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# Abstract

Obtaining a quick and accurate overview of climate model data is often complicated or time-consuming due to the large amount and complex structure of the data. This is particularly true for international collections of multi-model ensemble data sets containing contributions from many different modelling centers. Incomplete data sets, the use of non-standard units or missing files can complicate data analysis significantly. Additionally, some climate models simulate the regional climate poorly or have strong systematic biases, which is why future simulations of these models should be used cautiously. Especially in complex calculations, such model properties can be overseen, despite the influence on the results and on their interpretation.

Here, we present a Model Diagnostic Suite analyzing such properties of the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model ensemble climate simulations for the current climate and the 21$^{st}$ century. With the aid of the Model Diagnostic Suite different variables, regions, scenarios, time periods, etc. can be presented easily in various plot types. Plots can be generated for individual models and simple model combinations. In this report, the focus of the analysis is on Europe and in particular the Alpine region. The main parameters chosen are temperature and precipitation. This set of tools has been proven to be valuable for the quality control of climate model data. The tool was designed to be run semi-automatic and offers the possibility to include more models, variables or choosing different regions and their size. Furthermore, it can already be used for other projects such as ENSEMBLES and PRUDENCE (prediction of regional scenarios and uncertainties for defining european climate change risks and effects) and it can be easily extended to any other multi-model ensemble project.

The full currently available CMIP5 data set was analyzed for a variety of criteria. Some of the findings are summarized in this report. It is found that, in general, the models simulate the climate of Europe realistically and have a similar climate change signal. However, some models exhibit substantially different behavior, such as strong biases and different projections into the future. For the Alpine region, the results are ambiguous. It is evident, that several models are not capable to simulate a signal over the Alpine ridge. This could be due to a coarse resolution and unrealistic model topography. Next steps are to include additional observational data sets and more climate model data sets, such as EU-Coordinated Regional climate Downscaling Experiments (EURO-CORDEX) and CMIP5 decadal runs in the Model Diagnostic Suite and to expand the set of tools.

# Zusammenfassung

Eine schnelle und genaue Übersicht über Klimamodelldaten zu erlangen ist oftmals kompliziert oder zeitaufwendig aufgrund der großen Datenmenge und komplexen Struktur der Daten. Das gilt insbesondere für internationale Zusammenstellungen von multi-Modell Ensemble Datensätzen mit Beiträgen aus vielen verschiedenen Modellierungszentren. Unvollständige Datensätze, das Verwenden von nicht-Standardeinheiten oder fehlende Dateien können eine Datenanalyse erheblich erschweren. Hinzu kommt, dass manche Klimamodelle es nur bedingt schaffen, regionales Klima zu simulieren oder starke systematische Fehler haben, weswegen zukünftige Simulationen dieser Modelle nur vorsichtig verwendet werden sollten. Gerade in komplizierte Berechnungen können diese Modelleigenschaften übersehen werden, trotz ihres Einflusses auf Resultate und deren Interpretation.

Hier wird die „Model Diagnostic Suite“ vorgestellt, welche eben jene Modelleigenschaften von Coupled Model Intercomparison Project phase 5 (CMIP5) multi-Modell Ensemble Klimasimulationen des 20. und 21. Jahrhunderts untersucht. Mithilfe der „Model Diagnostic Suite“ können Variablen, Regionen, Szenarien, Zeitperioden, etc. in unterschiedlichen Figuren dargestellt werden. Figuren können für individuelle Modelle, aber auch einfache Modellkombinationen generiert werden. In diesem Bericht liegt der Fokus der Analyse auf Europa und insbesondere dem Alpenraum. Die ausgewählten Hauptparameter sind Temperatur und Niederschlag. Das Toolset hat sich für die Qualitätskontrolle von Klimamodelldaten als ausgesprochen wertvoll erwiesen. Das Tool wurde entwickelt, um halbautomatisch betrieben zu werden und bietet die Möglichkeit, weitere Modelle und Variablen zu integrieren oder andere Regionen und deren Größe auszuwählen. Darüber hinaus kann es bereits für andere Projekte wie ENSEMBLES und PRUDENCE (prediction of regional scenarios and uncertainties for defining european climate change risks and effects) verwendet und problemlos um weitere multi-Modell Ensemble Projekte erweitert werden.

Der vollständige, derzeit vorhandene CMIP5 Datensatz wurde hinsichtlich einer Vielzahl von Kriterien untersucht. Einige der Ergebnisse sind in diesem Bericht zusammengefasst. Generell simulieren die Modelle ein realistisches Klima über Europa und haben ein ähnliches Klimaänderungssignal. Manche Modelle jedoch zeigen ein maßgeblich anderes Verhalten, wie beispielsweise einen starken Bias und unterschiedliche Projektionen in die Zukunft. Für die Alpenregion sind die Resultate nicht eindeutig. Es ist offensichtlich, dass einige Modelle nicht in der Lage sind, ein Signal über dem Alpenkamm zu simulieren. Diese könnte an einer groben Auflösung oder einer unrealistischen Modelltopographie liegen. Die nächsten Schritte bestehen darin, zusätzliche Beobachtungsdatensätze und Klimamodelldatensätze wieEU-Coordinated Regional climate Downscaling Experiments (EURO-CORDEX) und dekadische CMIP5 Simulationsläufe zu integrieren sowie das Toolset allgemein zu erweitern.

# Contents

# 1 Introduction

The analysis of large climate model data sets can be time consuming and may require high computing power. Simple diagrams of the major variables often provide initial information on the structure, properties and characteristics of the climate data. In case of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) data framework, visualization tools exist online to illustrate the data (e.g. CMIP5 Global Climate Change Viewer[1]). Although many research groups have analyzed and corrected these data sets, there are still models that have data gaps in their time series, have incorrect labels of variables or use non-standard units. Partly these inconsistencies may occur due to or during the data transfer process. If the data is to serve as a basis for a more complex analysis, such information can be important.

The aim of this internship at MeteoSwiss was to implement a Model Diagnostic Suite, which automatically creates plots of large climate data sets. This offers the possibility that the user can easily visually inspect climate projections of different variables, emission scenarios and time periods. Different maps, time series and scatterplots of CMIP5, ENSEMBLES-GCMs and later, if available, EU-Coordinated Regional climate Downscaling Experiment (EURO-CORDEX) data sets are analyzed. The data will be used in the COST ELAPSE (Enhancing local and regional climate change projections for Switzerland) project, in which nested limited-area regional climate models (RCMs) will be compared to their driving general circulation models (GCMs). An unrealistic simulation of present-day climate can be easily detected by the Model Diagnostic Suite, as it allows to visualize the climate model data in comparison to observational data sets. It additionally allows to re-visit the underlying raw model data. For a user, the tool is also very helpful in terms of pattern recognition, in particular for climate change patterns. The functioning of the tools and the results of this analysis are presented in this technical report.

The focus of this report is on the CMIP5 data set, which is the basis of the IPCC Fifth Assessment Report. The report is structured as follows: in Chapter 2 the used data sets and programming tools used to set up the Model Diagnostic Suite are shortly presented. The third Chapter describes the functioning of the Model Diagnostic Suite and provides sample plots for the different plot types. In Chapter 4 found inconsistencies of the CMIP5 data set is discussed as well as particularly striking models. The summary is given in Chapter 5.

[1] http://regclim.coas.oregonstate.edu/gccv/index.html

# 2 Data and tools

## 2.1 Climate model datasets

### 2.1.1 CMIP5

In 2008 the Working Group on Coupled Modelling (WGCM) of the World Climate Research Programme (WRCP) has launched a project, the fifth phase of the Coupled Model Intercomparison Project (CMIP5[2]), to organize a coordinated set of experiments with climate and Earth system models. This new set of climate model experiments performed by several institutions provide a framework to research the characteristics of climate change. CMIP5 experiments aim to evaluate how realistic the models simulate the recent past, provide projections of near term and long term future climate and understand differences in model projections, especially feedbacks involving clouds and the carbon cycle (Taylor et al., 2009).

The CMIP5 long term experiments include a coupled control run, one 20$^{th}$ century experiment with all forcings (historical run) and different emission and mitigation scenarios, in which a representative concentration pathway leads to different approximate radiative forcing at the end of the 21$^{th}$ century (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). Some institutes provide historical simulations with natural forcings only (historicalNat run). Ensemble members of each model are distinguished by the realization number “n”, an initialization method indicator “m” and a perturbed physics number “p”. The realization number is used to describe a set of runs with different, but equally realistic, initial conditions. If forecasts are initialized from observations using different methods or observational datasets, the initialization method indicator is used (more likely for decadal experiments). Some models have closely related model versions and are referred to as a perturbed physics ensembles, which are numbered by the perturbed physics number. Time-independent variables do not differ across ensemble members and therefore all three numbers are zero (Taylor et al., 2012).

### 2.1.2 ENSEMBLES GCMs

The ENSEMBLES[3] project supported by the European Commission’s 6th Framework Programme is a EU-financed project in regional climate-modeling and ended in 2009. GCMs under historic and scenario forcing are run by the following European climate modeling centers: IPSL, CNRM, MPI, BCCR, UKMO, FUB, DMI. The aims of the ENSEMBLES project are (van der Linden and Mitchell, 2009):

– “to develop an ensemble prediction system for climate change based on the principal state-of-the-art, high-resolution, global and regional Earth system models developed in Europe, validated against quality-controlled, high-resolution gridded datasets for Europe, to produce for the first time an objective probabilistic estimate of uncertainty in future climate at the seasonal to decadal and longer time-scales;

[2] http://cmip-pcmdi.llnl.gov/cmip5/

[3] http://ensemblesrt3.dmi.dk/

- to quantify and reduce the uncertainty in the representation of physical, chemical, biological and human-related feedbacks in the Earth system (including water-resource, land-use and air-quality issues, and carbon cycle feedbacks);
- to maximize the exploitation of the results by linking the outputs of the ensemble prediction system to a range of applications, including agriculture, health, food security, energy, water resources, insurance and weather risk management."

For the generation of the multi-model ensemble seven atmosphere-ocean general circulation models (AOGCMs, Table 7 in the Appendix) with a variety of structural differences amongst each other are used within the ENSEMBLES project. Corresponding pre-industrial equilibrium runs provide the initial conditions for the 20$^{th}$ century simulations. In the 21$^{st}$ century, the simulations are forced only with greenhouse gases, while volcanic and solar forcing is constant at the historic level used for the 20$^{th}$ century projections. Multi-model ensemble emission scenarios are provided by all modeling institutes for the A1B scenario, some also produced simulations for the A2 and B1 scenario. The simulation output is spatially interpolated to a common, regular grid with a resolution of 2.5°x2.5° by a conservative mapping (Niehörster et al., 2008).

### 2.1.3 EURO-CORDEX

The EU-Coordinated Regional climate Downscaling Experiment (EURO-CORDEX[4]) project is the successor of the ENSEMBLES project sponsored by the WRCP. Its purpose is to evaluate model performance and produce climate projections for use in impact and adaptation studies. Regional-to-local scale climate change information is needed to evaluate effects of complex topography and land-surface characteristics. EURO-CORDEX will provide a framework of ensemble climate simulations based on multiple dynamical and empirical-statistical downscaling models forced by multiple global climate models from CMIP5 (Giorgi et al., 2009).

For the European domain, regional climate model simulations are conducted at two different spatial resolutions: 0.44° and 0.11° forced by different global climate models and emission pathways (rcp26, rcp45, rcp85). The data will be made available soon. First results have already been published (e.g. Jacob et al., 2013).

## 2.2 Observational and reanalysis datasets

In order to give an estimate of the model bias in present-day climate, three different observational and reanalysis datasets are used in the Model Diagnostic Suite:

- The E-OBS[5] dataset is a European land-only daily gridded observational dataset for precipitation and minimum, maximum, and mean surface temperature provided by the EU-FP6 project ENSEMBLES (version 8.0) and the data providers in the ECA&D project[6]. The covered area is 25°N-75°N and 40°W-75°E (Haylock et al., 2008).

[4] http://www.euro-cordex.net/

[5] http://www.ecad.eu/download/ensembles/download.php

[6] http://www.ecad.eu

- ERA-Interim is a reanalysis from 1979 onwards produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and continues to be extended. ERA-Interim has a spectral T255 horizontal resolution (approximately 79 km spacing on a reduced Gaussian grid) and uses a 30 min time step. For comparison, ERA-40 has a T159 horizontal resolution (~125 km spacing). This new atmospheric reanalysis replaced the ERA-40 and provides gridded data products for surface parameters, upper-air parameters and atmospheric fluxes (Dee et al., 2011). ECMWF ERA-Interim data used in this project have been obtained from the ECMWF data server[7].
- CRU[8] is a high-resolution gridded (0.5°x0.5°) climate datasets dataset from the Climate Research Unit (version CRU TS3.00 and CRU TS3.10) based on an archive of monthly mean temperatures provided by more than 4000 weather stations distributed around the world from 1901-2012 (Harris et al., 2013).

## 2.3 Tools

A combination of various tools and programming languages was used to build up the Model Diagnostic Suite such as C-Shell scripts, CDO and NCO, R and NCL, which are shortly presented in the next sections.

### 2.3.1 C-Shell

The C Shell oriented to a C-like syntax is a UNIX shell command execution program, which interprets commands line by line. C-shell[9] scripting is a timesaving tool for performing repetitive jobs. Scripts are text files containing a set of shell commands and constructs that perform a routine task, which can include UNIX commands. In the processing of the input external programs are started, if necessary (Currie, 2006).

### 2.3.2 CDO

The Climate Data Operators (CDO[10]) software was developed at the MPI in Hamburg and provides more than 400 operators for climate data processing on a UNIX command line interface. Supported data formats are GRIB and NetCDF as well as SERVICE, EXTRA and IEG, which are supported on various grid types. CDO can be used for statistical and arithmetic calculations, data selection, tool sampling or spatial interpolation (Schulzweida, 2013).

### 2.3.3 NCO

NCO[11] stands for NetCDF Operators and is a suite of operators, which was developed at NCAR. It is a command line program, which is executed at the shell-level to operate on NetCDF files to analyze

[7] http://data-portal.ecmwf.int/data/d/interim_daily/

[8] http://www.cru.uea.ac.uk/cru/data/hrg/

[9] http://www.starlink.rl.ac.uk/docs/sc4.htx/sc4.html

[10] https://code.zmaw.de/projects/cdo

[11] http://nco.sourceforge.net/

and manipulate data sets. Input and output are NetCDF files (Zender, 2013). In the Model Diagnostic Suite NCO is used rarely and only if no according CDO commands were available.

### 2.3.4 R

R[12] is an open source software for data manipulation, calculation and graphical display. The R environment includes data handling and storing facilities, tools for data analysis, a suite of operators and graphical facilities. The R Suite of implemented commands can be extended by a variety of packages, which can be found on their website[13] (Venables, Smith, and the R Core Team, 2013).

### 2.3.5 NCL

NCAR Command Language (NCL[14]), created by the Computational & Information Systems Laboratory at the National Center for Atmospheric Research (NCAR) and sponsored by the National Science Foundation, is a complete programming language. Its purpose is to visualize and analyze scientific data. It can read and write NetCDF-3, NetCDF-4 classic, NetCDF-4, HDF4, binary, and ASCII data; furthermore it also handles HDF-EOS2, HDF-EOS5, GRIB1, GRIB2, and OGR files (shapefiles, MapInfo, GMT, Tiger). NCL “is meant to provide an integrated environment where data can be selected, manipulated, and visualized interactively without requiring compilation” (NCAR, 2013). Apart from other languages, NCL has special features, which allow users to manipulate metadata, configure output graphics, import a variety of data formats or use algebra that supports array operations (NCAR, 2013).

[12] http://www.r-project.org/

[13] http://CRAN.R-project.org

[14] http://www.ncl.ucar.edu/

# 3 Product catalogue of the Model Diagnostic Suite

In this chapter the Model Diagnostic Suite is presented as well as selected products. Several tools to analyze and visualize large climate model data sets are combined to a Model Diagnostic Suite. This toolbox enables the user to download and update NetCDF data and generate a series of plot types by submitting configuration-files several times with different settings. The Model Diagnostic Suite is designed such that the user has the possibility to extend the Suite without difficulties. The operation and the use of the Model Diagnostic Suite is presented in detail in the Appendix.

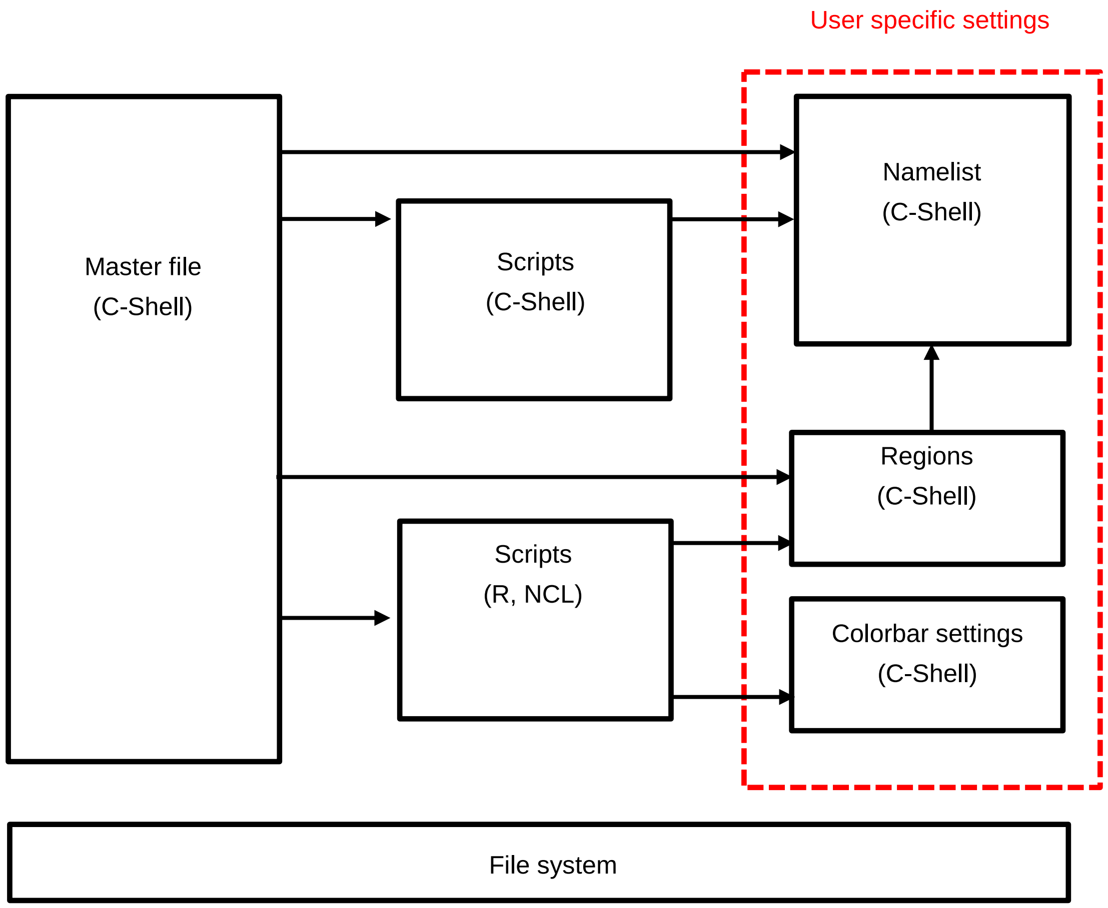



**Figure 1:** Schematic of the Model Diagnostic Suite. Dashed-red line indicates settings, which can be adjusted by the user.

The operation process of the Model Diagnostic Suite is roughly illustrated in Figure 1. All configurations are handled in one C-Shell script, which controls the other scripts. This master file sources the information given in the namelist file and transfers the settings to C-Shell scripts. These scripts execute CDO and NCO commands to prepare the raw data accordingly. Then R and NCL scripts create plots based on the arranged netCDF files. As far as possible, meta-data information is retrieved from the original files. The plots are saved in a file system. An overview over the number of files, their size and number of code lines as well as a number and size of produced plots is given in Table 5 in the Appendix.

This configuration requires only adjustments in the namelist file, while all other scripts remain unchanged. All possible settings are listed and shortly described in Table 1. The detailed description of all options and the explanation of their use can be found in the Appendix. Adjustments in the regions file and the colorbar settings are possible but not necessary. In the regions file different regions are predefined such as greater Europe, the PRUDENCE regions as shown in Figure 2 and Switzerland. To illustrate the plots that can be produced with the Model Diagnostic Suite, selected plots with different settings are presented in the next sections.

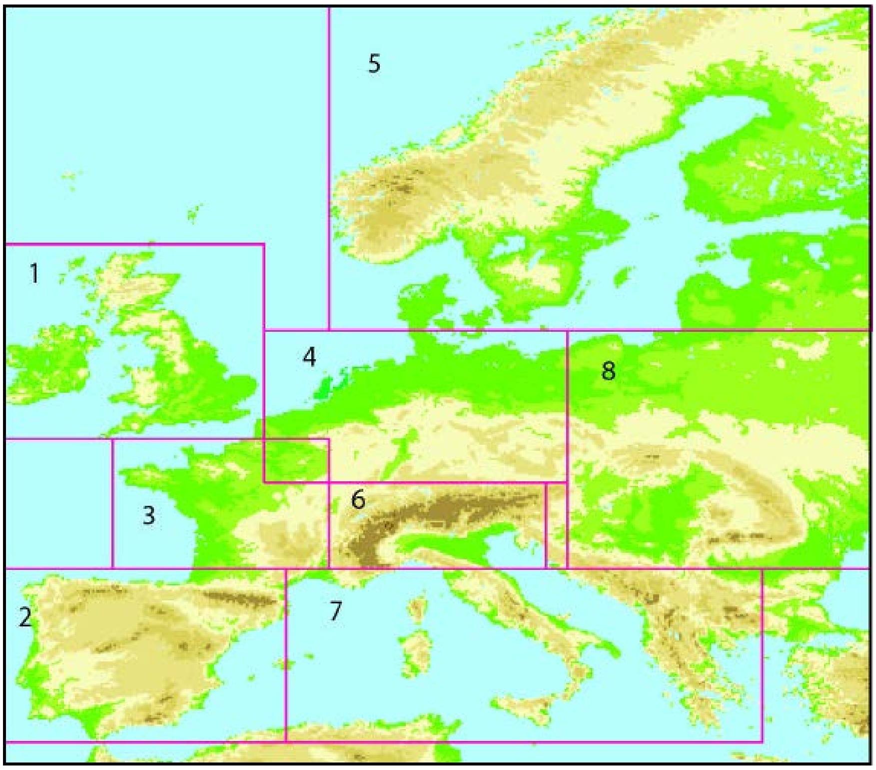



**Figure 2:** Predefined PRUDENCE regions: British Isles (1), Iberian Peninsula (2), France (3), Mid-Europe (4), Scandinavia (5), Alps (6), Mediterraneum (7) and Eastern Europe (8) (Christensen and Christensen, 2007).

**Table 1:** Settings in NAMELIST.sh

| Name | Options | Remarks |
|---|---|---|
| project | CMIP5, ENSEMBLES (GCMs) | sets path for the data |
| outpath | …/… | sets path for plots |
| workpath | …/Diagnostic_Suite | path of diagnostic suite |
| save_netcdfs | True or False | option to save NetCDFs |
| execute_ncl | True or False | option to plot maps |
| execute_R | True or False | option to plot time series or box plots |
| savepath | …/… | sets path where NetCDFs should be saved |
| maps | BIAS-ERA, BIAS-CRU, BIAS-EOBS DELTA, ABS | NCL; multiple choices possible |
| time series | TIME.ABS, TIME.DELTA, TIME.DETREND, TIME.STD ATTRIBUTION | R; multiple choices possible |
| scatter plots | SCATTER | R; multiple choices possible |
| singular | True or False | |
| overview | True or False | |
| multimodel | True or False | |
| plotformat | eps, ps, pdf,… | pdf recommended as standard format for ModelBrowser |
| startperiod | 1950-2099 | start year future period |
| endperiod | 1950-2099 | end year future period |
| startrefperiod | 1950-2099 | start year reference period |
| endrefperiod | 1950-2099 | end year reference period |
| length | 0- (only for time series) | length of running mean period, if 0 annual mean is plotted |
| granularity | annual or seasonal | |
| timeframe | DJF, MAM, JJA, SON | multiple choices possible |
| frequency | Amon, day | |
| variable | tas, pr, tasmin, tasmax huss, rsds, zg, clt | multiple choices possible |
| experiment | rcp26, rcp45, rcp60, rcp85 (CMIP5) A1B (ENSEMBLES) | multiple choices possible |
| change | absolute or relative | |
| area | EU, prudence regions (BI, IP, FR, ME, SC, AL, MD, EA), US (user specific, default : Switzerland) | set in regions |
| location | True or False (for R scripts) | set in regions; single grid point plotted |
| landmask | True or False | sets ocean points to missing value |
| remap | remapbil, remapnn,… | cdo command |

## 3.1 TIME.ABS

The first plot is a time series created in R showing the development of absolute values of a selected variable over time. The area-weighted mean is plotted as default in all R plots of this kind. An option is implemented to choose the area mean over land grid points only excluding oceanic grid points. Note that, due to the various grid-size configurations in the models, an area-mean does not necessarily consist of the same number of grid-points within a certain area. By default, plots are created for each individual model, with all ensemble members in one plot (called singular plot). It is also possible to display the mean over all models as well as the 5 and 95 % quantiles across the set of models (called overview plot). If a model has more than one ensemble member, the mean over all ensemble members is used for the quantile calculation. This approach is mathematically imprecise, but was chosen in the early stages of programming the Model Diagnostic Suite to maintain a clear overview. However, in later versions no ensemble means are shown, but single ensemble members. The intercepts are automatically set to the lowest and highest value of all model time series, however, the distance between two axis entries can be set manually.

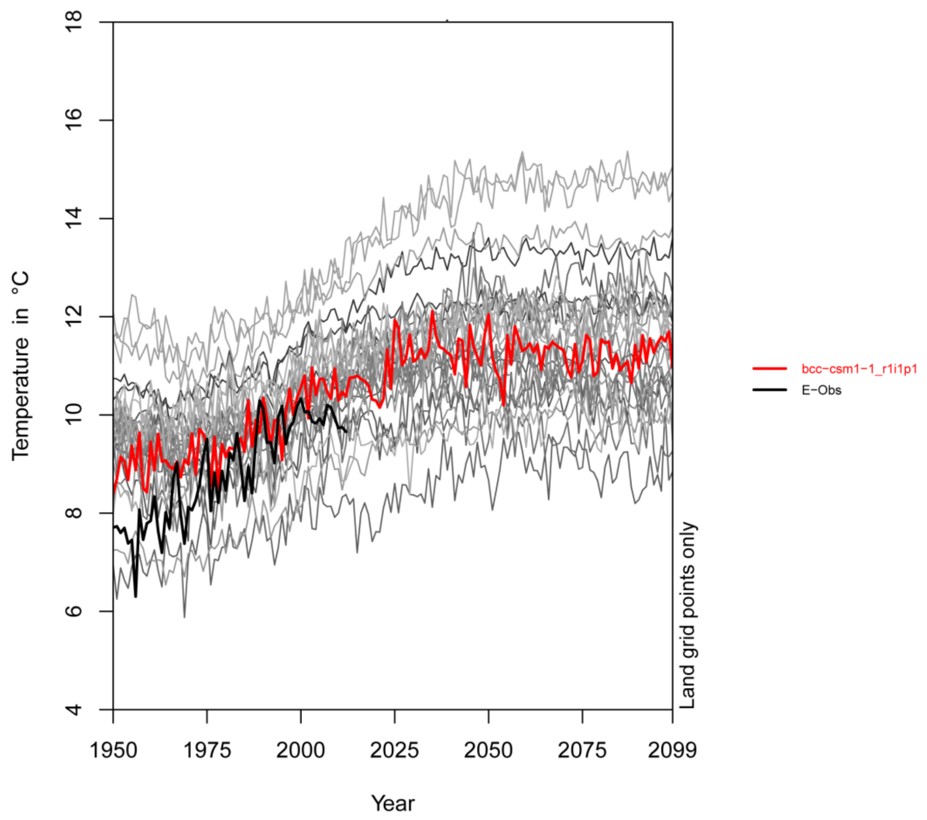



**Figure 3:** Annual surface temperature in °C over 1950-2099 for CMIP5 models (grey solid lines) for Europe in RCP2.6. bcc-csm1-1, r1i1p1 data over 1950-2099 (red solid line) indicated. E-OBS data over 1950-2012 (black solid line) indicated. Settings in namelist: TIME.ABS, singular, annual, Europe, landmask=True.

Figure 3 shows the annual mean temperature averaged over Europe in the RCP2.6 scenario over 1950-2099 for bcc-csm1-1, r1i1p1. The model is highlighted in red while all other models of the

RCP2.6 scenario are colored in grey. Additionally, observational data (E-OBS) is highlighted in black for a comparison. Note that E-OBS data is a land based data set and therefore cannot be compared to a model area weighted mean that includes oceanic grid points. Therefore, E-OBS will only be plotted if oceanic grid points are excluded. Otherwise ERA-Interim is used as a reference, which is also used in cases where a variable is not available in E-OBS (e.g. cloud cover or geopotential height at 500 hPa).

## 3.2 TIME.DELTA

Figure 4 shows how the signal of change of a variable develops over time with respect to a chosen reference period. Signals of change can either be in absolute or relative terms. Both, annual and seasonal averages can be plotted based on the tool. Similar to Figure 3, one model is highlighted and all other models of the scenario are colored grey in the background. If a model has more than one ensemble member, all members of the ensemble and their ensemble mean are plotted (again, in later versions only single ensemble members are shown). For example, Figure 4 shows the summer temperature change over 1950-2099 with respect to the reference period 1980-2009 for three ensemble members and their mean for Scandinavia. The initial and final year of the reference period can be chosen by the user.

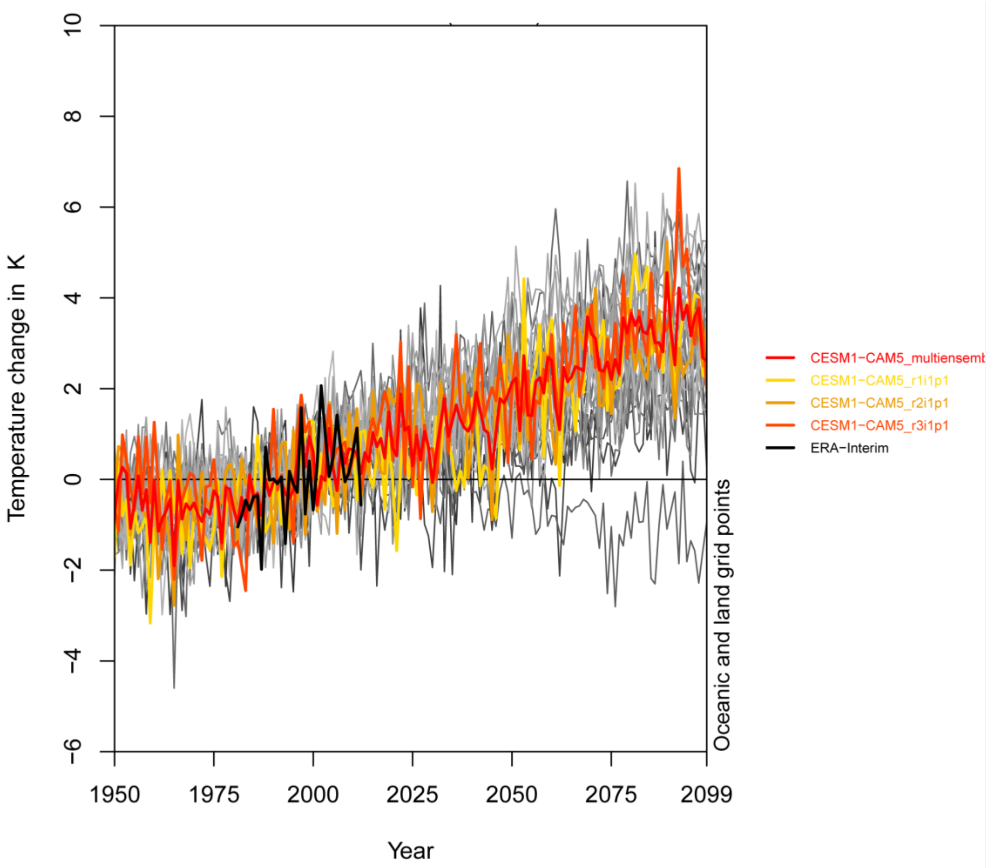
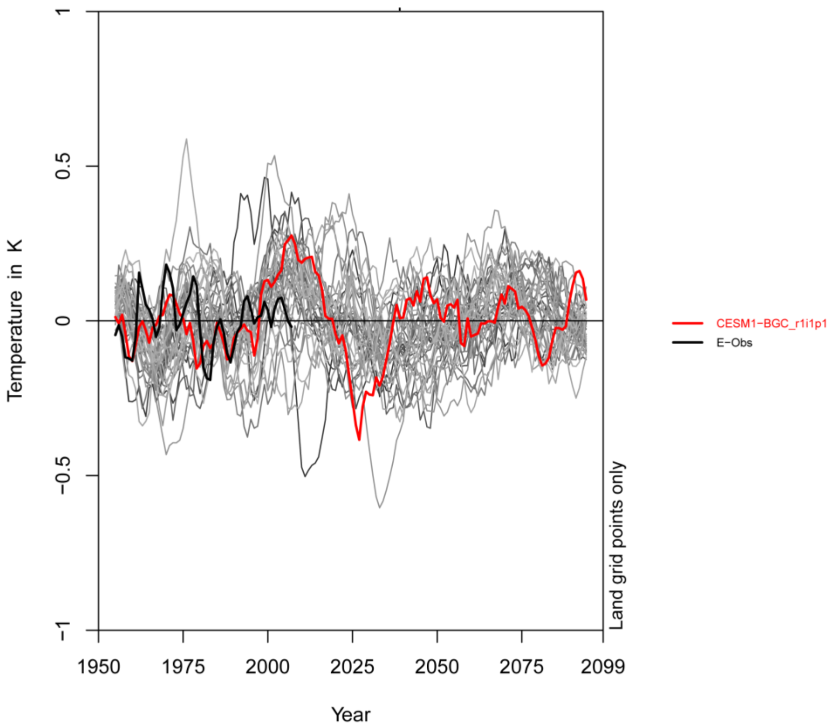



**Figure 4:** Summer (JJA) surface temperature change in K over 1950-2099 with respect to reference period 1980-2009 for CMIP5 models (grey solid lines) for Scandinavia in RCP6.0. CESM1-CAM5, r1i1p1 (yellow), r2i1p1 (light orange), r3i1p1 (dark orange) and ensemble mean (red solid line) over 1950-2099 indicated. ERA-Interim data over 1981-2012 (black solid line) indicated. Settings in namelist: TIME.DELTA, singular, seasonal, JJA, Scandinavia, landmask=False.

## 3.3 TIME.DETREND and TIME.STD

The time series can be detrended using a fourth-order polynomial fit. In order to smooth the curves, the 10-year running mean of the detrended time series is displayed in Figure 5, top panel. All the time series created in R can either be plotted as annual or seasonal means but also as moving averages. In the latter case, the length of the running time-period can be chosen. The same can also be done for plotting the standard deviation of the detrended time series (see Figure 5, bottom panel). For comparison with observational data, the observation data set is shown in both plots. All plot features are similar to the plots shown before. For both plot types no overview plots can be created.



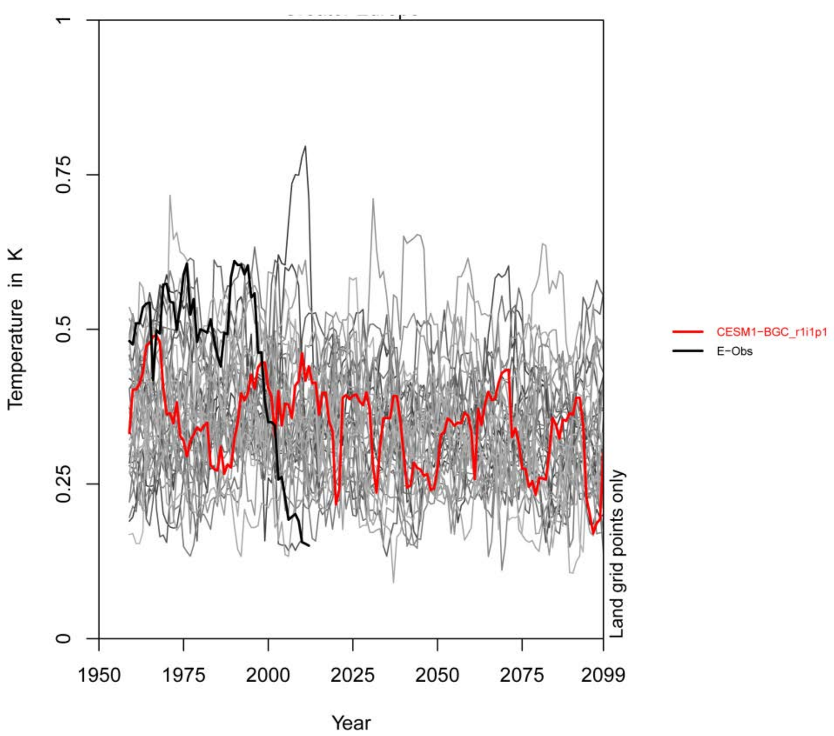




**Figure 5:** Detrended time series (top) and standard deviation of detrended time series (bottom) of a 10-year running mean of surface temperature in K over 1950-2099 for CMIP5 models (grey solid lines) for Europe in RCP8.5. CESM1-BGC, r1i1p1 data over 1950-2099 (red solid line) indicated. E-OBS data over 1950-2012 (black solid line) indicated. Settings in namelist: (top) TIME.DETREND, (bottom) TIME.STD, singular, annual, length=10.

## 3.4 SCATTER

Although the plot is not a true scatter plot, it is useful to assemble information from multiple sources into one graphic. The signal of change for all seasons and all models of a scenario are shown for three time periods (2020-2049, 2045-2074 and 2070-2099). Again, as shown in Figure 6, one model is highlighted in red, while the median of all models is shown in orange. The models evaluated at different time periods are colored with a different grey-shading. At the moment, no annual or overview plots can be created. If the time periods are to be changed, this must be done manually in the appropriate R file. All other features are similar to the features described for the plots previously.

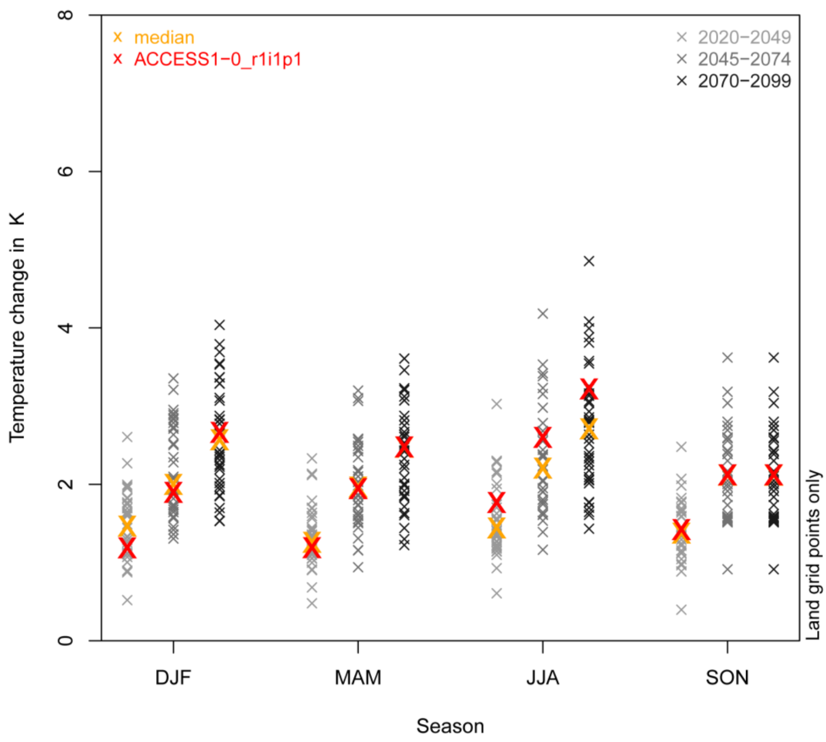



**Figure 6:** Annual surface temperature change in K averaged over 2020-2049 (light grey crosses), 2045-2074 (grey crosses) and 2070-2099 (dark grey crosses) for CMIP5 models for Europe in RCP4.5. Median over CMIP5 models indicated with orange crosses and ACCESS1-0, r1i1p1 with red crosses for all three projection periods. Settings in namelist: SCATTER, singular, annual.

## 3.5 ATTRIBUTION

For the CMIP5 data, in addition to the scenario-runs, two historical datasets over 1900-2005 are available for several models: one with natural forcing only, the other additionally with anthropogenic forcing included. The here-called attribution plots show the historical temperature curve over 1900-2004 for both forcings. The reference for the anthopogenic forced simulation and the E-OBS data is the historical scenario with only natural forcings averaged over 1950-1979. The average over all models is highlighted in red or blue. The shaded areas indicate the 5 and 95% quantiles across the set of available models. The observations from 1950-2004 over the area are plotted in black. For these type of plots only the land area is considered in order to compare with the observations. As the historical data sets do not depend on the scenario, RCP4.5 is arbitrarily chosen and the plots saved in the according directory. Of course, in this time period no scenarios are needed, but the number of models is largest for RCP4.5. No singular plots (showing a selected model) can be created for this figure type. Figure 7 is an example and shows the 10-year running mean temperature for natural forcing, anthropogenic forcing and E-OBS averaged over Europe.

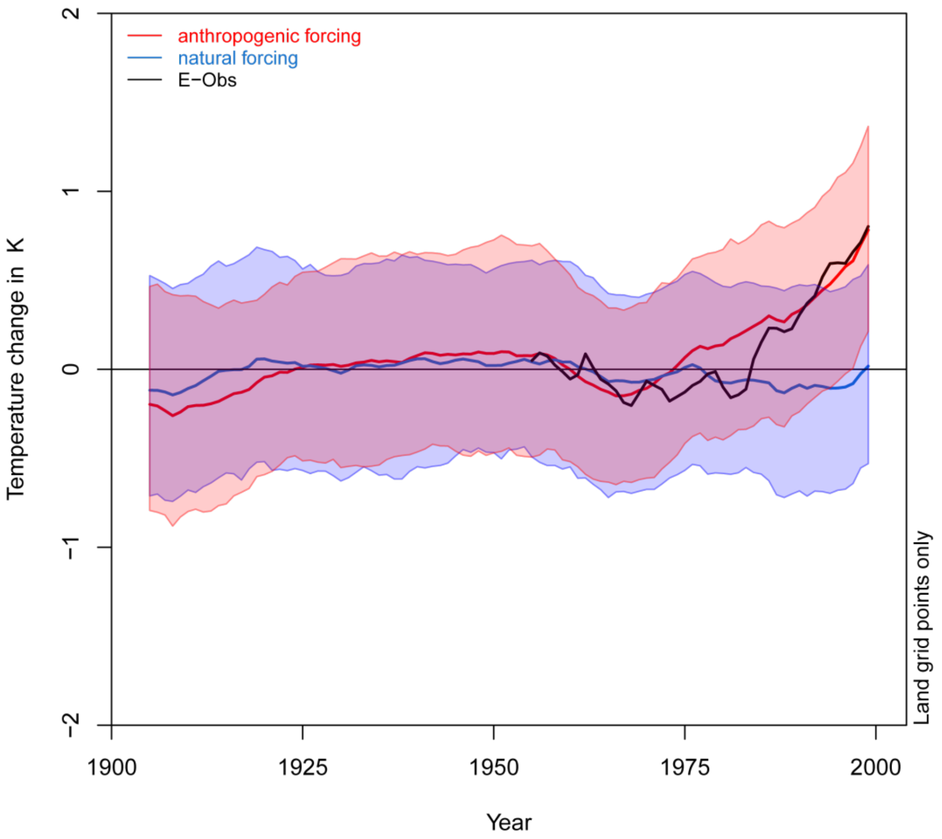



**Figure 7:** Detection and attribution signals (10-year averages) of annual surface temperature in K over 1900-2004 with respect to reference period 1950-1979 for 20 CMIP5 models for Europe. Mean over natural forced simulations (red solid line) and 5 and 95 % quantiles (light red shaded area) indicated. Mean over anthropogenic forced simulations (blue solid line) and 5 and 95 % quantiles (light blue shaded area) indicated. E-OBS data over 1950-2012 (black solid line) indicated. Settings in namelist: ATTRIBUTION, overview, annual, Europe.

## 3.6 ABS

Maps of the variables are plotted in NCL, the first plot shows the mean temperature over Europe averaged over 2070-2099. The initial and final year of this time period can be chosen by the user. All maps are shown for the respective model resolution. If the multi-model mean is plotted, the models are remapped to one model resolution (1.875°x1.25°). If seasons are to be plotted, a panel plot with all seasons is created for each ensemble member of a scenario as shown in Figure 8. This is not the case for overview plots as shown in the next section. The colorbars can be set individually for each NCL plot type and each variable. Note that currently for temperature and precipitation the IPCC standard colorbars are used. If the appearance of the plots should be adjusted, this must be done manually in the according NCL scripts.

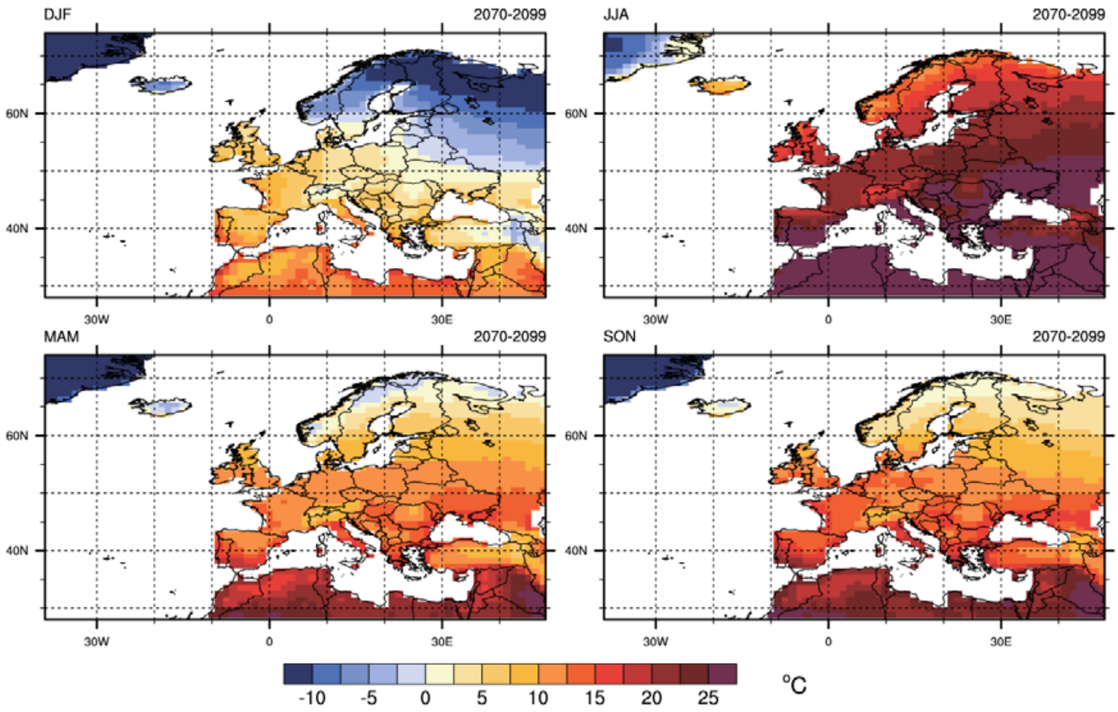



**Figure 8:** Winter (DJF), summer (JJA), spring (MAM) and fall (SON) absolute surface temperature in °C averaged over 2070-2099 for CCSM4, r1i1p1 for Europe in RCP4.5. Settings in namelist: ABS, singular, seasonal.

## 3.7 DELTA

It is also possible to plot the signal of change of a variable as a map over a region and averaged over a time period chosen by the user. The duration of the reference period can also be chosen. The maps in Figure 9 show the mean temperature change over Europe averaged over 2070-2099 with respect to the reference period 1980-2009. The average change over the area is printed in each panel in the upper right corner. These overview plots are a panel consisting of one plot of each model. If a model has more than one ensemble member or different perturbed physics numbers, the ensemble mean is shown and indicated as “multiensemble” or “physics 1-3” in the left corner of the plot (again, in later versions single ensemble members are shown and not the ensemble mean).

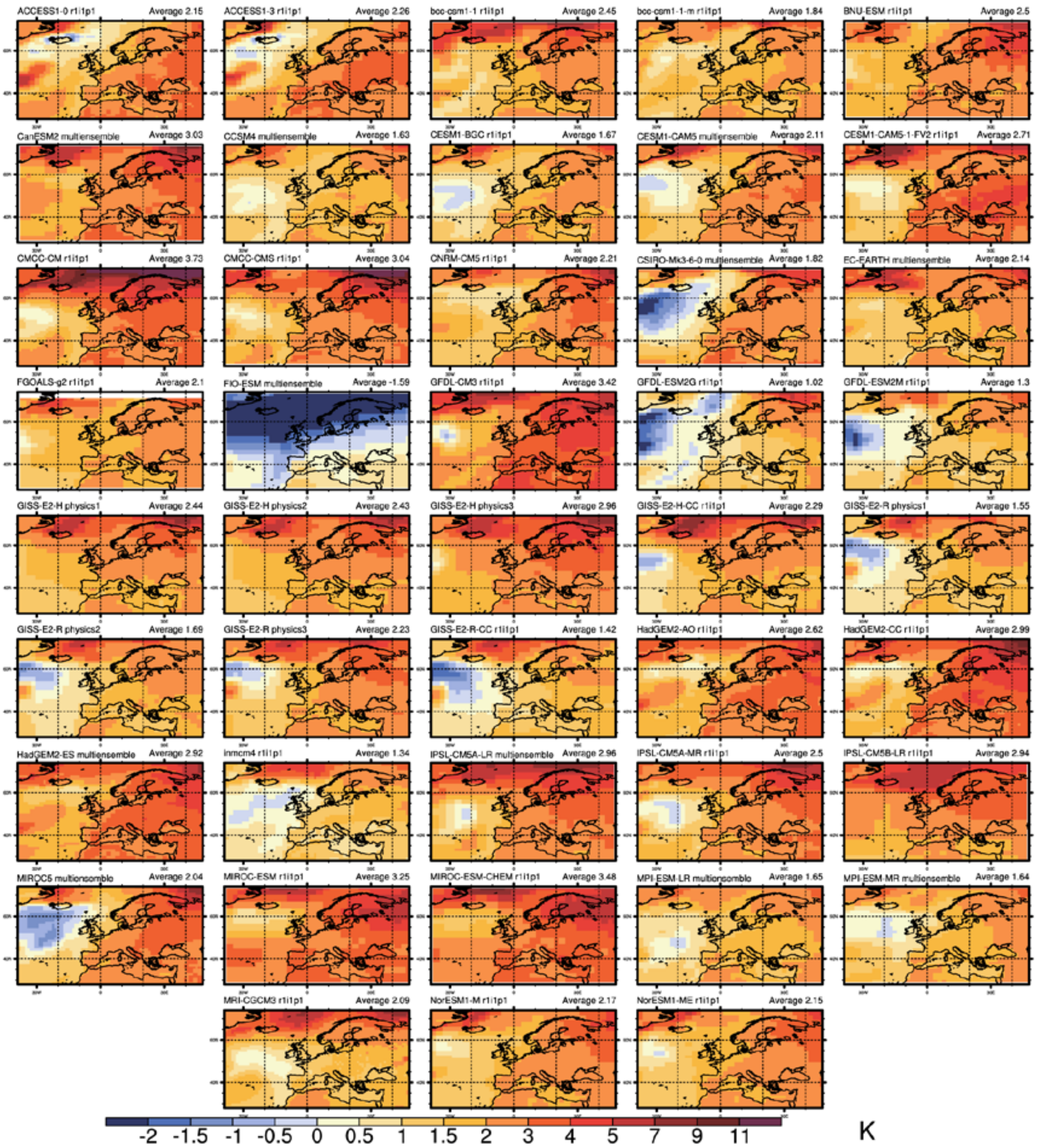



**Figure 9:** Annual surface temperature change in K averaged over 2070-2099 with respect to reference period 1980-2009 for CMIP5 models for Europe in RCP4.5. Settings in namelist: DELTA, overview, annual.

## 3.8 BIAS-ERA, BIAS-CRU, BIAS-E-OBS

The biases in the simulated present day climate can be shown as a map with the ERA-Interim data set as a reference, the CRU or E-OBS data set (Figure 10). The available observational and reanalysis data sets end in 2012, therefore only biases over 1950-2012 can be plotted. The historical CMIP5 experiments with largely predefined boundary conditions end in 2005. For 2006-2012 the RCP4.5 scenario is used automatically for all bias plots as the difference between the scenarios is low in the first years of the simulations. The observational and reanalysis data is regridded to model resolution. The regridding methods, which can be chosen by the user, are explained in detail in the Appendix. For all bias plots the root mean square error of the mean area is indicated in the upper right corner of each panel. This provides an order of magnitude at which the observational and reanalysis data sets are different. Bias plots provide information about the quality of climate models, however, as long as the interannual variability is not taken into account no general conclusions should be drawn. All other features are similar to the ones of the previous plots.

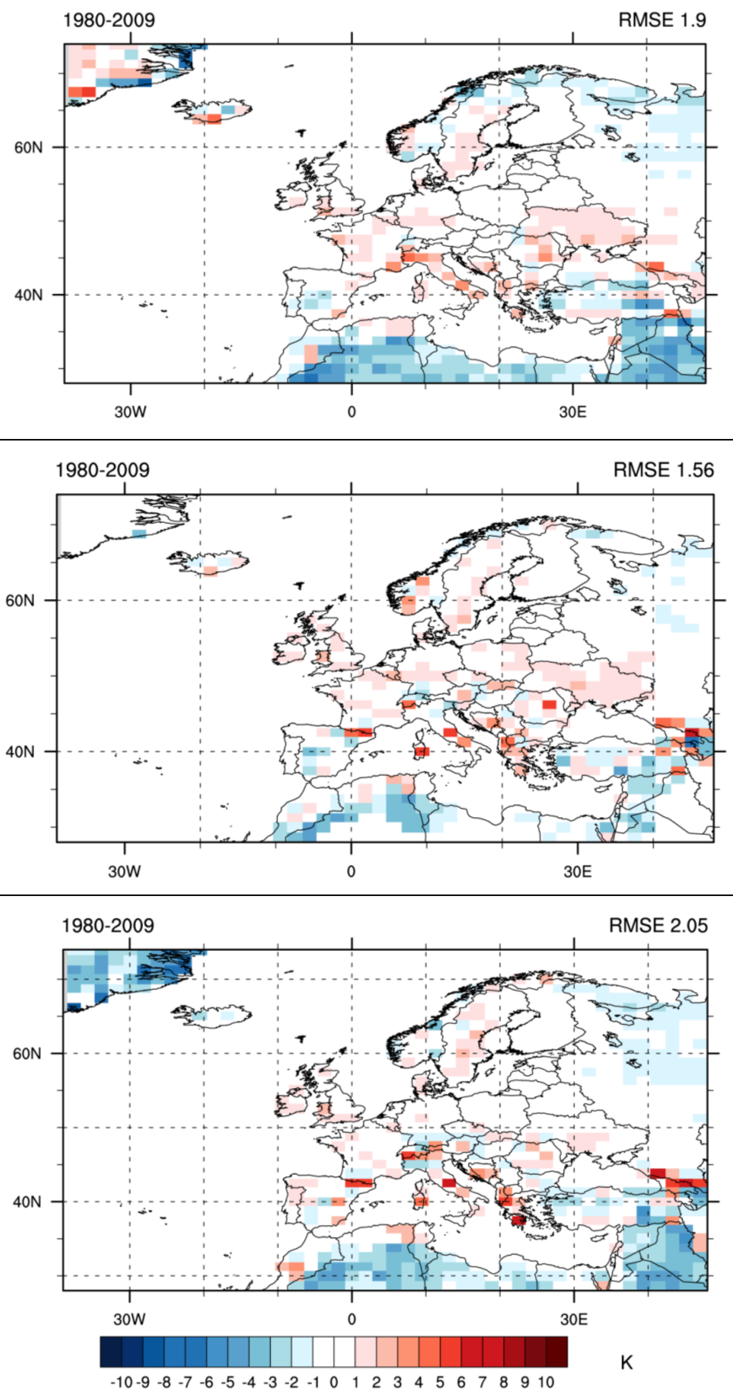



**Figure 10:** Annual surface temperature bias against (top) ERA-Interim, (middle) E-OBS or (bottom) CRU data in K averaged over 1980-2009 for ACCESS1-0, r1i1p1 for Europe in RCP4.5. Settings in namelist: (top) BIAS-ERA, (middle) BIAS-EOBS or (bottom) BIAS-CRU,singular, annual.

# 4 Data Analysis

## 4.1 Incomplete data sets

### 4.1.1 Time steps

The Model Diagnostic Suite only runs properly for the CMIP5 data, if the data set is complete from 1950-2099. The data import has a criterion incorporated which checks for the completeness of the time series of each run. If this criterion is not met, the data is rejected. Therefore, some models are no longer available after the data import, however, the raw data still exists if needed. Such an example is the HadCM3 model which only simulates future climate to 2035. There is also a lack of individual years within the selected time period in some ensemble members such as CESM1-WACCM, r2i1p1, which starts in 1955. The program transfers only ensemble members with the complete time series, therefore those ensemble members are removed. A list of all model features and found inconsistencies are listed in Table 2.

### 4.1.2 Time independent variables

Some climate modeling centers do not provide the land-sea mask automatically for all scenarios, variables and models. If such a file exists for at least one scenario for one variable, it is copied to all other scenarios. If not, such a file will be taken from a different model version of the same modeling center, assuming the horizontal grids are identical. For example, GISS-E2-H-CC has the same horizontal resolution as GISS-E2-H but no land-sea mask file (sftlf file), therefore, the sftlf-file is copied automatically from GISS-E2-H to GISS-E2-H-CC. There are still CMIP5 models without a publicly available land-sea mask:

- bcc-csm1-1-m
- BNU-ESM
- CESM1-CAM5-1-FV2
- EC-EARTH
- FIO-ESM

In the time series created with R, these models do not appear if all oceanic grid points were set to missing values by the option “landmask”. They are only plotted if no land-sea mask is applied or a smaller area with a high land area fraction is chosen. Especially for low-resolution models, the land-sea mask differs considerably from the actual coast lines. If the land-sea mask is applied, some models have for instance only one or two grid points left over the British Isles. The Black Sea is sometimes not implemented at all. These factors should be considered when analyzing these models.

In addition to the land-sea mask some CMIP5 models also lack the topography (orog file):

- bcc-csm1-1-m
- CESM1-CAM5-1-FV2
- EC-EARTH
- FIO-ESM

Again, there are large differences of the implemented topography of each model, which changes largely with the model resolution. The altitude above sea level and the location of the Alps (if present at all) for instance differs largely amongst the models.

**Table 2:** CMIP5 models, the used calendar type, horizontal resolution and found data inconsistencies by the Model Diagnostic Suite

| | **Calendar** | **Hor. resolution** | **Remarks, Errata** |
|---|---|---|---|
| ACCESS1-0 | proleptic_gregorian | 1.875°x1.25° | |
| ACCESS1-3 | proleptic_gregorian | 1.875°x1.25° | |
| bcc-csm1-1 | 365_day | ≈2.81°x2.81° | |
| bcc-csm1-1-m | 365_day | ≈2.81°x2.81° | sftlf, orog missing |
| BNU-ESM | 365_day | ≈2.8125°x2.8° | sftlf missing |
| CanCM4 | 365_day | ≈2.8125°x2.8° | year 1950 missing (?), deleted |
| CanESM2 | 365_day | ≈2.81°x2.81° | stop at 2035-12-31 |
| CCSM4 | 365_day | 1.25°x0.942408° | |
| CESM1-BGC | 365_day | 1.25°x0.942408° | http://www.cesm.ucar.edu/CMIP5/errata/ |
| CESM1-CAM5 | 365_day | 1.25°x0.942408° | |
| CESM1-CAM5-1-FV2 | 365_day | ≈2.5°x1.8947° | sftlf, orog missing |
| CESM1-WACCM | 365_day | ≈2.5°x1.8947° | r2i1p1 start year is 1955<br>r3i1p1, r4i1p1 end in 2065, deleted |
| CMCC-CM | standard | ≈0.75°x0.7484° | |
| CMCC-CMS | standard | ≈1.875°x1.8° | |
| CNRM-CM5 | standard | ≈1.40625°x1.4° | |
| CSIRO-Mk3-6-0 | 365_day | ≈1.875°x1.8° | |
| EC-EARTH | standard | ≈1.25°x1.1214° | r11i1p1 year 2005 missing<br>r13i1p1 years 2064, 2065 missing |

| | | | |
|---|---|---|---|
| | | | sftlf, orog missing |
| FGOALS-g2 | 365_day | ≈2.8125°x2.8° | |
| FIO-ESM | 365_day | ≈2.8125°x2.8° | sftlf, orog missing |
| GFDL-CM2p1 | standard | 2.5°x2.02247° | years missing; deleted |
| GFDL-CM3 | 365_day | 2.5°x2° | |
| GFDL-ESM2G | 365_day | 2.5°x2.02247° | |
| GFDL-ESM2M | 365_day | 2.5°x2.02247° | |
| GISS-E2-H | 365_day | 2.5°x2° | 3 perturbed physics numbers |
| GISS-E2-H-CC | 365_day | 2.5°x2° | |
| GISS-E2-R | 365_day | 2.5°x2° | 3 perturbed physics numbers |
| GISS-E2-R-CC | 365_day | 2.5°x2° | |
| HadCM3 | 360_day | 3.75°x2.5° | stop at 2035-12-31,deleted |
| HadGEM2-AO | 360_day | 1.875°x1.25° | |
| HadGEM2-CC | 360_day | 1.875°x1.25° | |
| HadGEM2-ES | 360_day | 1.875°x1.25° | |
| inmcm4 | 365_day | 2°x1.5° | |
| IPSL-CM5A-LR | 365_day | 3.75°x1.89474° | |
| IPSL-CM5A-MR | 365_day | 2.5°x1.2676° | |
| IPSL-CM5B-LR | 365_day | 3.75°x1.89474° | |
| MIROC4h | standard | ≈0.56°x0.56° | http://amaterasu.ees.hokudai.ac.jp/~fswiki/pub/wiki.cgi?page=CMIP5%2FKnownIssues |
| MIROC5 | standard | ≈1.40625°x1.4° | |
| MIROC-ESM | standard | ≈2.8125°x2.8° | |
| MIROC-ESM-CHEM | standard | ≈2.8125°x2.8° | |
| MPI-ESM-LR | proleptic_gregorian | ≈1.875°x1.8° | |
| MPI-ESM-MR | proleptic_gregorian | ≈1.875°x1.8° | |
| MRI-CGCM3 | proleptic_gregorian | ≈1.125°x1.1° | |
| NorESM1-M | 365_day | ≈2.5x1.89474 | |
| NorESM1-ME | 365_day | ≈2.5x1.89474 | |

## 4.2 Units

The climate modeling centers were asked to use standardized units, which are presented in Table 6 in the Appendix. Up to this point no mayor problems were found with the units of CMIP5 data. However, mainly temperature and precipitation data were analyzed in more detail. Variables that are less often needed might use other units than the standard units.

Precipitation data is converted to a precipitation rate in millimeter per day. The CRU data sets uses daily precipitation sums as a unit, which means that monthly data is divided by the number of days per month to get a precipitation rate. ERA-Interim has ½ daily precipitation rates in m per day, while the E-OBS data has already a precipitation rate dimension of millimeter per day.

The geopotential height of the ERA-Interim data set is given in $m^2/s^2$ and is therefore divided by the standard gravity in order to get a dimension of meters.

Unfortunately the Model Diagnostic Suite cannot recognize if the right unit is used. This can only be controlled by examine all plots for large deviations from the average. Some units are set manually in each shell script to adjust the according NetCDF files. However, most of the time the program would simply not run properly if wrong units are used.

## 4.3 Distinctive features of individual models

Some models differ considerably from the average over all models. Knowing these models is particularly important, if the data is used for complex analysis, where these model features no longer emerge. Some of these models are now presented exemplary. Including other variables into the analysis would probably reveal more striking model features.

### 4.3.1 Bias

Gridded monthly data of climate variables is often used to validate climate model simulations in the time of the observations. Those data sets have their own limitations, but are useful to get an impression about the magnitude of the difference between two gridded data sets. For certain variables some data sets are more suitable than others.

The temperature bias in simulating present day climate can be up to 10 K depending on the observational or reanalysis data set and the model. The CMIP5 models tend to be cold-biased of the order of 2-6 K over Europe in the RCP4.5 scenario not only for the ERA-Interim data but also the E-OBS and CRU data sets. Models with the largest bias in temperature are (see Figure 11):

- CMCC-CM
- FGOALS-g2
- IPSL-CM5B-LR

The precipitation bias is not as clearly as the bias in temperature for these three models. The CMCC-CM model for example simulates less precipitation than the ERA-Interim data set over Europe, while the FGOALS-g2 model tends to be wet-biased.

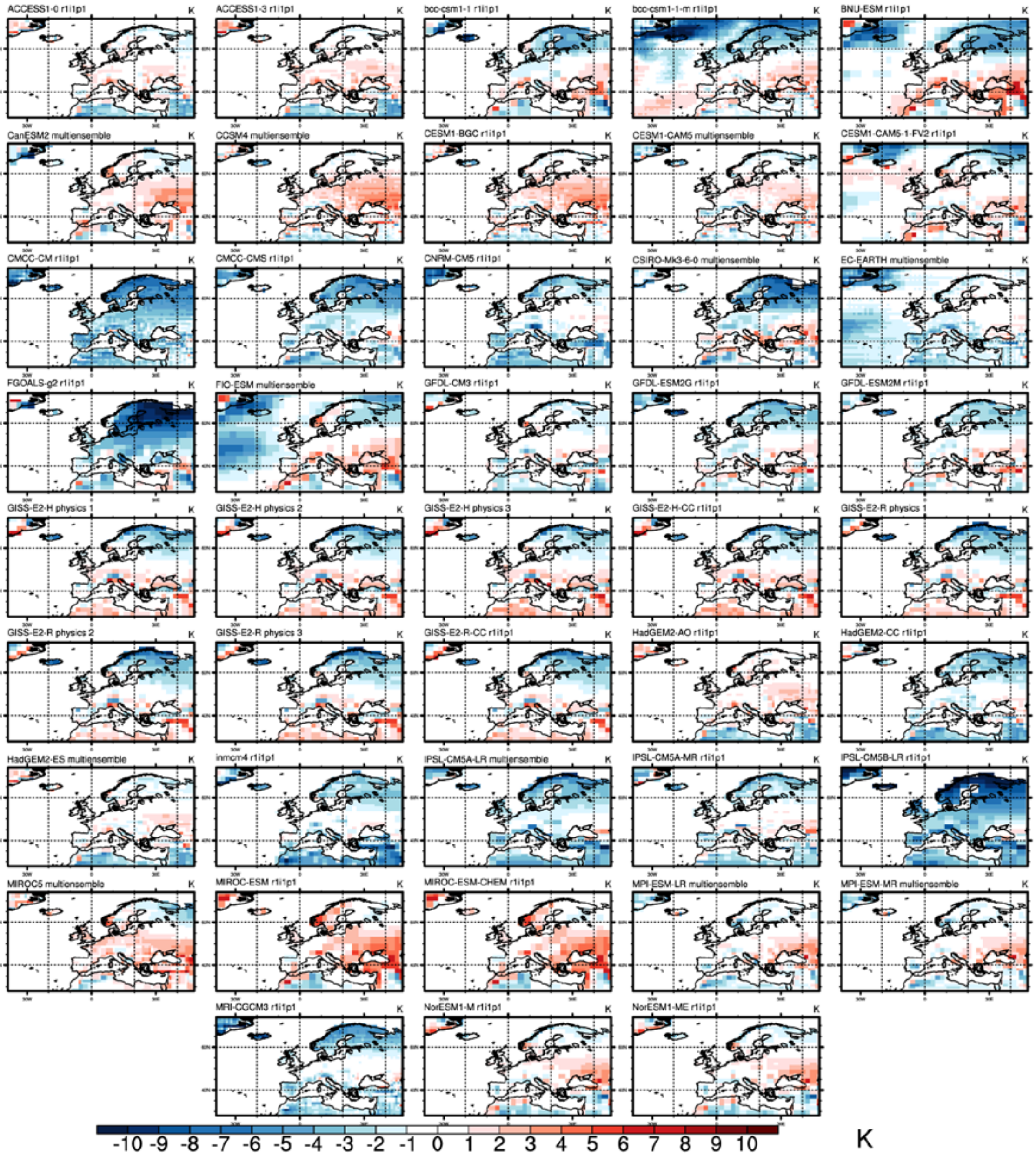



**Figure 11:** Annual surface temperature bias against ERA-Interim in K averaged over 1981-2005 for CMIP5 models for Europe in RCP4.5.

Additionally, the bias in cloud cover and geopotential height can be analyzed to clarify whether strong biases only occur for a single variable or whether an unrealistic climate is simulated over Europe. Some models tend to overestimate or underestimate high and low pressure systems over Europe, therefore the large scale circulation may strongly deviate from the actual observed circulation patterns, which in turn has an influence on temperature and precipitation on local scales. Of course, the bias analysis depends on the used observational or reanalysis data set, which is indicated by the root mean square error top right in each panel of the bias plots. However, the differences are generally small over Europe. As an example for the bias in total cloud cover, the ERA-Interim data set indicates strong biases over central Europe and the whole year, while only weak biases occur for the CRU data set (Figure 12). However, the same models show a tendency to overestimate or underestimate cloud cover but at a different magnitude. Regardless of the magnitude of the bias in various variables, bias patterns can be found (even some models from different climate modeling centers behave similar) and must be handled accordingly. A reliable validation of climate model data against recent climate is only partly possible with E-OBS, ERA-Interim or CRU data sets because of their own limitations. Therefore the amount and quality in those data sets needs to increase in order to increase the reliability of model validation.

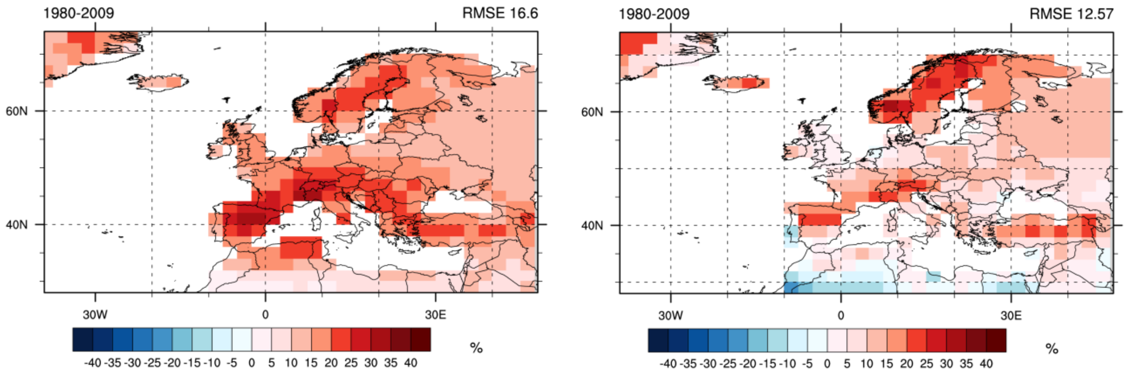



**Figure 12:** Annual total cloud fraction bias of GFDL-CM3, r1i1p1 against (left) ERA-Interim and (rigth) CRU in % averaged over 1980-2009 for Europe in RCP4.5.

### 4.3.2 Resolution

In general, it looks as if low resolved models perform worse than higher resolved models. An example for that is the IPSL-5B_LR model (horizontal resolution of 3.75°x1.90°). The absolute simulated temperature is about 2.5 K below the observed temperature as shown in Figure 13 (top panels), which alone may not be informative about the performance of the model. The higher resolved IPSL-CM5A-MR (2.5°x1.28°) performs much better. As previously shown, the low resolved model is largely cold-biased in the RCP4.5 scenario over Europe. The geopotential height (500 hPa) is largely biased as well and more than 80 m below the geopotential height of the ERA-Interim data set in that scenario (see Figure 13, bottom panels). This model simulates the actual climate worse than higher resolved models and therefore should be handled with care for further analysis on local scales.

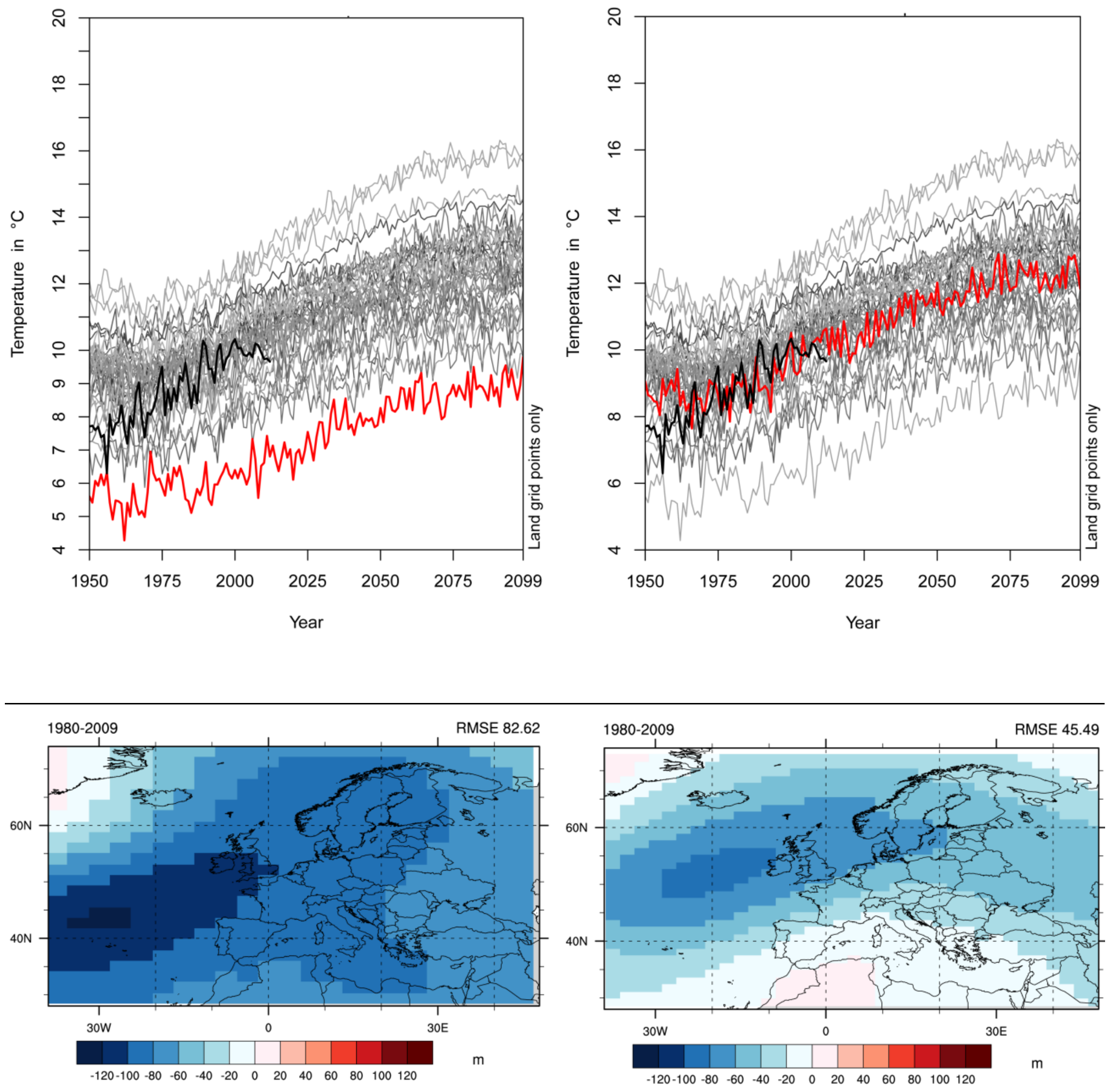



**Figure 13:** Absolute temperature (top row) and geopotential height (500 hPa) bias (bottom row) with respect to reference period 1980-2009. Absolute temperature over 1950-2099 for (top left) IPSL-CM5B-LR and (top right) IPSL-CM5A-MR. Annual geopotential height bias against ERA-Interim averaged over 1980-2009 for (bottom left) IPSL-CM5B-LR and (bottom right) IPSL-CM5A-MR for Europe in RCP4.5.

### 4.3.3 FIO-ESM

Some models simulate a more or less strong cooling in the northern Atlantic, which might be a result of relatively cold freshwater influx from the Arctic due to increased precipitation in that area (Weaver et al., 2012). However, all ensemble members of the FIO-ESM model simulate a strong temperature decrease all year long over the Atlantic until the end of the century in the RCP2.6, RCP4.5 and RCP6.0 scenario and a weak temperature decrease in the RCP8.5 scenario (see Figure 14). The temperature time series over 1950-2099 are shown in Figure 15. The temperature curve until the end of the century decreases, while all other models simulate an increase in temperature. The temperature bias is not particularly strong, as well as other biases as precipitation or cloud cover bias. The geopotential height (500 hPa) is slightly underestimated over the northern Atlantic and slightly overestimated over southern Europe. This indicates, that the model simulates present climate quite well but the simulated climatic changes evolve very unlikely until the end of the century. Including this model in further analysis influences the temperature spread substantially.

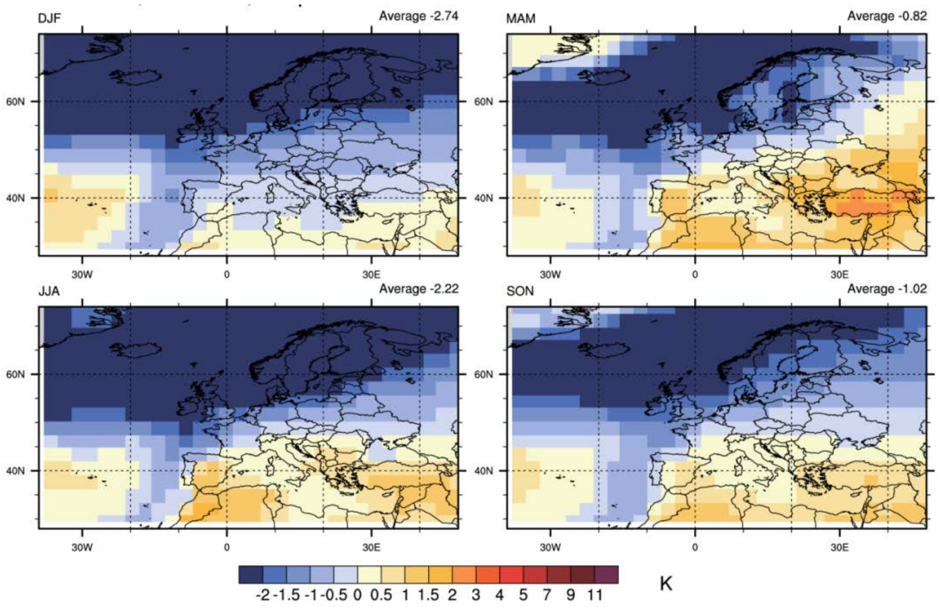



**Figure 14:** Seasonal mean near-surface temperature change from 2070 to 2099 with reference to 1980-2009 for FIO-ESM over Europe in RCP4.5.

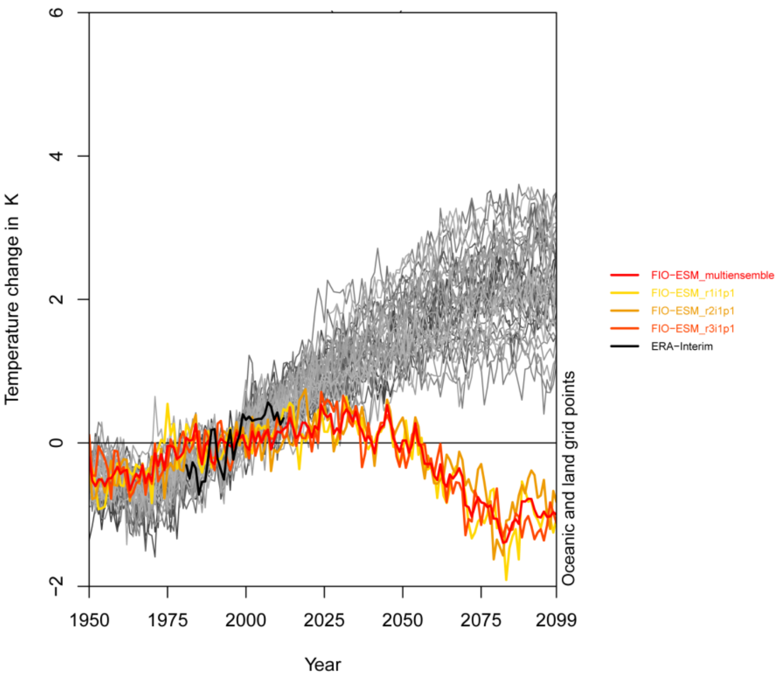



**Figure 15:** Annual mean near-surface temperature change from 1950 to 2099 for FIO-ESM in RCP4.5 over Europe including oceanic grid points. ERA-Interim data from 1981-2012 in black.

# 5 Summary

Aim of this technical report was to present the Model Diagnostic Suite developed during an internship at MeteoSwiss, its applications and exemplary plots within the scope of CMIP5 model data. Plots created with the provided tools have been proven to be useful to get a first impression of the climate model data over Europe and the Alpine region. The data can be compared to observational or reanalysis data sets to evaluate the performance of the models in simulating present day climate. Thus, the Model Diagnostic Suite can help to examine whether specific climate models simulate a realistic climate that match the observations. At the same time, the magnitude and trends in simulations until the end of the century can be analyzed for various scenarios and variables to test assumptions.

Using the Diagnostic Suite, several data inconsistencies could be detected. Missing time steps are reported immediately during data transfer, lacking land-sea mask files are noted easily in NCL plots and striking model features become evident in various plots. Maybe not new, but still interesting details of CMIP5 model data found by using the Diagnostic Suite were presented. Dealing with large climate data sets can be tricky, therefore one must use the Diagnostic Suite carefully, because there might still be unknown mistakes in it, which occurred while scripting. Nevertheless, it has been proven to be a valuable set of tools for data visualization, which can be extended at any time. It will become even more interesting if new observation based data sets such as the EURO4M precipitation data set (Isotta et al, 2013), ERA-Clim, and new model data sets as EURO-CORDEX or decadal runs of the CMIP5 data are included to the Model Diagnostic Suite.

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# A Appendix 1: Data upload

## A.1 CMIP5 data upload

The CMIP5 data is provided by the C2SM. In order to decrease the quantity of data used for this project, only monthly data for greater Europe from 1950 to 2099 for selected variables is transferred to CSCS (directory layout: /store/msclim/Prediction/CMIP5/experiment/frequency/variable/model/ensemble/).

Other variables, regions or frequencies can be added very easily. A list of the available variable output is shown in Table 6 in the appendix. Models and their ensemble members in the RCP simulations from 2006 to 2099 are only used, if the corresponding historical run from 1950 to 2005 with the same realization number and perturbed physics number is available. Historical data with natural and anthropogenic forcing is available from 1900 to 2005.

The tool for the data upload is similar to the Model Diagnostic Suite. In a master file the main variables are set (e.g. workpath, variables, experiments, region). This file will be sourced by all shell scripts. The first script creates all directories, the second one prepares the historical data and the third one matches the historical data and the RCP simulations. The scripts can be started simultaneously by submitting a sbatch job at CSCS. Because of defined job dependencies, the second job will only start if the first one is finished. Three shell scripts are needed to create the NetCDF files efficiently, without repeatedly reading in identical data from 1950 to 2005 for each scenario. Only data with the full length of the time period is transferred, therefore not all models stored at C2SM are stored at the CSCS. Table 3 shows the number of climate data files and their size uploaded to the CSCS.

**Table 3:** Approximated data properties of data stored at the CSCS and used by the Model Diagnostic Suite (01/13/2014).

| Data set | Number of files | Size |
|---|---|---|
| CMIP5 | 12522 | 61 GB |
| ENSEMBLES GCMs | 51 | 12 GB |
| ERA-Interim | 2047 | 22 GB |
| E-OBS | 14 | 2.2 GB |
| CRU | 11 | 14 GB |

## A.2 Other data

The ENSEMBLES GCM precipitation and temperature data for the 20C3M and the A1B scenario has been partly downloaded from the DKRZ, the WCRP and the ENSEMBLES data portals and stored at CSCS (see Table 7 for model information).

ERA-Interim synoptic monthly means are provided as ½ day sums, therefore time 00:00:00 and step 12 and time 12:00:00 and step 12 are downloaded. The sum of both fields is the total monthly mean. Available are temperature, precipitation, cloud cover and geopotential (500 hPa) fields at the CSCS. To add new variables, data can be retrieved from the ECMWF homepage[15].

[15] http://apps.ecmwf.int/datasets/data/interim_full_daily/

# B Appendix 2: Operation and use of the Model Diagnostic Suite

## B.1 Variable settings

The possible variable settings in the namelist file are divided into four parts: general options, plot types, plot organization and plot options. Table 1 gives a short overview over all possible settings in the namelist file.

### B.1.1 General options

In the first part, "General Options", settings must be performed to configure the directory structure of input and output data. First, the project can be set to CMIP5 or ENSEMBLES (at this point, CORDEX will follow) to determine the folder structure of the input data. CMIP5 data is stored as follows:

/CMIP5 /experiment/frequency/variable/model/ensemble/*.nc.

ENSEMBLES GCM data is stored in a similar way:

/ENSEMBLES/GCM/A1B/RAW/model/frequency/variable/ensemble/*.nc.

In the ENSEMBLES projects ensembles do not really exist, however, for the EGMAM and MPI model there are three runs and for the HadCM3 model three sensitivity levels (low, standard, high). If a new project should be added, a similar folder structure is necessary.

The option "outpath" is the directory where the plots should be saved. Note that a folder structure will be created automatically in this directory, where plots are saved, which then can be imported by the ClimateBrowser but only if the existing folder structure remains unchanged. The work directory ("workpath")must be the directory, where the Model Diagnostic Suite and its tools are saved.

It is possible to save the created NetCDF files and to determine the directory, where the files should be saved. The created folder structure is similar to that of the input data. This can only be changed in the working file itself, if the files should e.g. be saved in one folder. There is also the ability to execute NCL and R or not, if there is only an interest in the NetCDF files. If both options are set to "False", the program will not start. Currently, either execute_NCL or execute_R must be "True", if both are "True", there is no guarantee that the Program works properly. That means that it must be decided which plot types are selected.

If the directory structure to save plot or NetCDF files is to be changed, this must be done manually in the work file in the appropriate sections.

### B.1.2 Plot organization

If "singular" is set to "True", one plot for each model and ensemble is created. R plots show time series where all ensemble members of one model are highlighted for better comparability. If "overview" is set to "True", one plot for each model is created (NCL) or all models, their mean and confidence intervals is shown (R). If the model has more than one ensemble member, the mean over all the ensemble members is shown and indicated as “multiensemble”. If more than one perturbed physics number exist, the mean over the ensembles with the same perturbed physics number is shown and regarded as individual models. At the level “model” in the output direction a new folder “overview” is created. “multimodel” can be set to “True”, if “singular” is set to “True. A map should be created showing the mean over all models and ensembles (this option does not exist for R plots as it is already included under “overview”). As for the overview plot, the mean over all ensemble members or perturbed physic numbers is taken first to ensure each model is weighted the same. At the level “model” in the output direction a new folder “multimodel” is created.

The format of the plot is set with the option ”plotformat”. The file format should be “pdf”, if the plots are shown in the ClimateBrowser.

### B.1.3 Plot options

For time series in R, “startperiod” is set automatically to 1950, “endperiod” to 2099; for the attribution plot the shown time period is always 1900-2004. For NCL plots however, the shown time period can be chosen. The beginning and the end of the reference time period for change signal plots can be set with “startrefperiod” and “endrefperiod”. If maps are plotted showing the difference between a future and a reference time period, both time periods must be of equal length. If "length” is set to zero, annual or seasonal means are plotted in R. If not, a running mean is plotted, e.g. “10-year running mean of…”.

The option “granularity” specifies whether an annual or seasonal plot is generated. For maps, a seasonal, singular plot is a panel of all four seasons, whereas for seasonal, overview plots, individual seasons are plotted, which are defined with “timeframe”. Here, multiple choices are possible as well.

The “frequency” can only be set to Amon (choosing the monthly data set), because the daily data sets are not transferred completely to the CSCS yet.

“Variable” sets the variable to be analyzed; multiple choices are possible. Note that for ENSEMBLES data, only temperature and precipitation can be analyzed. E-OBS and CRU data is available for precipitation and minimum, maximum, and mean surface temperature; ERA-Interim for precipitation, geopotential, cloud cover and temperature only.

With “experiment” the scenario can be chosen. For CMIP5 data four experiments are available: rcp26, rcp45, rcp60 and rcp85. For the ENSEMBLES GCMs only the A1B scenario is available. For CMIP5 data the experiment will be set to rcp45 automatically for all BIAS-plots, because the data from 1950 to 2005 within the observation period is the same for each experiment.

The “change” can be absolute or relative. This option is only relevant for plots showing a change signal between a future and reference time period. For variables, whose unit is already in percent (e.g. cloud fraction), this option should be set to absolute.

The “area” defines the region, which will be plotted as a map or which area mean will be used for time series. For R plots, “location” can be set to “True”, then data for a single grid point will be plotted. The coordinates for both options are determined and can be changed in the file “region”. If “landmask” is “True”, oceanic grid points are set to missing numbers. Only models are plotted for R figures, where the land-sea mask exists. If "landmask" is False, E-OBS is still plotted, although it is a dataset with only land points. In all R plots the area-weighted, therefore latitude-corrected area means are shown.

Depending on the variable, the method of interpolating grids might be of interest. With the option "remap", a cdo command to interpolate the input field to a new horizontal grid can be altered. If "remap" is set to remapbil, a bilinear interpolation is performed, which is preferable for precipitation or geopotential heigth. If it is set to remapnn, the nearest neighbor remapping on all input fields is performed, which might be optimal for temperature plots. Other interpolation methods are: remapbic (bicubic interpolation), remapdis (distance-weights average remapping), remapcon (first order conservative remapping), remapcon2 (second order conservative remapping) and remaplaf (largest area fraction remapping). Note that some interpolation methods only work on quadrilateral curvilinear grids (Schulzweida, 2013).

## B.2 Colorbar and plot settings

For each plot type and variable the colorbar settings for NCL-plots are set in colorbar_settings_{plottype} and can be changed. In the NCL-code colorbar, minlevel and maxlevel, spacelevel and the colorstart will be replaced:

- gsn_define_colormap(wks,"colorbar")
- res@cnMinLevelValF = minlevel
- res@cnMaxLevelVal = maxlevel
- res@cnLevelSpacingF = spacelevel
- res@gsnSpreadColorStart = colorstart

For temperature and precipitation the IPPC standard colorbars are used, therefore "colorbar" has to be set to "cmap". If a new colorbar is to be added, this must be done manually in the NCL script matching the already existing code in that form.

In order to change other features of the NCL (or R) plots the NCL-code can be changed as well. The scripts are organized as follows: the first name indicates the plot type, the second part the plot organization (singular annual, singular seasonal or overview plot): {plottype}_{plot organization.ncl}. The multimodel plot is created as a singular, annual plot.

The names, which appear in the R plots, are defined the names_list function. The information is passed by the master file by replacing the variable names. If new variables or regions are added, this file must be adjusted otherwise the titles and labels of axes are missing. The option space defines the distance between two axis entries. It can happen, however, that this must be adjusted manually in the according R script.

## B.3 Region definition

The plots can be generated for different regions, which are defined in the file regions. It is also possible to add a user specific region or a new area to the existing regions in that file. For this, the coordinates are needed, which define the area (north, south, west, east). If only a single grid point should be plotted in R, the coordinates can be defined here as well. The default is Zurich, Fluntern. The R scripts then looks for the grid point closest to the given longitude and latitude. Global data can be used without difficulty, but then it is necessary to adjust the shell scripts, which create the NetCDFfiles. All cdo commands "cdo sellonlatbox (Schulzweida, 2013)" must be removed in order to plot global data.

Predefined options are (Figure 2 shows the Prudence regions according to Christensen and Christensen (2007):

- Greater Europe EU
- Prudence regions:
  - British Isles BI (1)
  - Iberian Peninsula IP (2)
  - France FR (3)
  - Mid-Europe ME (4)
  - Scandinavia SC (5)
  - Alps AL (6)
  - Mediterraneum MD (7)
  - Eastern Europe EA (8)
- User specific US (default: Switzerland)

## B.4 Starting the Model Diagnostic Suite

If all variable settings are correct, the Suite can be run by submitting a batch job at CSCS:

sbatch WORKFILE.sh

How long it does take until the program has calculated a run, can be checked in workfile.out: the first line shows the start time and the last time the end time. To check the progress, use:

tail –f workfile.out

Generally, it takes longer to plot maps in NCL than to produce plots in R. It also is faster to plot smaller regions than larger regions. The program has finished completely, if the end time is printed as the last line of the workfile.out. The work file interprets the variable settings of the namelist file. After submitting the batch job, NetCDF files are created in a temporary subfolder by using cdo (or nco) commands from a shell script. Such a shell script exists for each project and each plot type. Therefore such a shell script has to be created, if a new plot type or a new project is added to the existing tools. The adjusted NetCDF files are plotted with NCL or R by a NCL or R script. These scripts exist for each plot type and display type (singular or overview). The plots are then moved from the temporary subfolder to the output folder. The folder structure should not be changed because this is necessary to open the plots in the "ClimateBrowser". All created NetCDFfiles are removed, if not otherwise indicated.

If more than one option is set for selected variables in the namelist file, a loop sequence is started. The program will loop over all ensemble members of each model, over all variables, scenarios, plot types and last over all specified areas. If multiple options are set, they must be written in brackets.

## B.5 Error messages and exit structures

Some combinations of the variable settings lead to error messages and force the program to stop. There are some exit structures in the work file, which always produce an error message (see Table 4). If the script does not work properly, first check the spelling of the variable settings in the namelist file. Problems with the directory structure often lead to errors as well. Sometimes warnings appear as "rm: could not remove…". This does not mean that the program did not work properly, therefore these warnings can be ignored. Sometimes variables are set automatically, then only warnings occur as well.

## B.6 Expansion of the Model Diagnostic Suite

In principle, all programs are similar, therefore it is very easy to expand the tool. A new plot type can be added by adding a shell script to create the adjusted NetCDF files and adding a R or ncl script. The easiest way to do that is to copy an existing script and adjust the relevant commands. Table 5 shows the current number of NCL, R and C-Shell scripts, their size and number of code lines. Additionally, the so far produced number of NCL and R plots, their size and total are listed.

New variables can be set very easy in the NAMELIST.sh file. All programs will now source the new variable. If the variable is used in a NCL or a R-script, the according replace functions in the WORKFILE.sh must be adjusted. The following

-e 's/variable_name_in_R/NCL_script/'$variable_name_in_ namelist'/g'

must be added (for a directory use "|" instead of "/") to the according cat command. It is strongly recommended to use long variable names, which are not used anywhere else (as variables, commands, texts,…), because otherwise this will lead to interferences with the existing scripts and probably to program failure.

If new data variables are added, the scripts have to be adjusted. First, the exit structures in the master file needs to be adjusted. Additionally, the units of some variables are converted automatically in all shell scripts. In the shell scripts for the bias plots, the variable names are changed (to the CMIP5 variable names), which has to adjusted as well. In all shell scripts there are code lines, which adjust the units of the data. Possibly these need to be adjusted for new variables. If a variable is defined on vertical levels as well, one level needs to be selected and all others deleted (via nco command). Otherwise NCL cannot create plots.

A new project can be added in the same way: for each plot type a shell script is needed for the new project. Now, the folder structure of the input data needs to be adjusted.

**Table 4:** Commented error messages and warnings caused by incorrect variable settings or variable combinations in the namelist file.

| Message | comment |
|---|---|
| choose project: ENSEMBLES - CMIP5 - EU-CORDEX | check spelling of project |
| [variable] empty | set [variable] |
| Reference time period length: …<br>Future time period length: …<br>Reference time period is longer / shorter than future time period | check time periods and the length of future and reference time period |
| experiment for CMIP5: rcp26, rcp45, rcp60, rcp85<br>experiment for ENSEMBLES: A1B | check the experiment and the project |
| warning: startperiod set to 1950!<br>warning: endperiod set to 2099! | only for R plots (except attribution plots) |
| singular, overview and multimodel empty / False | execute_ncl and/or execute_R is True |
| warning: multimodel option does not exist for plot type | execute_R is True |
| timeframe not annual | only for scatterplots |
| landmask False!<br>startperiod not 1900 for ATTRIBUTION!<br>endperiod not 2004 for ATTRIBUTION!<br>endrefperiod not 2004 for ATTRIBUTION!<br>warning: singular set to False, overview set to True! | only for attribution plots; landmask must be True (for E-OBS data); only overview plots available |
| execute_R not True | if save_NetCDFs False; for R plots |
| execute_ncl not True | if save_NetCDFfs False; for NCL plots |
| warning: set landmask to False for geopotential! | not common for geopotential plots |
| variable: tas, tasmax, tasmin, clt or pr for CRU data | check variable and plottype |
| variable: tas, tasmax, tasmin or pr for E-OBS data | check variable and plottype |
| variable: tas, zg, clt or pr for ERA-Interim data | check variable and plottype |

**Table 5:** Technical details of the Model Diagnostic Suite including the number, size and number of code lines of NCL, R and C-Shell scripts as well as the number and size of the produced plots (01/13/2014).

| Tool | Number of scripts | Size | Number of code lines | Number of plots | Size of plots |
|---|---|---|---|---|---|
| NCL | 15 | 77.1 KB | 3103 | 14014 | 13.4 GB |
| R | 18 | 104.9 KB | 3494 | 8446 | 3.7 GB |
| C-Shell | 28 | 315.4 KB | 7058 | - | - |
| Total | 61 | 497.4 KB | 13655 | 22460 | 17.1 GB |

# C Appendix 3: Climate data properties

**Table 6: Standard output variables of CMIP5 simulations**[16]

| long name | units | comment | questions & notes | output variable name | standard name |
|---|---|---|---|---|---|
| Time-Invariant Fields on atmospheric grid – fx | | | | | |
| Surface Altitude | m | height above the geoid; as defined here, "the geoid" is a surface of constant geopotential that, if the ocean were at rest, would coincide with mean sea level. Under this definition, the geoid changes as the mean volume of the ocean changes (e.g., due to glacial melt, or global warming of the ocean). Reported here is the height above the present-day geoid (0.0 over ocean). | | orog | surface_altitude |
| Land Area Fraction | % | | For atmospheres with more than 1 mesh (e.g., staggered grids), report areas that apply to surface vertical fluxes of energy. | sftlf | land_area_fraction |

[16] http://cmip-pcmdi.llnl.gov/cmip5/docs/standard_output.pdf

| long name | units | comment | questions & notes | output variable name | standard name |
|---|---|---|---|---|---|
| 2-D daily mean atmospheric and surface fields | | | | | |
| Near-Surface Specific Humidity | 1 | | normally, report this at 2 meters above the surface | huss | specific_humidity |
| Precipitation | kg $m^{-2}$ $s^{-1}$ | at surface; includes both liquid and solid phases from all types of clouds (both large-scale and convective) | | pr | precipitation_flux |
| Surface Downwelling Shortwave Radiation | W $m^{-2}$ | | | rsds | surface downwelling shortwave flux in air |
| Near-Surface Air Temperature | K | | normally, report this at 2 meters above the surface | tas | air_temperature |
| Daily Maximum Near-Surface Air Temperature | K | | normally, report this at 2 meters above the surface | tasmax | air_temperature |
| Daily Minimum Near-Surface Air Temperature | K | | normally, report this at 2 meters above the surface | tasmin | air_temperature |

| | | | | | |
|---|---|---|---|---|---|
| Total Cloud Fraction | % | for the whole atmospheric column, as seen from the surface or the top of the atmosphere. Includes both large-scale and convective cloud. | | clt | cloud_area_fraction |
| Surface Upward Latent Heat Flux | W $m^{-2}$ | | | hfls | surface_upward_laten t_heat_flux |
| Surface Upward Sensible Heat Flux | W $m^{-2}$ | | | hfss | surface_upward_sensi ble_heat_flux |
| Convective Precipitation | kg $m^{-2}$ $s^{-1}$ | at surface; includes both liquid and solid phases. | | prc | convective_precipitati on_flux |
| Snowfall Flux | kg $m^{-2}$ $s^{-1}$ | at surface; includes precipitation of all forms of water in the solid phase | | prsn | snowfall_flux |
| Sea Level Pressure | Pa | | | psl | air pressure at sea level |
| Near-Surface Relative Humidity | % | This is the relative humidity with respect to liquid water for T> 0 C, and with respect to ice for T<0 C. | normally report this at 2 meters above the surface | rhs | relative_humidity |
| Surface Downwelling Longwave Radiation | W $m^{-2}$ | | | rlds | surface downwelling longwave flux in air |
| Surface Upwelling Longwave Radiation | W $m^{-2}$ | | | rlus | surface_upwelling_lon gwave_flux_in_air |
| Surface Upwelling Shortwave Radiation | W $m^{-2}$ | | | rsus | surface_upwelling_sh ortwave_flux_in_air |

| | | | | | |
|---|---|---|---|---|---|
| Daily-Mean Near-Surface Wind Speed | m $s^{-1}$ | | normally report this at 10 meters above the surface | sfc | wind_speed |
| Sea Surface Temperature | K | temperature of liquid ocean. Note that the correct standard_name for this variable is "sea_surface_temperature", not "surface_temperature", but this was discovered too late to correct. To maintain consistency across CMIP5 models, the wrong standard_name will continue to be used. | Report on the ocean grid. This variable appears in WGOMD Table 2.2 | tos | surface_temperature |
| Eastward Wind | m $s^{-1}$ | daily mean 3-D atmospheric fields on the following pressure surfaces: 1000, 850, 700, 500, 250, 100, 50, and 10 hPa | | ua | eastward_wind |
| Eastward Near-Surface Wind | m $s^{-1}$ | | normally, report this at 10 meters above the surface | uas | eastward_wind |
| Northward Wind | m $s^{-1}$ | daily mean 3-D atmospheric fields on the following pressure surfaces: 1000, 850, 700, 500, 250, 100, 50, and 10 hPa | | va | northward_wind |
| Northward Near-Surface Wind | m $s^{-1}$ | | normally, report this at 10 meters above the surface | vas | northward_wind |
| Geopotential Height | m | daily mean 3-D atmospheric fields on the following pressure surfaces: 1000, 850, 700, 500, 250, 100, 50, and 10 hPa | | zg | geopotential_height |

**Table 7:** ENSEMBLES Stream 1 (Niehörster et al., 2008)

| Partner | Model | Resolution | Scenario A1B for 21st century | Atmosphere component | Calendar |
|---|---|---|---|---|---|
| IPSL | IPSL-CM4 | 2° part. refined L31 | yes | LMDZ-4 | 360 day |
| MPI | ECHAM5 MPI-OM | 1.5° L40 | yes ( 3 x ) | ECHAM 5 | standard |
| DMI | ECHAM5 MPI-OM | 1.5° L40 | yes | ECHAM 5 | standard |
| CNRM | CNRM-CM3 | 2° part. refined L31 | yes | ARPEGE V3 | standard |
| FUB | EGMAM | T42 equat. refined L20 | yes ( 3 x ) | ECHAM4-MA | 360 day |
| METO | HadGEM1 | 1° equat. Refined L40 | yes | HadGAM1 | 360 day |
| -HC | HadCM3 | 1.25° L20 | yes | HadAM3 | 360 day |
| NERSC | BCM2 | 1.5° equat. Refined L35 | yes | ARPEGE V3 | standard |

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