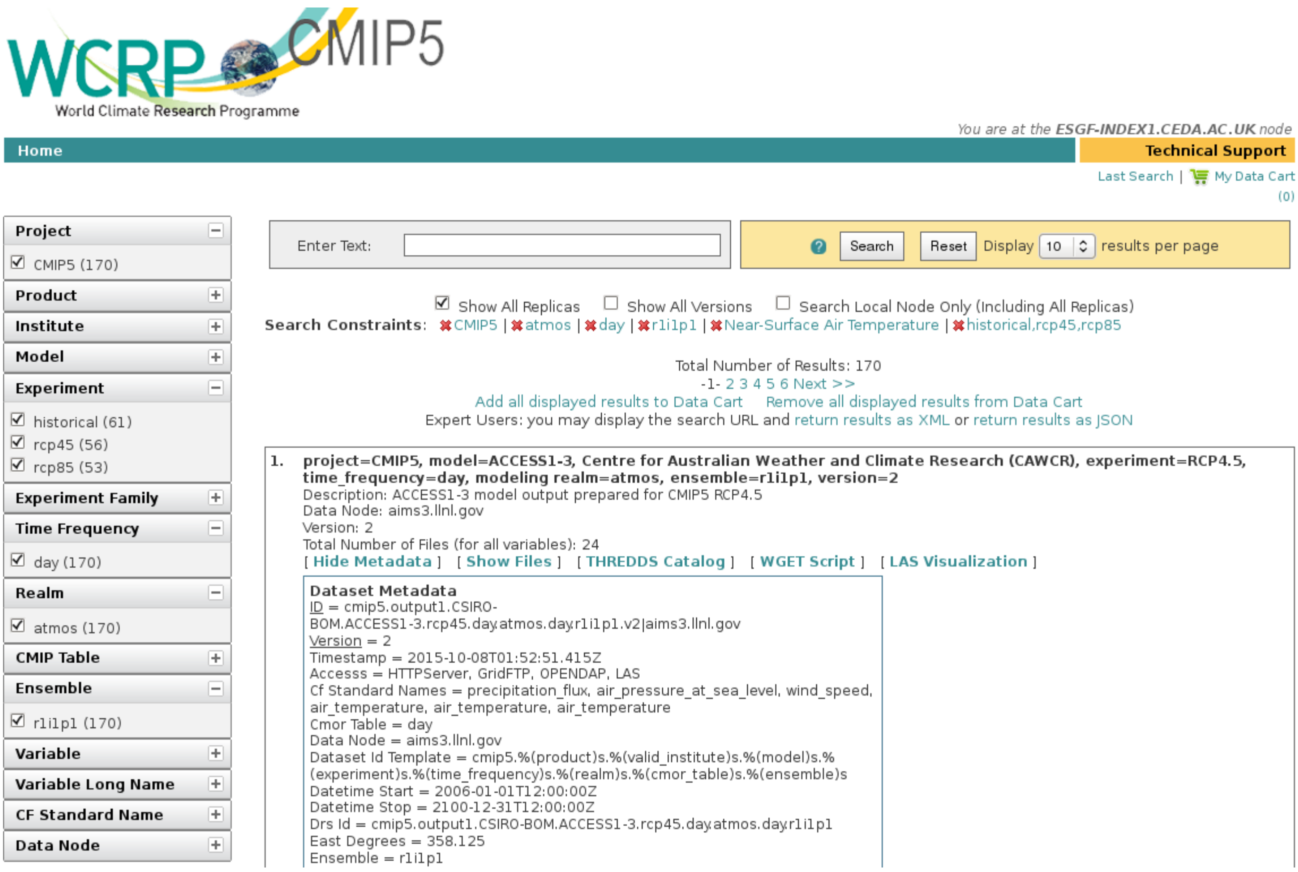

Figure 3: Search options in the CEDA node of ESGF.

2.2.2 RCM-GCM combinations

In the evaluation of CMIP5 database, we are concentrating on the historical and RCP scenario runs as mentioned above. Table 1 provides an overview about the models involved in the investigation.

Table 1: List of CMIP5 models with responsible institutes, model types (ESM: Earth System Model, AGCM: Atmosphere General Circulation Model, AOGCM: Atmosphere–Ocean General Circulation Model), and references.

	Model	Institute	Type	Reference
1.	ACCESS1.0	Centre for Australian Weather and Climate Research (Australia)	ESM	Bi et al. (2013)
2.	ACCESS1.3			
3.	BCC-CSM1.1	Beijing Climate Center – China Meteorological Administration (China)	ESM	Xin et al. (2013)
4.	BCC-CSM1.1(m)			
5.	BNU-ESM	College of Global Change and Earth System Science – Beijing Normal University (China)	ESM	Ji et al. (2014)
6.	CCSM4	National Center for Atmospheric Research (US)	ESM	Gent et al. (2011)
7.	CESM1(BGC)	National Science Foundation; Department of Energy; National Center for Atmospheric Research (US)	ESM	Hurrell et al. (2013)
8.	CESM1(CAM5)			
9.	CESM1(CAM5.1,FV2)			
10.	CESM1(FASTCHEM)			
11.	CESM1(WACCM)			
12.	CMCC-CESM	Centro Euro-Mediterraneo per I Cambiamenti Climatici (Italy)	ESM	Alessandri et al. (2012)
13.	CMCC-CM		AOGCM	Scoccimarro et al. (2011)
14.	CMCC-CMS			
15.	CNRM-CM5	Centre National de Recherches Météorologiques; Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (France)	ESM	Voldoire et al. (2012)
16.	CNRM-CM5-2			
17.	CSIRO-Mk3.6.0	Queensland Climate Change Centre of Excellence (Australia)	AOGCM	Rotstayn et al. (2010)
18.	CSIRO-Mk3L-1-2	University of New South Wales (Australia)	AOGCM	Phipps et al. (2011)
19.	CanCM4	Canadian Centre for Climate Modelling and Analysis (Canada)	AOGCM	Arora et al. (2011)
20.	CanESM2		ESM	Chylek et al. (2011)
21.	EC-EARTH	Irish Centre for High-End Computing (Ireland)	AOGCM	Hazeleger et al. (2012)
22.	FGOALS-g2	Institute of Atmospheric Physics – Chinese Academy of Sciences; Tsinghua University (China)	AOGCM	Zhang and Yu (2011)
23.	FGOALS-s2		ESM	Bao et al. (2013)
24.	FIO-ESM	First Institute of Oceanography (China)	ESM	Qiao et al. (2013)
25.	GFDL-CM2.1		AOGCM	Delworth et al. (2006)

26.	GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory (US)	AOGCM	Griffies et al. (2011)
27.	GFDL-ESM2G		ESM	Dunne et al. (2012)
28.	GFDL-ESM2M			
29.	GISS-E2-H	NASA Goddard Institute for Space Studies (US)	AOGCM	Schmidt et al. (2014)
30.	GISS-E2-H-CC		ESM	
31.	GISS-E2-R		AOGCM	
32.	GISS-E2-R-CC		ESM	
33.	HadCM3	Met Office Hadley Centre (UK)	AOGCM	Gordon et al. (2000)
34.	HadGEM2-AO	National Institute of Meteorological Research – Korea Meteorological Administration (Korea)	AOGCM	
35.	HadGEM2-CC	Met Office Hadley Centre (UK)	ESM	Martin et al. (2011)
36.	HadGEM2-ES	Met Office Hadley Centre (UK); National Institute for Space Research (Brazil)	ESM	Martin et al. (2011)
37.	INM-CM4	Institute for Numerical Mathematics (Russia)	ESM	Volodin et al. (2010)
38.	IPSL-CM5A-LR	Institut Pierre-Simon Laplace (France)	ESM	Dufresne et al. (2013)
39.	IPSL-CM5A-MR			
40.	IPSL-CM5B-LR			
41.	MIROC-ESM	Atmosphere and Ocean Research Institute – University of Tokyo; National Institute for Environmental Studies; Japan Agency for Marine-Earth Science and Technology (Japan)	ESM	Watanabe et al. (2011)
42.	MIROC-ESM-CHEM			
43.	MIROC4h		AOGCM	Sakamoto et al. (2012)
44.	MIROC5		AOGCM	Watanabe et al. (2010)
45.	MPI-ESM-LR	Max Planck Institute for Meteorology (Germany)	ESM	Giorgetta et al. (2013)
46.	MPI-ESM-MR			
47.	MPI-ESM-P			
48.	MRI-CGCM3	Meteorological Research Institute (Japan)	AOGCM	Yukimoto et al. (2013)
49.	MRI-ESM1		ESM	Yukimoto et al. (2011)
50.	NorESM1-M	Norwegian Climate Centre (Norway)	ESM	Bentsen et al. (2013)
51.	NorESM1-ME		ESM	Tjiputra et al. (2013)

To the EURO-CORDEX dataset 12 European institutions contributed with results of 11 RCMs (Table 2). Lateral boundary conditions for the projections were provided by 10 different GCMs. 3 RCMs have only ERA-Interim driven experiment without further projection runs. On the 50 km resolution (EUR-44) grid, altogether 8 RCMs were driven by 10 GCMs resulting in 18 simulations. Smaller amount of simulations was conducted on the finer resolution (EUR-11) grid with combination of 7 RCMs and 5 GCMs. Most simulations are performed on both resolutions. Uncertainties of RCM results principally depend on how widely the global models are applied. EC-EARTH is the most represented GCM in EUR-11 with 4 RCMs (CCLM4-8-17, HIRHAM5, RACMO22E, RCA4), while CNRM-

CM5, EC-EARTH, MPI-ESM-LR are providing forcings for 2 or 3 RCMs both in EUR-44 and EUR-11 (blue cells in Figure 4). These sets of model simulations allow to study how the pattern or signal provided by the driving GCM propagate to RCMs. Regrettably, the outputs of CanESM2, CSIRO-Mk3-6-0, GFDL-ESM2M, MIROC5, NorESM1-M global models are only applied in EUR-44. RCA4 is the only regional model coupled to all GCMs over the EUR-44 grid, and in EUR-11 it is still driven by 5 global models (CCLM4-8-17 is the second widely used RCM with 4 different LBCs and also RACMO22E is driven with 2 GCMs; red crosses in Figure 4).

Table 2: List of EURO-CORDEX models with responsible institutes and references.

	Model	Institute	Reference
1.	ALADIN52	Hungarian Meteorological Service (Hungary)	Herrmann et al. (2011)
2.	ALADIN53	Météo France (France)	Colin et al. (2010)
3.	CCLM4-8-17	CLM Community with contributions by Brandenburg University of Technology (Germany), German Climate Computing Centre (Germany), Swiss Federal Institute of Technology in Zürich (Switzerland)	Rockel et al. (2008)
4.	HIRHAM5	Danish Meteorological Institute (Denmark)	Christensen et al. (2006)
5.	HadGEM3-RA	Met Office Hadley Centre (UK)	Jones et al. (2004)
6.	HadRM3P	Met Office Hadley Centre (UK)	Murphy et al. (2009)
7.	RACMO22E	Royal Netherlands Meteorological Institute (The Netherlands)	Meijgaard van et al. (2012)
8.	RCA4	Swedish Meteorological and Hydrological Institute (Sweden)	Kupiainen et al. (2011)
9.	REMO2009	Climate Service Center Germany (Germany)	Jacob et al. (2012)
10.	RegCM4-2	Croatian Meteorological and Hydrological Service (Croatia)	Giorgi et al. (2012)
11.	WRF331F	Institut Pierre Simon Laplace (France)	Skamarock et al. (2008)

EUR-44 (Insitution-GCMs)	ALADIN52	ALADIN53	CCLM4-8-17	HIRHAM5	HadGEM3-RA	HadRM3P	RACMO22E	RCA4	REMO2009	RegCM4-2	WRF331F	Total number
CCCma-CanESM2								x				1
CNRM-CERFACS-CNRM-CM5	x	x						x				3
CSIRO-QCCCE-CSIRO-Mk3-6-0								x				1
ICHEC-EC-EARTH				x			x	x				3
IPSL-IPSL-CM5A-MR								x			x	2
MIROC-MIROC5								x				1
MOHC-HadGEM2-ES							x	x				2
MPI-M-MPI-ESM-LR			x					x	x			3
NCC-NorESM1-M								x				1
NOAA-GFDL-GFDL-ESM2M								x				1
Total number	1	1	1	1			2	10	1		1	18

EUR-11 (Institution-GCMs)	ALADIN52	ALADIN53	CCLM4-8-17	HIRHAM5	HadGEM3-RA	HadRM3P	RACMO22E	RCA4	REMO2009	RegCM4-2	WRF331F	Total number
CCCma-CanESM2												
CNRM-CERFACS-CNRM-CM5		x	x					x				3
CSIRO-QCCCE-CSIRO-Mk3-6-0												
ICHEC-EC-EARTH			x	x			x	x				4
IPSL-IPSL-CM5A-MR								x			x	2
MIROC-MIROC5												
MOHC-HadGEM2-ES			x				x	x				3
MPI-M-MPI-ESM-LR			x					x	x			3
NCC-NorESM1-M												
NOAA-GFDL-GFDL-ESM2M												
Total number		1	4	1			2	5	1		1	15

Figure 4: Applied regional climate models (RCMs) and drivings from global climate models (GCMs) in EURO-CORDEX simulations on 0.44- (EUR-44) and 0.11-degree (EUR-11) resolutions. Red crosses denote the RCMs which have experiments driven by different GCMs, while blue cells represent the simulations in which the same GCM was downscaled by several RCMs.

In MED-CORDEX, seven GCMs provided LBCs for scenario runs with 10 RCMs, but some simulations cannot be considered as independent ones as they are based on the same RCMs (e.g., CCLM, RegCM) differing only in the version numbers. This has to be taken into account at choice of an RCM ensemble as the uncertainty estimation can be biased by the different model versions. It is especially valid for the ERA-Interim runs (although some RCMs have only evaluation experiment). Double nesting is also applied, i.e., driving a high-resolution RCM by its coarser resolution version. Some atmospheric RCMs (CCLM4-21, LMDZ4, WRF311) were coupled to regional ocean models like NEMO-MED8, POM, NEMO-MFS.

In MENA-CORDEX only one RCM, RCA4 has been used, but with 3 different GCMs, GFDL-ESM2M, ICHEC-EC-EARTH and CNRM-CM5 to involve model uncertainty in the projection results. Arctic-CORDEX simulations are available for 7 different RCMs driven with 4 GCMs, however, scenario runs were conducted only with 4 of the 7 RCMs: HIRHAM5, RCA4, RCA4-SN and RRCM. In Central Asia CORDEX, in the ESGF there is simulation only with MOHC-HadRM3P regional model developed by the Met Office Hadley Centre and it was used to downscaling of the ERA-interim re-analysis data for the period of 1989−2008. According to the latest status (end of 2016, personal communication) no further simulations, neither with RCP scenarios, nor with different models will be uploaded in the near-future.

2.2.3 Spatial resolution

All CMIP5 model outputs are given on a Gaussian grid, which is a rectangular grid with constant longitude and (slightly) varying latitude resolution. The horizontal resolution of the model outputs varies widely from 0.56° as the highest to 5.6° as the most sparse resolution. Most models have a 1°–2° (approximately 100-250 km) resolution, with a total of 25 members belonging to that category. The second most frequent category is the 2°–3° (approximately 200-350 km) resolution with 20 models. 8 models (only 6 from different model families) are found in the highest, 0°–1° resolution category. However, most of these high-resolution models do not have future RCP scenarios available. 2 of the total number of models have a horizontal resolution lower than 4 degrees.

EURO-CORDEX data are available on 4 grid types with different spatial resolution:

- EUR-44 is a rotated latitude-longitude grid with 0.44° (approx. 50 km) horizontal resolution;
- EUR-11 is a rotated latitude-longitude grid with 0.11° (approx. 12 km) horizontal resolution;
- EUR-44i is a regular (non-rotated) latitude-longitude grid with 0.5° (approx. 57 km) horizontal resolution;
- EUR-11i is a regular (non-rotated) latitude-longitude grid with 0.125° (approx. 14 km) horizontal resolution.

Data of 10 and 5 evaluation runs are available on the coarser EUR-44 grid and higher-resolution EUR-11 grid, respectively. 18 RCM projections were carried out on EUR-44 grid and 13 of them have outputs also on the non-rotated EUR-44i version. Data of 15 RCMs can be downloaded on the high-resolution EUR-11 grid and only 5 simulations provide results on the EUR-11i grid type. The EURO-CORDEX domain covers the entire European continent and the Northern coast of Africa. Turkey is located in the vicinity of the eastern domain border, which is not an ideal position because RCM results can be hampered by the numerical noises originating from LBC treatment. If we look at the other four domains covering a part of Europe, we can conclude that Turkey is situated similarly in each case.

MED-CORDEX projections are available mostly on the 0.44-degree resolution rotated MED-44 grid, furthermore, on the 0.11-degree resolution rotated MED-11 grid and on the 0.5-degree resolution regular MED-44i grid. Evaluation runs were carried out on various resolutions, but their majority are accessible on MED-44. MENA-CORDEX results are available on the 0.44-degree resolution MNA-44 grid and on the 0.22-degree resolution MNA-22 grid. In Arctic-CORDEX two grids are applied: all results are available on the 0.44-degree horizontal resolution rotated ARC-44 grid and almost every model output is also archived on an additional 0.5° resolution regular non-rotated ARC-44i grid.

Availability of the upper-level atmospheric variables is important especially for downscaling the GCM data with regional climate models and applying GCM outputs as lateral boundary conditions. In CMIP5, the upper level atmospheric data is either given on predefined pressure levels (on 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa) or on the vertical model levels. Pressure level variables are available for 51 GCMs. Different vertical coordinates are used in the models, e.g., terrain following, theta (potential temperature), sigma (pressure) or hybrid (combination of terrain following and pressure) coordinates. When the pressure of model levels cannot be calculated from the vertical coordinate information, the annual pressure climatology on model levels is also provided. 46 GCMs have data available on the model levels (although not for the prognostic variables which are used in dynamical downscaling methods). Availability of the upper-level atmospheric variables is important also for downscaling the RCM data with dynamical impact models. CORDEX mostly consists of surface data, but all simulations provide horizontal wind components, temperature and geopotential heights on 850 hPa, 500 hPa, 200 hPa pressure levels, as well. Model level variables however are not stored.

Model orography and land-sea fraction can be essential in certain studies and applications (e.g., in interpolation, vertical correction of 2-meter temperature). Both constant fields can be downloaded for 55 global climate models and for all investigated RCMs.

2.2.4 Time horizon

With the simulated time span reaching 2100, RCP scenario runs provide input data for long-term adaptation, while simulations going beyond 2100 serve as essential information about the relevant paths towards the far-future, which might orientate the decision making related to mitigation to climate change. In CMIP5, 42 GCMs provide data for impact studies and downscaling until 2100. 13 models have simulations beyond 2100 until 2300 for atmospheric variables. Even though originally these multi-centennial simulations were planned as tier experiments for RCP2.6 and RCP8.5 scenarios, the outputs are diverse. All models have projections for the RCP4.5 scenario at monthly level, most of them also for the RCP8.5 scenario and/or at daily level (but very few with the RCP6.0 scenario and 6-hourly data).

CORDEX evaluation experiments commonly run for the period of 1989–2008, but outputs of some simulations are available also for the years before 1989 and after 2008. Control runs uniformly go until 2005, but their starting dates are various: 80% of the simulations are conducted from 1951, while from 1971 all are available. The initial date for projections is 2006, 16 and 12 RCM runs reach 2100 on EUR-44 and EUR-11 grids, respectively. Nevertheless, the experiments driven by HadGEM2-ES global model forcings go until 2099, so they can also provide input data for long-term adaptation. In MED-CORDEX, MENA-CORDEX and Arctic-CORDEX most projections end in 2100. Simulations going beyond 2100 are not available in any of the selected CORDEX domains.

2.2.5 Available RCP scenario runs

The uncertainty range arising from the description of future anthropogenic activity in the model simulations is important both from a scientific point of view and from users' perspective. 51 GCMs have historical runs, but a smaller sub-ensemble, 47 GCMs provide one RCP run at minimum. The most commonly used scenarios are RCP4.5 and RCP8.5: 44 and 42 GCMs have simulations forced by them, respectively. These two groups produce the core simulations of CMIP5. The highly idealistic RCP2.6 scenario is used with 30 models, while the medium RCP6.0 scenario is the least exploited one with 22 GCMs. Altogether 21 models have simulations for all RCPs. Projected temperature change shows a nearly linear relationship with the greenhouse gas emissions (Stocker et al., 2013), so the largest spread in temperature projections can be captured already by examining 3 RCPs, RCP2.6, RCP4.5 and RCP8.5, available for 29 models. Considering the "probability" of the different forcing scenarios (i.e., noting that RCP2.6 is an ultra-optimistic scenario), the possible range of future warming is reflected by taking RCP4.5, RCP6.0 and RCP8.5. This option is available for 21 models, i.e., for the same GCMs which have experiments with all RCPs. Focusing only on the core experiments, 39 models provide simulations with both RCP4.5 and RCP8.5, forming an ensemble catching the optimistic and pessimistic paths of the future.

In EURO-CORDEX, 18 and 15 control runs are conducted on EUR-44 and EUR-11 grids, respectively and scenario runs are naturally available with them. RCP8.5 and RCP4.5 scenarios are uniformly used in the projections, with exception of one RCM. RCP2.6 is the least used scenario resulting in 7 EUR-44 simulations and in 5 EUR-11 simulations. This latter sample is not a subset of the 7-member ensemble: only three simulations have projections with RCP2.6 scenario on both grids. In MED-CORDEX, the RCP8.5 scenario is used the most widely: 9 and 2 simulations were carried out over the MED-44 and MED-11 grids, respectively. RCP4.5 was applied in 7 and 1 experiments on the two grids, resulting in 5 simulations conducted with both anthropogenic forcings. Solely one RCM have an RCP2.6 simulation over MED-44. In MENA-CORDEX, scenario runs are available over the MNA-44 domain for both RCP4.5 and RCP8.5, but over MNA-22 only RCP8.5 was applied. The most frequently applied emission scenario within Arctic-CORDEX is RCP8.5 (resulting in 9 simulations), the RCP4.5 scenario was applied in 5 projections, while RCP2.6 was considered only in one experiment.

2.2.6 Temporal resolution

For RCP scenario runs in CMIP5, 46 out of 47 GCMs provide monthly data. 41 GCMs have daily data, 32 and 26 models serve 6- and 3-hourly outputs, respectively (Table 3). In CORDEX, daily and monthly outputs are archived for all simulations (both evaluation and projection runs). Sub-daily outputs are not usual: they are available mostly for evaluation runs, meaning that impact studies cannot target sub-daily processes. Only RCA4 has 3- and 6-hourly EUR-11 data on ESGF.

Table 3: List of CMIP5 models with daily and sub-daily data stored on ESGF.

	ACCESSx.0	ACCESSx.3	BCC-CSMx.x	BCC-CSMx.x(m)	BNU-ESM	CCSM4	CESMx(BGC)	CESMx(CAM5)	CMCC-CESM	CMCC-CM	CMCC-CMS	CNRM-CM5	CSIRO-Mk3.6.0	CSIRO-Mk3L-x-2	CanCM4	CanESM2	EC-EARTH	FGOALS-g2	GFDL-CM3	GFDL-ESM2G
3-hourly	x	x	x	x	x	x				x		x					x	x	x	x
6-hourly	x	x	x	x	x	x				x		x	x			x	x	x	x	x
daily	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

	GFDL-ESM2M	GISS-E2-H	GISS-E2-R	HadCM3	HadGEM2-AO	HadGEM2-CC	HadGEM2-ES	INM-CM4	IPSL-CM5A-LR	IPSL-CM5A-MR	IPSL-CM5B-LR	MIROC-ESM	MIROC-ESM-CHEM	MIROC4h	MIROC5	MPI-ESM-LR	MPI-ESM-MR	MRI-CGCM3	MRI-ESMx	NorESMx-M	NorESMx-ME	**SUM**
3-hourly	x	x	x				x	x	x	x		x	x	x	x			x	x	x		**26**
6-hourly	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		**32**
daily	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	**41**

2.2.7 Available variables

Considering all climate models and all the different experiment types within CMIP5, the total number of available variables adds up to more than 600 (Taylor, 2012a). The availability of a given variable is different between the models, experiment types and even temporal resolutions. This large number of options and diverse structure makes it difficult to have general assumptions on the availability of the specific variables to be interested by the users. The methods and models of impact researchers generally require several climate variables from the same model simulation as input data; therefore, the joint existence of certain groups of variables could yield useful information. To address this issue, "variable packages" were defined and evaluated for each climate model. The variable packages are listed in Table 4. There are normal packages as well as their extended version containing extra parameters often available for a smaller number of model runs. The *basic, extended basic, extended basic 2* and *radiation packages* are composed of surface variables. The *extended radiation package* includes also some additional radiation component at the top of the atmosphere, *pressure level packages* obviously contain pressure level variables, and *model level package* consists of the variables available on models' vertical levels.

Variables belonging to the basic package are the near-surface air temperature, the daily minimum near-surface temperature, the daily maximum near-surface temperature, and the precipitation. The package is stored with monthly and daily output frequency for more than 40 GCMs in CMIP5 and for all of the GCM-RCM model chains both on EUR-44 and EUR-11 grids. Basic package is extended with wind components, sea level pressure, specific humidity, cloudiness, global radiation, and snowfall. Monthly means or sums of this group are found for 31 GCMs, while daily values for 23 models. In EURO-CORDEX, it is available with daily output frequency for 15 EUR-44 and 9 EUR-11 simulations. Adding the water vapour path to the list, the extended basic 2 package is available only on monthly scale and in 29 GCMs, while in EURO-CORDEX daily data are also stored for 14 EUR-44 and 8 EUR-11 simulations. The radiation package consisting of 2 shortwave and 2 longwave surface radiation components is found with monthly, daily and 3-hourly archive frequency for 44, 33 and 24 GCMs, respectively, and with monthly and daily archive frequency for almost every RCM simulation. Its extended version has no sub-daily occurrence. The pressure level packages are widely available among the models, with more than 40 monthly, around 30 daily and 26 6-hourly occurrences in case of CMIP5 and for almost all scenario runs in EURO-CORDEX. Until April 2017, only few cloud-related model level variables were archived mostly with monthly frequency for 29 GCMs. Since then further 6-hourly model level data for temperature, wind components and specific humidity are uploaded (together with sea or surface level air pressure) to ESGF from 26 GCMs (Table 5) due to the gap evaluation carried out by different C3S Lots. These data are especially important for dynamical downscaling of global fields. In MED-CORDEX, MENA-CORDEX and Artic-CORDEX, mostly variables of the basic, radiation and pressure packages are archived on monthly and daily resolutions.

Table 4: The defined variable packages.

Package name	Variable long name	Variable name	Unit
Basic	Near-Surface Air Temperature	tas	K
	Daily Maximum Near-Surface Air Temperature	tasmax	K
	Daily Minimum Near-Surface Air Temperature	tasmin	K
	Precipitation	pr	kg m^{-2} s^{-1}
Extended basic	Basic +		
	Sea Level Pressure	slp	Pa
	Eastward Near-Surface Wind	uas	m s^{-1}
	Northward Near-Surface Wind	vas	m s^{-1}
	Near-Surface Specific Humidity	huss	1
	Surface Downwelling Shortwave Radiation	rsds	Wm^{-2}
	Total Cloud Fraction	clt	%
	Snowfall Flux	prsn	kg m^{-2} s^{-1}
Extended basic 2	Extended basic +		
	Water Vapour Path	prw	kg m^{-2}
Radiation	Surface Downwelling Longwave Radiation	rlds	Wm^{-2}
	Surface Upwelling Longwave Radiation	rlus	Wm^{-2}
	Surface Downwelling Shortwave Radiation	rsds	Wm^{-2}
	Surface Upwelling Shortwave Radiation	rsus	Wm^{-2}
Extended radiation	Radiation +		
	TOA Incident Shortwave Radiation	rsdt	Wm^{-2}
	TOA Outgoing Shortwave Radiation	rsut	Wm^{-2}
	TOA Outgoing Longwave Radiation	rlut	Wm^{-2}
Pressure level	Temperature at 200, 500, 850 hPa	ta[200,500,850]	K
	Eastward Wind at 200, 500, 850 hPa	ua[200,500,850]	m s^{-1}
	Northward Wind at 200, 500, 850 hPa	va[200,500,850]	m s^{-1}
	Geopotential height at 200, 500, 850 hPa	zg[200,500,850]	m

Table 5: List of CMIP5 models with model level variables stored on ESGF.

Long name	Name	Unit	Freq.	ACCESS1.0	ACCESS1.3	BCC-CSM1.1	BCC-CSM1.1(m)	BNU-ESM	CCSM4	CMCC-CM	CNRM-CM5	CSIRO-Mk3.6.0	CanESM2	FGOALS-g2	GFDL-CM3	GFDL-ESM2G	GFDL-ESM2M	GISS-E2-H	GISS-E2-R	HadGEM2-ES	IPSL-CM5A-LR	IPSL-CM5A-MR	IPSL-CM5B-LR	MIROC-ESM	MIROC-ESM-CHEM	MIROC4h	MIROC5	MRI-CGCM3	NorESM1-M	SUM
Air Temperature	ta	K	6 h	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	**26**
Eastward Wind	ua	ms^{-1}	6 h	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	**26**
Northward Wind	va	ms^{-1}	6 h	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	**26**
Specific Humidity	hus	-	6 h	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	**26**

2.2.8 Bias-adjusted data

Impact models typically require high-resolution unbiased climate input data. Global and regional climate models, however, are in general biased. Thus, many users demand some form of bias-adjusted data. However, there is still a scientific debate going on whether bias-adjustment methods can plausibly correct climate change trends (Maraun, 2016).

The uncertainty related to bias correction is three-fold. One source of uncertainty comes from the choice of method to be applied. There are numerous methods available, which all have different focus and qualities. However, there does not exist the one perfect method. Therefore, the result of the adjustment and thus the uncertainty depends strongly on the chosen method. Assessing this uncertainty is part of the bias correction inter-comparison project (BCIP, Nikulin 2015). Applying different bias-correction methods and different modifications of the same method to the same input datasets allows assessing impact of bias-adjusted technique on climate simulations. These efforts have led to an application of six applied methods (mostly based on quantile mapping) that are currently available at the ESGF (Table 6).

Table 6: Bias-adjustment methods applied in EURO-CORDEX with corresponding references.

Bias-adjustment method	**Reference**
SMHI-DBS45	Yang et al. (2010)
UCAN-EQM	Déqué (2007), Wilcke et al. (2013)
TUC-MSBC	Grillakis et al. (2013)
METNO-QMAP	Gudmundsson et al. (2012)
UCAN-ISI-MIP	Hempel et al. (2013)
IPSL-CDFT21	Vrac et al. (2016)

A second source of uncertainty is the choice of reference data used to calibrate the bias-adjustment methods. High quality of the reference is crucial for these methods. Up to date, the bias-adjusted data available at ESFG are based on three different observational datasets: MESAN, EOBS12, WFDEI. However, bias-adjustment community plans to extend the set of data with additional observational datasets (personal communication).

A third source of uncertainty is the choice of calibration period, time frame and length. The length but also the choice of years for the calibration is linked to the relationship built between observation and simulation data. This issue is related to the non-stationarity of the bias, i.e., that the bias for each quantile can be varying over time (Maraun, 2013). All statistical methods assume the stationarity of biases over time. Consequently, there is a need to maximise the calibration period in order to reduce this part of the uncertainty (Reiter et al., 2015). The calibration period depends on the observational dataset and varies for the available data in 1981–2010 (EOBS12), 1979–2005 (WFDEI) and 1989–2010 (MESAN).

Bias-adjustment data were recently added to the ESGF and as mentioned they are visible on all ESGF index nodes under the project name “CORDEX-Adjust”. In total 485 bias-adjusted EURO-CORDEX datasets are available covering mainly daily temperature and precipitation as output. In order to avoid any confusion and to clearly distinguish original and bias-adjusted CORDEX simulation data, the

CORDEX variable names received the appending “Adjust” to the variable names, for example in case of precipitation and near-surface air temperature, *pr* and *tas* are modified to *prAdjust* and *tasAdjust*, respectively.

So far, bias adjustment was applied for simulations achieved with combination of 10 different driving GCMs and 7 RCMs. On the EUR-44 grid, bias-adjusted data are available from 26 RCM-GCM combinations, while from 24 ones on EUR-11. However, the two subsets are rather complementary of each other. Post-processing was employed for the whole time period on which the raw data are available: i.e., until 2100, apart from the simulations driven by HadGEM2-ES. The datasets are available for three different RCPs, whereas the most data can be accessible for RCP4.5 scenario (21 EUR-44 and 25 EUR-11 simulations). Outputs of 21 and 16 RCP8.5 experiments were bias-adjusted over the EUR-44 and EUR-11 grids, respectively. Data of all the 3 RCP runs were post-processed only for 2 RCMs over the EUR-44 grid, and for one simulation over the EUR-11 grid. All simulations have daily outputs, sub-daily (3-hourly) outputs are available only for the bias-adjustment method 2IPSL-CDFT21-WFDEI over the EUR-11 grid. For the EUR-11 simulations that were bias-adjusted with the SMHI-DBS45 method and MESAN reference, monthly means are provided in addition to the daily output. The bias adjustment was employed primarily for daily precipitation and daily minimum, maximum and mean temperature values. In case of some EUR-11 simulations, some methods were applied for the 3-hourly radiation (resulting in rsdsAdjust) and wind (resulting in sfcWindAdjust).

Presumably, the bias-adjusted datasets at ESGF will grow (personal communication). On the one hand, it is planned to apply more available observational datasets for the calibration. On the other hand, the development and refinement of bias-adjustment methods is ongoing.

2.3 Suggestions what could be delivered to CDS

To assess the different aspects together, in a summarized way, a multi-criteria filtering method is presented with the aim of giving some guidance on choosing a climate model ensemble from all of the available options. The first criterion is applied on the available variables, the second is concerning the spatial resolution and the third one is related the available scenarios.

Considering the first criterion for CMIP5, those models are selected, for which the extended basic, the radiation and the pressure level packages are all available, either with daily or monthly output frequency. This condition remains the same throughout all the columns. The second criterion gives a stricter (0°–2°) and a more tolerant (0°–3°) option regarding the horizontal resolution of CMIP5 GCMs. The third criterion specifies the availability of scenario runs:

- Historical and RCP8.5 runs;
- Historical, RCP8.5 and RCP4.5 runs;
- Historical, RCP8.5, RCP4.5 and RCP2.6 runs;
- Historical and scenarios runs with all RCPs.

The included models between the ensembles obtained using the different criteria, differ significantly. Looking at the strictest criterion group (i.e., high-resolution runs with all scenarios and their daily outputs covering all the defined variable packages), only 5 CMIP5 models remain. Three of them are AOGCMs, namely CSIRO-Mk3.6.0, MIROC5 and MRI-CGCM3; the other two are ESMs: BCC-CSM1.1(m) and HadGEM2-ES. Loosening up the criterion regarding the available scenarios for just the RCP8.5, 9 models are left. In this case, however, the ensemble has several members from the same model family (ACCESS, HadGEM, MRI). If we extend the upper limit of the horizontal resolution to 3 degrees, twice or almost three times as much models meet the criterion than above. If the criterion regarding spatial resolution is completely ignored, the lists expand only slightly further (recall that horizontal resolution exceeds 3 degrees only for a few models): 27 GCMs have data from experiments conducted with RCP8.5 scenario and 16 of them have been run with all the four RCP scenarios (with monthly outputs). Doing efforts to filter the model-dependency (for more details see deliverable 2.1), an 8-member ensemble can be designed, providing climate projections for all RCP scenarios at daily level for any of the selected (surface, pressure-level and radiation) atmospheric variables (Table 7).

Considering the first criterion for EURO-CORDEX dataset, those models are selected, for which the extended basic, the radiation and the pressure level packages are all available with daily output frequency. The second criterion splits the data to two sets of 0.44-degree and 0.11-degree resolution experiments. The third criterion specifies the availability of scenario runs:

1. Historical and RCP8.5 runs;
2. Historical, RCP8.5 and RCP4.5 runs;
3. Historical, RCP8.5, RCP4.5 and RCP2.6 runs.

The third scenario criteria results in 7- and 4-member ensembles depending on the applied resolution (right columns of Table 8). If bias-adjusted data are also requested for daily precipitation and for daily minimum, maximum and mean temperature, the size of ensembles further decrease to 2 members consisting of RACMO22E and RCA4 both driven by HadGEM2-ES, and 1 member of REMO2009 driven by MPI-ESM-LR. Looking at the strictest criterion group (i.e., high-resolution runs with all scenarios and their daily outputs covering all the defined variable packages), only 3 EURO-CORDEX simulations remain with HIRHAM5 and RCA4 both driven by EC-EARTH, and RACMO22E driven by HadGEM2-ES. Loosening up the criterion regarding the available scenarios, the same subsets of simulations are resulted for RCP8.5 and RCP4.5: 8 simulations are available. If we do not need high-resolution outputs, these ensembles can be extended with 5 additional simulations of RCA4 RCMs.

It must be emphasised that these tables do not present any qualitative assessment of the model outputs and give no information on model skills and validation results. Therefore, these models are not considered the “best ones”, only the ones with the most abundant available (and downloadable) data. However, it was already concluded that there are both RCMs (e.g., RCA4) and driving GCMs (HadGEM2-ES) in the RCM-GCM chains which are used more frequently in the simulations than other ones. In case of GCMs, we dedicated some efforts to reduce the number of simulations carried out with the same model families in the ensemble. Nevertheless, in case of RCM results it is difficult to identify their “similarities” based on the applied models, because the climate change signal is affected by the non-linear interaction of the regional model and the forcing field. Consequently, to judge the independency of the RCM simulations in the resulted ensembles, thorough assessments of the dynamics and physics of the applied RCMs and GCMs as well as their outputs are needed.

Table 7: A tentative proposal for selection of CMIP5 GCM simulations considering the availability of given scenarios, atmospheric variables and the model interdependency.

Extended basic, Radiation, Pressure level		Extended basic, Radiation, Pressure level	
historical, RCP8.5		historical, RCP8.5, RCP4.5	
daily data	monthly data	daily data	monthly data
ACCESS1.0	ACCESS1.0	ACCESS1.0	ACCESS1.0
BCC-CSM1.1(m)	BCC-CSM1.1(m)	BCC-CSM1.1(m)	BCC-CSM1.1(m)
BNU-ESM	BNU-ESM	BNU-ESM	BNU-ESM
	CNRM-CM5		CNRM-CM5
CSIRO-Mk3.6.0	CSIRO-Mk3.6.0	CSIRO-Mk3.6.0	CSIRO-Mk3.6.0
CanESM2	CanESM2	CanESM2	CanESM2
GFDL-ESM2M	GFDL-ESM2M	GFDL-ESM2M	GFDL-ESM2M
	GISS-E2-R-CC		GISS-E2-R-CC
HadGEM2-CC	HadGEM2-CC	HadGEM2-CC	HadGEM2-CC
	INM-CM4		INM-CM4
IPSL (CM5A-MR or CM5B-LR)	IPSL (CM5A-MR or CM5B-LR)	IPSL (CM5A-MR or CM5B-LR)	IPSL (CM5A-MR or CM5B-LR)
MIROC (ESM-CHEM or MIROC5)	MIROC (ESM-CHEM or MIROC5)	MIROC (ESM-CHEM or MIROC5)	MIROC (ESM-CHEM or MIROC5)
MRI-CGCM3	MRI-CGCM3	MRI-CGCM3	MRI-CGCM3
MRI-ESM1	MRI-ESM1		
NorESM1-M	NorESM1-M	NorESM1-M	NorESM1-M
Number of models	**Number of models**	**Number of models**	**Number of models**
12	**15**	**11**	**14**

Extended basic, Radiation, Pressure level		Extended basic, Radiation, Pressure level	
historical, RCP8.5, RCP4.5, RCP2.6		historical, all RCPs	
daily data	monthly data	daily data	monthly data
BCC-CSM1.1(m)	BCC-CSM1.1(m)	BCC-CSM1.1(m)	BCC-CSM1.1(m)
BNU-ESM	BNU-ESM		
	CNRM-CM5		
CSIRO-Mk3.6.0	CSIRO-Mk3.6.0	CSIRO-Mk3.6.0	CSIRO-Mk3.6.0
CanESM2	CanESM2		
GFDL-ESM2M	GFDL-ESM2M	GFDL-ESM2M	GFDL-ESM2M
	GISS-E2-R		GISS-E2-R
HadGEM2-ES	HadGEM2-ES	HadGEM2-ES	HadGEM2-ES
IPSL-CM5A-MR	IPSL-CM5A-MR	IPSL-CM5A-MR	IPSL-CM5A-MR
MIROC (ESM-CHEM or MIROC5)	MIROC (ESM-CHEM or MIROC5)	MIROC (ESM-CHEM or MIROC5)	MIROC (ESM-CHEM or MIROC5)
MRI-CGCM3	MRI-CGCM3	MRI-CGCM3	MRI-CGCM3
NorESM1-M	NorESM1-M	NorESM1-M	NorESM1-M
Number of models	**Number of models**	**Number of models**	**Number of models**
10	**12**	**8**	**9**

Table 8: Joint availability of given scenarios and atmospheric variables in GCM-driven RCM experiments on different EURO-CORDEX resolutions. Existence of bias-adjusted data for daily precipitation and daily minimum, maximum and mean temperature is highlighted in red.

Extended basic + Radiation + Pressure level	Extended basic + Radiation + Pressure level	Extended basic + Radiation + Pressure level
0.44° horizontal resolution (EUR-44)	0.44° horizontal resolution (EUR-44)	0.44° horizontal resolution (EUR-44)
historical + RCP8.5	historical + RCP8.5 + RCP4.5	historical + RCP8.5 + RCP4.5 + RCP2.6
HIRHAM5 - EC-EARTH	**HIRHAM5** - EC-EARTH	
RACMO22E - EC-EARTH	**RACMO22E** - EC-EARTH	
RACMO22E - HadGEM2-ES	**RACMO22E** - HadGEM2-ES	**RACMO22E** - HadGEM2-ES
RCA4 - CanESM2	**RCA4** - CanESM2	
RCA4 - CNRM-CM5	**RCA4** - CNRM-CM5	
RCA4 - CSIRO-Mk3-6-0	**RCA4** - CSIRO-Mk3-6-0	
RCA4 - EC-EARTH	**RCA4** - EC-EARTH	**RCA4** - EC-EARTH
RCA4 - IPSL-CM5A-MR	**RCA4** - IPSL-CM5A-MR	
RCA4 - MIROC5	**RCA4** - MIROC5	**RCA4** - MIROC5
RCA4 - HadGEM2-ES	**RCA4** - HadGEM2-ES	**RCA4** - HadGEM2-ES
RCA4 - MPI-ESM-LR	**RCA4** - MPI-ESM-LR	**RCA4** - MPI-ESM-LR
RCA4 - NorESM1-M	**RCA4** - NorESM1-M	**RCA4** - NorESM1-M
RCA4 - GFDL-ESM2M	**RCA4** - GFDL-ESM2M	
REMO2009 - MPI-ESM-LR	**REMO2009** - MPI-ESM-LR	**REMO2009** - MPI-ESM-LR
Number of simulations: 14	**Number of simulations: 14**	**Number of simulations: 7**

Extended basic + Radiation + Pressure level	Extended basic + Radiation + Pressure level	Extended basic + Radiation + Pressure level
0.11° horizontal resolution (EUR-11)	0.11° horizontal resolution (EUR-11)	0.11° horizontal resolution (EUR-11)
historical + RCP8.5	historical + RCP8.5 + RCP4.5	historical + RCP8.5 + RCP4.5 + RCP2.6
HIRHAM5 - EC-EARTH	**HIRHAM5** - EC-EARTH	**HIRHAM5** - EC-EARTH
RACMO22E - EC-EARTH	**RACMO22E** - EC-EARTH	
RACMO22E - HadGEM2-ES	**RACMO22E** - HadGEM2-ES	**RACMO22E** - HadGEM2-ES
RCA4 - CNRM-CM5	**RCA4** - CNRM-CM5	
RCA4 - EC-EARTH	**RCA4** - EC-EARTH	**RCA4** - EC-EARTH
RCA4 - IPSL-CM5A-MR	**RCA4** - IPSL-CM5A-MR	
RCA4 - HadGEM2-ES	**RCA4** - HadGEM2-ES	
RCA4 - MPI-ESM-LR	**RCA4** - MPI-ESM-LR	
REMO2009 - MPI-ESM-LR	**REMO2009** - MPI-ESM-LR	**REMO2009** - MPI-ESM-LR
Number of simulations: 9	**Number of simulations: 9**	**Number of simulations: 4**

2.4 Identified gaps

During the evaluation of the CMIP5 and CORDEX datasets, several technical difficulties and gaps were concluded. Many of them are related to the browsing method and the documentation, both having key importance for the users:

- Description of “all replicas” and “all versions” options is missing from the ESGF data search nodes. To find all CMIP5 data, one must tick all replicas and not all versions. Furthermore, even when “all versions” is not selected, more versions are resulted, which can be confusing. Not all experiment types can be chosen in the drop-down list „Experiment” on ESGF search pages (e.g., time-slice experiments can be found among the decadal experiments, since they have no separate category).
- No information is found on the available parallel runs. Not always r1i1p1 is the most commonly used realization through the different scenarios within a single model.
- Selecting the time horizon is missing from the search options. User must dig into metadata information to find out which collection of variables has “followed” the time horizons suggested by the syntax or is available up to 2100 or below/beyond. DKRZ node does not provide this information.
- Starting date of the historical RCM runs is various and runs with HadGEM2-ES LBC go until 2099.
- When one variable is selected, still all variables appear in the output list making it extremely time-consuming to find the desired parameter. Browsing the variables lacks the option selecting multiple variables at the same time. In general, introduction of the AND logical function would be useful within each search category.
- Encoding the meteorological variables is not unified along the whole database, e.g., near-surface relative humidity is abbreviated as ”rhs” in daily data and ”hurs” in monthly and sub-daily data.
- Topographic data (e.g., orography, land-sea mask) is highly desirable to perform further interpolations of the model outputs, so they should be completed.
- The usage of leap years is not common within the global model calendars, complicating the treatments of different global model results.
- Lots of GCMs produce unrealistic relative humidity values, maybe due to the post-processing method employed for the calculation of the relative humidity. Since many users are interested to apply relative humidity instead of specific humidity, a new reliable algorithm should be constructed in CDS.
- The wide applicability of CMIP5 model outputs as boundary forcings for dynamical downscaling is limited due to the lack of model level data. Driving data can be used in those regional climate models which are able to utilize pressure level data instead of model level data.
- Lots of errors were identified and fixed through the CMIP5 website (http://cmip-pcmdi.llnl.gov/cmip5/errata/cmip5errata.html), but some leftovers are still ahead of getting fixed. Last update on errors was in February 2015.
- Some scenarios are inadequately represented within the models, RCP6.0 being the least extensively used scenarios, resulting in a less sound uncertainty estimation of the results. Also RCP2.6 scenario is underrepresented in EURO-CORDEX (due to the limited availability of GCM runs). This forces the users to analyse basically two future pathways (RCP4.5 and RCP8.5).

- No collected information was found on the main differences between different model versions of the same model-family (e.g., CMCC-CESM, CMCC-CM, CMCC-CMS). A short summary with some recommendation describing which version to take for different purposes would be useful.
- Some GCMs are not represented through a single RCM in the EUR-11 simulations, while some could deviate the uncertainty if all results are used in an ensemble and a selection method is not applied before data assessment. EC-EARTH GCM is overrepresented in EUR-11. This could be also a problem for the RCA4 RCM under EUR-44, which is forced by all available global models. Deep assessment is needed regarding independency of the available RCM simulations and every choice has to be done considering the user objective.
- Sub-daily outputs are not stored on ESGF, apart from RCA4 RCM. Access to these data has to be organized bilaterally between data user and the institution performing the simulation.
- Based on a decision made with considerations of storage space, CORDEX atmospheric data are stored on ESGF on 3 pressure levels: 850 hPa, 500 hPa and 200 hPa. For some study this vertical resolution may be coarse. If additional storage capacity could be dedicated to regional climate model outputs in the future, for further downscaling the current roughly 50 daily fields for each model simulations could increase by around 4 (times per day) x 30 (number of model levels) x 4 (at least four variables) times the present amount.
- ALADIN53 RCM output does not contain pressure level variables, while all the other RCMs within EURO-CORDEX have some of them.
- MED-CORDEX data are not stored on ESGF, but in a different database with a very simple browsing possibility. Metadata are sometimes incomplete in this portal.
- Territory of Turkey is located in the vicinity of the border in all the available CORDEX domains. This issue can be handled with definition of a new domain.
- Bias-adjusted data are available only for EURO-CORDEX data on ESGF.

3. Summary

In the data inventory, climate projections of the CMIP5 and CORDEX databases were assessed regarding their spatial and temporal characteristics, their available variables and anthropogenic scenarios, and their feasibility and limitations in different user applications. In CORDEX, these aspects were investigated for EURO-CORDEX simulations in detail, and summarized concisely for MED-CORDEX, MENA-CORDEX, Central Asia CORDEX and Arctic-CORDEX (all covering partly Europe).

Considering the available CMIP5 projection results, our investigation was started with 47 GCMs. Among them, 42 models have simulations until the end of the century and 13 GCMs go beyond 2100 (up to 2300). Four representative RCP scenarios are used in the experiments: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Data are archived with monthly, daily, 6- and 3-hourly frequency. For the ocean, only monthly outputs are available, apart from the daily sea surface temperature, the daily sea ice fraction and the daily sea ice thickness. Sub-daily atmospheric parameters are the near-surface temperature, the wind components, the sea level and surface pressure, the near-surface specific humidity, the precipitation, the pressure level variables and some radiation components. Pressure-level data are important also for dynamical downscaling, nevertheless, they are not always sufficient as driving fields, since some RCMs require the prognostic variables on model levels. Since our last investigation (in April 2017) 6-hourly model level data for temperature, wind components and specific humidity were uploaded to ESGF due to the gap evaluation carried out by different C3S Lots. An 8-member ensemble can be designed from global climate projections with the four RCP scenarios which have daily outputs for any of the selected (surface, pressure-level and radiation) atmospheric variables. Not requiring the RCP6.0 scenario, two GCMs can be added to the selection, resulting in a 10-member ensemble; while focusing only on RCP4.5 and RCP8.5 runs, a further additional model family also steps into the group. In the case of monthly data requests, the ensemble can be further extended. Finally if the spatial resolution is required to be higher than 2 degrees, only 5 GCMs are left: their results are available for all the relevant atmospheric and surface variables on daily scale under each of the 4 representative anthropogenic scenarios.

Considering all the available EURO-CORDEX model results, our investigation was started with 18 and 15 RCM projections on 0.44- and 0.11-degree resolutions, respectively. Among them only the simulations driven by HadGEM2-ES GCM do not reach 2100 (running only until 2099), and none of the experiments goes beyond 2100. RCP6.0 scenario is not used in CORDEX simulations. Data are archived mainly with monthly and daily output frequencies. Daily precipitation sum, daily mean near-surface air temperature, daily minimum and maximum temperature data are available for all simulations. Pressure-level data are stored only on three levels of 850, 500 and 200 hPa. A 7-member ensemble can be designed from climate projections with all the three RCP scenarios which have daily outputs for the surface, pressure-level and radiation variables with 0.44-degree resolution. This ensemble consists of 4 members over the EUR-11 grid. If bias-adjusted data are also requested for daily precipitation and for daily minimum, maximum and mean temperature, the size of ensemble further decreases to 2 members consisting of RACMO22E and RCA4 both driven by HadGEM2-ES on EUR-44, and to 1 member of REMO2009 driven by MPI-ESM-LR on EUR-11. Not requiring the RCP2.6 scenario (nor the bias-adjusted data), 5 and 7 extra RCM simulations are added to the selections, resulting in 14- and 9-member ensembles per RCPs over EUR-44 and EUR-11, respectively.

In EURO-CORDEX, RCA4 is the only regional model coupled to at least 5 GCMs; while among the GCMs, CNRM-CM5, EC-EARTH, MPI-ESM-LR, HadGEM2-ES provide forcings broadly. It has to be noted that from them solely HadGEM2-ES outputs are stored in CMIP5 dataset on the ESGF with sufficient details (daily outputs etc.). It renders, that much more GCM data are available than it was resulted by the browsing the ESGF. All this makes difficult to provide a consistent set of GCM and RCM simulations with detailed data availability based on the existing CMIP5 and CORDEX results. Furthermore, these selections do not represent any qualitative assessment of the model outputs and do not give any information on model skills. Nevertheless, to judge the independency of the simulations in the resulted ensembles, evaluation of the applied RCMs and GCMs as well as of their outputs is needed. In order to improve the homogeneity, a new CORDEX-CORE framework is envisioned to achieve a standard core set of RCMs downscaling a core set of GCMs over most CORDEX domains for a minimum set of (high and low end) scenarios (Gutowski et al., 2016).

4. Outlook

CMIP5 is a finalized dataset, the latest and currently ongoing Coupled Model Intercomparison Project, CMIP6, started the planning phase in 2013. The scope and diversity of topics as well as the data volume involved in CMIPs have grown tremendously in the last 20 years. A thorough investigation at the end of CMIP5 resulted in a structural change of CMIP (Stouffer et al., 2016; Eyring et al., 2016), with three major components:

1. Five common experiments: four Diagnostic, Evaluation and Characterization of Klima (DECK) experiments and a CMIP historical simulation, which can be used to establish model characteristics and serve as an entry card for participating in one of CMIP's phases or in other Model Intercomparison Projects (MIPs, see below) organized between CMIP phases. The 4 baseline experiments include historical atmospheric model simulation, pre-industrial control simulation, simulation forced by an abrupt quadrupling of CO_2 and by a 1% yr^{-1} CO_2 increase.
2. Common standards: alignment of coordination, technical standards, infrastructure, and documentation. A regular benchmarking and evaluation process will provide a standardized comparison of model performance.
3. More autonomy for MIPs: projects can be endorsed by CMIP if they address at least one of the key scientific questions of the CMIP6 or demonstrating connectivity to the DECK experiments and the CMIP6 historic simulation.

CMIP6 scientific achievements are intended to support the IPCC Sixth Assessment Report (AR6) as well as other national and international climate assessments or special reports. The CMIP6 experiments target 7 specific topics through WCRP Grand Science Challenges (GCs):

1. Advancing the understanding of the role of clouds in the general atmospheric circulation and climate sensitivity;
2. Assessing the response of the cryosphere to a warming climate and its global consequences;
3. Understanding the factors that control water availability over land;
4. Assessing climate extremes, what controls them, how they have changed in the past and how they might change in the future;
5. Understanding and predicting regional sea level change and its coastal impacts;
6. Improving near-term climate predictions;
7. Determining how biogeochemical cycles and feedback control greenhouse gas concentrations and climate change.

21 MIPs with varying scientific emphases around the above-mentioned GCs have been endorsed by CMIP6. Four of them are diagnostic and focus on applying output provided by other MIPs, the remaining 17 MIPs proposed 190 experiments. Scenario experiments In CMIP6 are run in ScenarioMIP. Forcings for the future projections are provided by the IAM community spanning the periods 2015–2100 and 2015–2300. 10-30 year forecasts are provided by the decadal climate prediction project (DCPP) with the aim of increasing the skill of the predictions and understanding forced climate change and internal variability of the near future. The data will be freely available after registration through the ESGF using digital object identifiers (DOIs). For the first time in a CMIP phase, a vulnerability, impacts, adaptation and climate services advisory board is included to improve the communication between the climate modelling and the user community (for more information, see Ruane et al., 2016).

Today CORDEX has the status as a major WCRP project: there is no funding directly associated with CORDEX, but currently 17 different institutions or institutional collaboration units have performed CORDEX simulations and provided data to the network. A CORDEX project office at SMHI in Sweden takes care of organizational matters and an international 12-member Scientific Advisory Team (SAT) takes decisions. CORDEX-SAT promotes greater interactions between climate modellers, downscalers and end-users to better support adaptation activities and to better communicate the scientific uncertainty inherent in climate projections and downscaled products. In EURO-CORDEX a guidance (Benestad et al., 2017) has been prepared to provide background information, best practices and links to further information for users of RCM data, mainly for impact researchers, engineers in industry or small and medium enterprises.

The conclusions drawn in the current deliverable reflect the status of the dataset in March 2017, however, CORDEX archive is continuously extended with new model simulations. The first EURO-CORDEX ensemble will receive a “snapshot date” (1 July, 2017) soon: the simulations available in the ESGF until this date can be cited via a DOI number (simulations added to the ESGF after the snapshot date need to be mentioned separately) in publications.

In the recent CORDEX 2 framework, focus has shifted towards more science-based questions. At the same time, it was recognised that addressing these scientific challenges might be problematic within the general CORDEX framework that employs standard sets of simulations for large domains. Thus more targeted experimental setups, called “Flagship Pilot Studies” (FPS) have been developed. The FPSs are focusing on sub-continental-scale target regions, so as to allow a number of capabilities towards addressing key scientific questions motivated by several issues:

- Run RCMs at a broad range of resolutions, down to convection-permitting;
- Promote side-by-side experimental design and evaluations of both statistical and dynamical downscaling techniques at scales more typical of VIA (vulnerability, impacts, adaptation) applications;
- Design targeted experiments aimed at investigating specific regional processes and circulations;
- Investigate the importance of regional scale forcings (aerosols, land-use change, vegetation etc.);
- Compile and use high quality, high spatial and temporal resolution, multi-variable observation datasets for model validation and analysis of processes;
- Coordinate with specific activities in other WCRP projects, most notably the GEWEX (Global Energy and Water cycle Exchanges) regional hydroclimate projects;
- Design end-to-end, climate-to-end-user, projects demonstrating the actionable value of downscaled climate change projections;
- Increase the potential for funding by focusing on specific issues of interest for a certain region.

Focusing on the European territory, four flagship pilot studies are endorsed (more information is available at https://www.cordex.org/cordexnews/276-fps-2.html):

1. Convective phenomena at high resolution over Europe and the Mediterranean: Convective extreme events are a priority under the WCRP Grand Challenge on climate extremes, because they carry both society-relevant and scientific challenges that can be tackled in the coming years. In the FPS present and future convective extremes and their processes will be investigated with models at convection-permitting resolutions over selected sub-regions of

Europe and the Mediterranean. Advanced statistical techniques will also be employed in parallel to evaluate the performance of dynamical models. The added value of fine scale representation of convection will be rigorously evaluated with respect to both coarser resolution simulations up to GCM scales and VIA applications. The availability of observational datasets at very high resolutions in both space and time allows unprecedented evaluation opportunities. The FPS mobilizes the EURO- and MED-CORDEX communities and is also open to new partners who bring fresh perspectives and expertise to bear on issues surrounding convective phenomena.

2. Impact of land use changes on climate in Europe across spatial and temporal scales: The LUCAS (Land Use & Climate Across Scales) FPS for Europe is supported by WCRP CORDEX and the GEWEX-GLASS (Global Land/Atmosphere System Study) international programs. The spatial fragmentation of land use dynamics in Europe requires fine-scale modelling techniques, and their biophysical impacts on climate are often dominant on local to regional scales. Overall objective is to identify robust biophysical impacts of land use changes (LUC) in Europe on climate across regional to local spatial scales and at various time scales from extreme events to multi-decadal. Coordinated RCM ensemble LUC experiments will be carried out on high spatial resolutions based on consistent land use dynamics for the past and the future. A new generation of RCMs will be included, which couple regional atmosphere interactively with terrestrial biosphere and hydrosphere. The multi-model experiments shall be conducted over multiple gridded nests to refine the continental simulations down to resolutions below 5 km. Pilot regions are chosen to evaluate the validity of coupled atmosphere-land simulations and to better resolve the heterogeneity of land use changes in Europe and its local impacts on climate. Essential variables and fine-scale processes will be evaluated against multi-variable observations from flux towers, satellite sensors and new airborne and spaceborn radar techniques. The FPS aims at building further collaborations with modelling activities over other CORDEX regions towards coordinated LUC experiments over multiple world regions.

3. Role of the natural and anthropogenic aerosols in the Mediterranean region: past climate variability and future climate sensitivity: Aerosols strongly affect the Mediterranean basin located at the crossroads of air masses carrying both natural and anthropogenic particles. They have strong effects on the regional climate fluctuations from daily to multi-decadal scales and also represent one of the main sources of uncertainty in future climate change projections at global and regional scales. Aerosols show high spatio-temporal variability and are influenced by numerous fine-scale processes. The FPS will use high-resolution RCMs to better understand solar radiation variability and future changes. Besides, this FPS will contribute to several WCRP Grand Challenges, to the CORDEX Challenge about the coupled regional climate models and to the climate modelling activities of the Mediterranean regional programmes of GEWEX (HyMeX; Hydrological Cycle in the Mediterranean Experiment) and CLIVAR (MedCLIVAR; Mediterranean Climate Variability and Predictability).

4. Role of the air-sea coupling and small scale ocean processes on regional climate: The mechanisms modifying the regional climate through air-sea coupling will be investigated in this FPS, with special emphasis on the role of small scale ocean processes and waves. The FPS is a natural continuation of the activities of MED-CORDEX, HyMeX and MedCLIVAR. The selected region is the area surrounding the Mediterranean Sea, which is often referred to as an ocean in miniature due to the strong air-sea interactions, active mesoscale and sub-

mesoscale dynamics and a permanent thermohaline overturning circulation. Moreover, this area is one of the best observed regions in the world. A detailed analysis of how air-sea coupling at high resolution can modify the regional climate, and consequently the global climate. The FPS intends to run high resolution coupled regional atmosphere-ocean model simulations over the region to provide an added value to RCMs in both present climate and future scenarios, and to understand the underlying mechanisms. This FPS will moreover provide to the broad community focusing on the impacts of climate change on marine environments (e.g., marine ecosystems, fisheries, coastal infrastructures) a database of regional ocean and atmosphere projections.

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