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Copernicus Climate Change Service

Agroclimatic Indicators

Product User Guide and Specification

C3S Global Agriculture SIS

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History of Modifications

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Acronyms

Acronym	Description or definition
C3S	Copernicus Climate Change Service
CDS	Climate Data Store
CMIP5	Coupled Model Intercomparison Project Phase 5
GCM	General Circulation Models
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
RCP	Representative Concentration Pathways
SIS	Sectoral Information System

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1. Scope of the document

This document serves as Product user Guide Specifications for Agroclimatic Indicators datasets, as part of the C3S Global Agriculture Sectoral Information Systems (SIS). More information about the project can be found at https://climate.copernicus.eu/global-agriculture-project.

2. Executive summary

The C3S Global Agriculture (SIS) project aims to develop climate services in support of decision-making in agriculture sector. It does so in a process of co-creation with partners representing international crop research, international agricultural policy development and commercial agricultural consultancy services.

As part of the C3S Global Agriculture SIS, the agroclimatic indicators are generated to represent features of the climate that are used to characterise plant-climate interactions. Agroclimatic indicators are useful in conveying climate variability and change in the terms that are meaningful to agriculture. The objective of this service is to provide these indicators at global scale in an easily accessible and usable format for further downstream analysis and forcing of agricultural impact models, both gridded and location specific.

A total of 26 indicators are provided, covering the global land area at the spatial resolution of 0.5°x0.5° lat-lon grid. For many indicators a dekad[1] resolution is used, a unit often used in agricultural sciences that allows aggregation of (summable) indicators to varying growing seasons and crop phenological phases around the world, more precisely than a monthly resolution would. A brief review of the agroclimatic indicators provided by C3S global agrilculture SIS is given in tables below:

DATA DESCRIPTION	
Horizontal coverage	Global
Horizontal resolution	0.5° x 0.5°
Temporal coverage	1951 to 2099
Temporal resolution	Dekad (10 daily) Seasonal Yearly
Seasonal	netCDF-4
Yearly	Grid

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[1] 10-Day period (1st-10th, 11th-20th, 21st – end of month). 36 dekads for each year. See section 2.2.4 for more information

MAIN VALRIABLES		
Variable	Description	Units
CDD	Maximum number of consecutive dry days (Drought spell)	day
CFD	Maximum number of consecutive frost days (Cold spell)	day
CSDI	Cold-spell duration index	day
WSDI	Warm-spell duration index	day
CSU	Maximum number of consecutive summer days (Hot spell)	day
CWD	Maximum number of consecutive wet days (Wet spell)	day
WW	Warm and wet days	day
DTR	Mean of diurnal temperature range	°C
BEDD	Biologically Effective Degree Days	°C
GSL	Growing Season Length	day
FD	Frost Days	day
ID	Ice Days	day
R10mm	Heavy precipitation days	day
R20mm	Very heavy precipitation days	day
RR	Precipitation sum	mm
RR1	Wet Days	day
SDII	Simple daily intensity index	mm
SU	Summer days	day
TG	Mean of daily mean temperature	K
TN	Mean of daily minimum temperature	K
TNn	Minimum value of the daily minimum Temperature	K
TNx	Maximum value of the daily minimum temperature	K
TR	Tropical nights	day
TX	Mean of daily maximum temperature	K
TXn	Minimum value of daily maximum temperature	K
TXx	Maximum value of daily maximum temperature	K

From this list the following indicators: CDD, CFD, CSDI , WSDI, CSU, CWD have a seasonal resolution, and the GSL has an annual resolution. All others have dekadal resolution.

3. Product description

3.1. Introduction

Agroclimatic indicators represent features of the climate that are used to characterise plant-climate interactions. They can be derived from daily or monthly meteorological variables (e.g. temperature and rainfall). They are often used in species distribution modelling and related ecological modelling techniques, and also in studying phenological developments of plants under varying climate conditions.

Agroclimatic indicators are based on formulas that measure climatic factors and conditions that may positively/negatively affect vegetation and may correlate to the main type of vegetation of an area. They are commonly used in agriculture to reconstruct climate and environmental changes such as climatically induced phases of plant growth, moisture and heat supply, drought spells, etc.

Agroclimatic indicators provided by this service are calculated directly from climate variables, and consist of two main categories of indicator:

- **Generic Agroclimatic Indicators:** generally these are aggregation, accumulation or occurrence indicators calculated as a function of particular atmospheric variable (temperature and precipitation).

- **Tailored crop-specific indicators:** These indicators require information such as sowing date, harvest date, growing range of min and max temperatures, etc. in order to provide outputs specific to the crops of interest.

C3S Global Agriculture SIS provides both pre-computed indicator datasets and workflows for on-demand generation of crop-specific indicators. The former ensures that indicators of common interest, that do not require tailoring, are readily available to users via the C3S CDS Catalogue and CDS Toolbox. The latter case provides the opportunity for users to generate data that is specific to their purpose, with appropriate guidance and support provided.

All of the generic agroclimatic indicators are pre-computed and the crop-specific indicators are computed on-demand, using standard CDS Toolbox workflows. The crop specific indicators cover four main crops of global interest: wheat, maize, rice and soybean.

3.2. Geophysical product description

3.2.1. Generic agroclimatic indicators

C3S Global Agriculture SIS agroclimatic indicator products include 26 indicators and cover global land areas. All indicators are computed from realizations of daily data, derived from two essential climate variables (ECV):

1. Surface air temperature

- Daily 2m surface air temperature minimum (TN)
- Daily 2m surface air temperature maximum (TX)
- Daily 2m surface mean air temperature (TG)

2. Precipitation
   - Daily total precipitation (RR)

A total of 26 indicators were adapted from the European Climate Assessment & Dataset project (ECA&D; Klein Tank, 2007) collection for their general relevance to agriculture, especially the priority crops, but not specific to any particular crop. Table 1 lists the agroclimatic indicators provided by C3S global agriculture SIS along with information on their application in agriscience.

Table 1. List of agroclimatic indicators, their description and general application in agriscience

Acronym	Description	Application
CDD	Maximum number of consecutive dry days (Drought spell)	Drought monitoring, drought damage indicator
CFD	Maximum number of consecutive frost days (Cold spell)	General frost damage indicator
CSDI	Cold-spell duration index	Provides information on reduced blossom formation or reduced growth
WSDI	Warm-spell duration index	Provide an indication concerning the occurrence of heat stress on reduced blossom formation or reduced growth.
CSU	Maximum number of consecutive summer days (Hot spell)	Provides information on heat stress or on optimal growth for C4 crops (e.g. maize)
CWD	Maximum number of consecutive wet days (Wet spell)	Provides information on drought/oxygen stress/ crop growth (i.e. less radiation interception during rainy days)
WW	Warm and wet days	Provide an indication of occurrence of various pests insects and especially fungi Provides an indication concerning the crop development, especially leave formation.
DTR	Mean of diurnal temperature range	Provides information on climate variability and change. Also serves as the proxy for information on the clarity (transmittance) of the atmosphere

BEDD*)	Biologically Effective Degree Days	Determines crop development stages/rates. Crop development will decelerate/accelerate below and above certain threshold temperatures.
GSL	Growing Season Length	Provides an indication whether a crop or a combination of crops can be sown and subsequently reach maturity within a certain time frame
FD	Frost Days	Provides information on frost damage
ID	Ice Days	Provides information on frost damage
R10mm	Heavy precipitation days	Provides information on crop damage and runoff losses
R20mm	Very heavy precipitation days	Provides information on crop damage and runoff losses
RR	Precipitation sum	Provides information on possible water shortage or excess.
RR1	Wet Days	Provides information on intercepted reduction
SDII	Simple daily intensity index	Provides information on possible run off losses.
SU*)	Summer days	Provide an indication concerning the occurrence of heat stress. Also base for crop specific variants for heat/cold stress (above/below the crop specific optimal temperature thresholds)
TG	Mean of daily mean temperature	Provides information on long-term climate variability and change
TN	Mean of daily minimum temperature	Provides information on long-term climate variability and change
TNn	Minimum value of the daily minimum Temperature	Provides information on long-term climate variability and change
TNx	Maximum value of the daily minimum temperature	Provides information on long-term climate variability and change
TR	Tropical nights	Provide an indication of occurrence of various pests.
TX	Mean of daily maximum temperature	Provides information on long-term climate variability and change
TXn	Minimum value of daily maximum temperature	Provides information on long-term climate variability and change
TXx	Maximum value of daily maximum temperature	Provides information on long-term climate variability and change

*) these indicators have been pre-calculated for the range of threshold temperatures

The finest temporal resolution that is commonly used in climate science for generating climate indicators is 1 month. For agronomical practices an accurate indication of for example crop emergence, flowering occurrence etc., is useful. Therefore, to have a better indication when crop emergence, flowering, etc., takes places (given the provided weather data series) the temporal resolution should be finer than one month. Interpolation from two one month periods will provide a less accurate indication for example flowering indication than can be obtained when two 10 day periods are used. Hence the temporal resolution of agroclimatic indicators have been improved by a factor of 3, splitting the calendar year into chunks of nominally 10 day periods (also known as “dekads”). Thus the date scale within each year would be:

- 01-10 Jan (10 days)
- 11-20 Jan (10 days)
- 21-31 Jan (11 days)
- 01-10 Feb (10 days)
- 11-20 Feb (10 days)
- 21-28/29 Feb (8/9 days)
- …

From the dekadal resolution, it will be possible to aggregate the data up to calendar months, quarterly seasons, or indeed to approximate any arbitrary growing season. The aggregation method will depend on the indicator, e.g. min, max, sum, mean. To compensate for slightly varying number of days, the mean should be weighted accordingly.

It should be noted that dekadal resolution is not appropriate for indicators representing a continuous spell of weather (e.g. warm, cold, wet, dry, etc.), since the 10 day boundary will interfere with the number of consecutive days attaining a threshold. Therefore these indicators are computed for 3 month periods representing the standard meteorological seasons:

- Dec, Jan, Feb (DJF)
- Mar, Apr, May (MAM)
- Jun, Jul, Aug (JJA)
- Sep, Oct, Nov (SON)

Note: The winter season (DJF) of a year is composed of December the current calendar year and January and February of the following calendar year (e.g. DJF 2000 is composed of Dec 2000, Jan 2001 and Feb 2001)

3.2.2. Input Data

To generate the agroclimatic indicators for historical and future time periods, bias-corrected climate datasets provided through Inter-Sectoral Impact Model Intercomparison Project (ISIMIP[2]) have been used. ISIMIP is a community-driven climate impacts modelling initiative aimed at contributing to a quantitative and cross-sectoral synthesis of the differential impacts of climate

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[2] https://www.isimip.org/protocol/

change. ISIMIP project was organised into 3 main simulation rounds, of which the 'ISIMIP Fast Track' product has been used to produce the present indicator set.

For each simulation round a set of gridded bias-corrected climate variables have been produced to be used as input data for running impact models. These climate datasets contain daily-resolution, bias-corrected climate data from 5 CMIP5 GCMs covering the period 1950-2099 (historical run up to 2005), downscaled to a 0.5°x0.5° lat-lon grid. They cover the global land area.

The ISIMIP Fast Track climate forcing data is used for generating the current Agroclimatic indicators. Climate variables from ISIMIP Fast Track are bias-corrected using method described by Hempel et al. (2013). Table 2 shows the availability of ISIMIP Fast Track datasets for different GCM/emission scenarios, covering 1951 - 2099.

Table 2. Availability of ISIMIP Fast Track climate datasets

Climate Model	**Scenario**				
	Historical	rcp26	rcp45	rcp60	rcp85
GFDL-ESM2M	✓	✓	✓	✓	✓
HadGEM2-ES	✓	✓	✓	✓	✓
IPSL-CM5A-LR	✓	✓	✓	✓	✓
MIROC-ESM-CHEM	✓	✓	✓	✓	✓
NorESM1-M	✓	✓	✓	✓	✓

Agroclimatic indicators have been pre-calculated for this complete matrix of GCM/RCP combinations.

For the historical 'observations', the "Watch Forcing Data methodology applied to ERA-Interim (WFDEI)" (Weedon et al. 2014) were used to generate observational historical Agroclimatic indicators for the 1981-2010 climatological period. This datasets is available at the same spatial resolution of ISIMIP climate datasets and covers the time range of 1979 to 2013 (Weedon et al. 2014).

3.2.3. Crop specific parameters and maps

To facilitate the assessment of tailored crop-specific indicators we have chosen not to precalculate these as the number of options is near indefinite. Instead we provide the necessary information to allow the user to calculate these on demand, such as sowing date, harvest date, growing range of min and max temperatures, thermal requirements, geographical distribution, etc. This way the user can generate outputs specific to the crops of interest.

Crop specific maps and parameters have been compiled, that can be accessed through the specific tools (getCropVariable, getCropMask) in the C3S Toolbox above, but that cannot be directly downloaded by the user. For the world's four main staple crops (wheat, rice, soybean and maize/corn) they provide grid based information on

- acreage under various technologies (subsistence, low input, high input or irrigated) that serve to spatially aggregate indicators
- crop calendar information (early average and late sowing and harvest dates) that serve to temporally aggregate indicators
- crop thermal requirements (tsums defining emergence to anthesis, emergence to maturity and anthesis to maturity periods)
- crop mega-environments that serve to spatially aggregate indicators (only for wheat and maize)

For further documentation on the origin and processing of these data see Global Agriculture SIS Algorithm Theoretical Basis Document (ATBD) document.

The following variables can be accessed through the Toolbox:

Variable	Description
area_rs_h	harvested area, rainfed, subsistence
area_rs_p	physical area, rainfed, subsistence
area_rh_h	harvested area, rainfed, high input
area_rh_p	physical area, rainfed, high input
area_rl_h	harvested area, rainfed, low input
area_rl_p	physical area, rainfed, low input
area_ir_h	harvested area, irrigated
area_ir_p	physical area, irrigated
sow_a	average sowing/planting dekad
sow_e	early sowing/planting dekad

sow_l	late sowing/planting dekad
har_a	average harvest dekad
har_e	early harvest dekad
har_l	late harvest dekad
tsumEA	temperature sum from emergence to anthesis
tsumAM	temperature sum from anthesis to maturity
tsumEM	temperature sum from emergence to maturity
ME1*)	mega environment 1
...	mega environment n
ME8/12	mega environment 12 for wheat, mega environment 8 for maize

*) only provided for wheat and maize; definition of each mega environments in terms of climatic constraints differ per crop; see ATBD document.

3.3. Product target requirements

Data from over 30 Global Climate and Earth System Models (GCMs and ESMs) contributing to the Climate Model Inter-comparison Project phase 5 (CMIP5) are available for use in climate impacts assessments. The CMIP5 provided a framework for coordinated climate change experiments aimed at:

- evaluating how realistic the models are in simulating the recent past,
- providing projections of future climate change on two time scales, near term (out to about 2035) and long term (out to 2100 and beyond), and
- understanding some of the factors responsible for differences in model projections, including quantifying some key feedbacks such as those involving clouds and the carbon cycle.

The models are driven by Representative Concentration Pathways (RCP) emissions scenarios, specifically RCP4.5 and RCP8.5, which in contrast to the previous set of emissions scenarios, the SRES scenarios (Nakicenovic et al. 2000), take policy intervention and mitigation into consideration.

The typical horizontal resolution of the latest versions of CMIP5 models is around 1°- 2° for the atmospheric component and 1° for the ocean. For this reason, their ability to capture local-scale (usually tens of kilometres) or even regional-scale patterns that are directly relevant to end users in agriculture sector for decision making and mitigation strategy planning is limited. Thus, downscaling approaches, either physical process-based dynamic downscaling or statistical downscaling, are required to remove systematic biases in models and transform simulated climate patterns at coarse grid to a finer spatial resolution of local interest.

Since the technical and human resources needed to downscale the entire suite of CMIP5 GCMs are very large, a limited set of CMIP5 GCMs have been selected for bias correction for ISIMIP Fast Track. Selection of the climate models for the ISIMIP Fast Track has been intended to aid in quantifying the uncertainty in the impacts of a given level of global mean temperature change. Selecting the models have been carried out by exploring the relationship between changes in temperature (either global mean or land-averaged) and precipitation. As a result, 5 models representing the full range between warm & wet and cold & dry climates are included in the set.

The selected GCM datasets are corrected based on a statistical bias correction algorithm, a modified version of Piani et al. (2010) approach to preserve the absolute temperature changes and the relative changes in precipitation and other variables as fundamental elements of the GCM projections (Hempel et al. 2013). Details of bias correction methodology applied for ISIMIP Fast Track climate datasets are further described in Appendix.

The downscaling/bias correction methodology was tested using the global dataset of observed hydrological forcing data (WATCH forcing data, WFD) of the last 50 years and an initial conditions ensemble of simulations performed with the ECHAM5 global climate model for the same period. The results confirm the effectiveness of the methodology for all tested variables (Hempel et al. 2013, Piani et al. 2010, Hagemann et al. 2011).

That, and the fact that AgERA5 was not yet available at the production date, is the reason that for historic data WFD have been used.

3.4. Product Gap analysis

For many users in the agricultural community also assessments of crop development and associated climate anomalies for the running cropping season are highly relevant. This is especially true for the agro-policy and the agro-business communities, as early indications of production anomalies are of paramount importance for tax/subsidies and price volatility.

For that reason the agro-climatic indicators should ideally also be available in near real time, and thus be precalculated for the historical AgERA5, and then to e daily updated once ERA5T becomes online in the CDS.

4. Data usage information

4.1. Practical usage considerations use of products

Despite the recent progress in the development of GCMs, they still exhibit a number of significant systematic biases in their ability to simulate key features of the observed climate system (Randall et al. 2007). Although the application of the bias correction has shown that it effectively improves both the mean and the variance of the precipitation and temperature fields (Hagemann et al. 2011), the users should still be cautious regarding the use of data from a single model in their applications.

Bearing in mind the consideration that has been given in selecting the GCMs, it is recommended to use a multi-model ensemble of agroclimatic indicators instead of individual models in order to achieve reliable results in any impact assessment applications. Also temporal aggregation of data over climatological periods are recommended to remove the uncertainties associated with inter-annual variation of GCM results.

4.2. Known Limitations of product

While the accuracy of GCMs in simulating the large-scale atmospheric circulation has improved markedly in recent years, global models have difficulty resolving the processes that govern local precipitation. One of the drawbacks of the bias correction method that has been used in ISIMIP Fast Track was that at grid points and within months where the monthly mean precipitation of the GCM is very low and the observational data are significantly higher, the correction factor can get extremely high.

Since a multiplicative correction based on the ratio between the monthly mean precipitation from the WATCH forcing data and the simulated data is applied in this method, this can mean that singular high daily precipitation values might be multiplied by a very high correction factor, leading to unphysically high values of daily precipitation. To fix that problem a limit is imposed on the correction factor μ to 10. In addition, the remaining extremely high precipitation values are truncated at 400 mm/day.

Despite the criteria that are imposed to avoid generating unrealistic precipitation values, comparison between bias corrected data and observational data indicated high values in some regions. Hence the results should be interpreted with caution.

5. Data access information

5.1. Climate Data Store

The Copernicus Climate Change Service provides data storage infrastructure and make ECV data products available through the CDS. The store provides not only consistent estimates of ECVs, but also climate indicators, and other relevant information about the past, present, and future evolution of the coupled climate system, on global, continental, and regional scales. It supports users with data dissemination and visualization tools.

The C3S 422 Lot1 service provides dedicated level 2 user support to the CUS Jira Ticketing Service. In addition to submitting enquires through the portal a knowledge base is available to users which can be searched for information.

5.2. C3S Global Agriculture data

All C3S422 Global Agriculture data, data stream 1 agroclimatic indicators, are expected to be available via the CDS starting in Q2 2019.

5.3. User Support

A dedicated service desk has been set up, the Copernicus User Support (CUS) team, which provides support to users of the CAMS and C3S services at ECMWF. All enquiries about the C3S422 Global Agriculture datasets must be submitted through the service desk where appropriate agents will deal with it.

There is a portal (http://copernicus-support.ecmwf.int) where customers can submit enquiries using a form (split into “Data Request”, “Documentation and Scientific Questions”, “Events, Media and Legal” and “Report an Incident”). The information provided in this form is received by the CUS. Once submitted, the user may add comments or further information to the issue, including responding to questions / requests for additional information from the support team.

6. Concluding remarks

By providing access to these generic and crop specific agro-climatic indicators C3S will greatly facilitate the use of climate data by the agricultural community. User workshops repeatedly confirmed interest in these data. The route chosen here, providing pre-calculated indicators based on a selection of bias corrected GCMs/RCPs scenarios, will a) make life much easier for agronomists with relatively limited expertise on climate change, and b) immensely improve response time of any online apps that users may built to interact with such data.

Of course this comes at the cost of limitations in climate model selection from the CMIP5 collection (and in the future CMIP6), let alone that RCM output can be selected for similar purposes. Two recommendations are related to this

- Pre-calculated these indicators for the AgEra5 archive and especially, also for the near real time data from this source once these become available; many users have stressed repeatedly the great potential value of analysing the running cropping campaign.
- To allow the more experienced agricultural users complete freedom in the choice of climate input for indicator calculation it is recommended to make available the (python) software used for offline calculation of the indicators under this contract, as an online tool in the C3S Toolbox.

7. References

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8. List of tables

9. Appendix

[The information regarding the bias correction methodology for ISIMIP Fast Track is directly provided from the fast track bias correction fact sheet, available at https://www.isimip.org/documents/16/Fact_Sheet_Bias_Correction.pdf]

Bias correction methods are often applied within Climate impact studies to correct the climate input data provided by General Circulation Models (GCMs) or regional climate models for systematic statistical deviations from observational data. They generally adjust the long-term mean by adding the average difference between the simulated and observed data over the historical period to the simulated data, or by applying an associated multiplicative correction factor. In addition, differences between the variance of the simulated and observed data are often corrected. Bias correction is advantageous for the following reasons:

- It allows for comparison of observed and simulated impacts during the historical reference period, and for a smooth transition into the future.

- The bias corrected data for the future period account for changes in the climate variables in comparison to the current status. Accurate description of impacts that are triggered when certain critical thresholds (in temperature or precipitation, for example) are exceeded, require such an adjustment to the reference starting level. Simply describing the change in impacts starting from an uncalibrated climate-model-based reference level, cannot capture this threshold activated behaviour.

- Adjustment of the variance of the simulated data may help to get a more realistic understanding of the impacts that depend on changes in both the mean and variability of the data. As the GCM data are provided on a coarser grid (approximately 2 x 2 degree) than the observational data, correction of the variance ensures that a realistic (higher) variance is attributed to the downscaled data (on the 0.5 x 0.5 degree ISIMIP grid). Such a variability change is not captured by a simple interpolation of the GCM data.

- Bias correction also incorporates the more detailed height information associated with the observational data.

On the other hand, there are serious disadvantages:

- Even the most basic bias correction method (adding the mean deviation from the observed data to the simulated data) destroys the physical consistency of the data.

- Some bias correction methods (such as the one described by Piani et al., 2010) have the potential to change the trend in the simulated climate data. While adequately representing the mean state of the observed period and the associated variability, these methods may change the climate signal (absolute changes in temperature and relative changes in precipitation) projected by the GCMs. This corresponds to introducing a new level of uncertainty, comparable in magnitude to the inter-GCM spread of the climate projections (Hagemann et al., 2011).

Within ISIMIP we decided to apply a bias correction method, fully aware of these disadvantages, since the described advantages are essential to the description of changes in impacts. However, given the lively debate related to this issue, we are committed to describing transparently what climate change information is actually retained from the GCMs and what is lost.

We modified the Piani et al. (2010) approach to preserve the absolute temperature changes and the relative changes in precipitation and other variables as fundamental elements of the GCM projections. Here we describe the algorithm.

9.1. Adjustment of the monthly mean values

9.1.1. Temperature

The bias correction algorithm for temperature preserves the monthly mean values provided by the GCM, by adding a grid-point and month specific (one for January, one for February etc.) constant offset. In this way the absolute changes in temperature are not modified by the bias correction but the reference starting level is adjusted to the observational level provided by a 40-year average of the Watch data.

It is essential for ISIMIP that the absolute temperature changes projected by the GCMs are not changed, since the project is dedicated to the description of impacts at different levels of global warming. As the global warming information provided will be based on the non-bias-corrected monthly GCM data (the observational data needed for the bias correction are not available over the ocean) we must ensure that it stays consistent with the climate change signal used within the impact simulations.

The minimum and maximum daily temperatures (Tmin and Tmax respectively) are also corrected for systematic bias. The algorithm ensures that in the historical period, the mean distance between the maximum (minimum) daily temperature value and the daily average temperature (T) is preserved. This is achieved by calculating the following factor over the historical period:

$$k = \text{mean}[\text{Tmin(max)}_{.\text{Watch}}-\text{T}_{\text{Watch}}]/\text{mean}[\text{Tmin(max)}_{\text{GCM}}-\text{T}_{\text{GCM}}],$$

and the resulting bias-corrected maximum (minimum) temperature is then given by:

$$\text{Tmin(max)}_{\text{BC}}=k[\text{Tmin(max)}_{\text{GCM}}-\text{T}_{\text{GCM}}]+\text{T}_{\text{GCM}}$$

9.1.2. Precipitation

For precipitation data we use a multiplicative correction to adjust the monthly mean values in the historical period to the observed climatological monthly mean values. This ensures that the monthly mean precipitation values are preserved up to a constant multiplicative factor. The monthly means are multiplied by a grid-point and month specific (one for January, one for February etc.) constant correction factor (*hereafter* μ). We thereby ensure that the relative change in precipitation as described by the original GCM data is preserved.

In combination with the applied temperature correction, we preserve the hydrological sensitivity of the GCM (relative change of precipitation per degree of warming). In comparison to the additive approach used for the temperature correction, a multiplicative approach was chosen for the precipitation data to ensure non-negative precipitation values.

Snowfall is not directly bias corrected, but rather the ratio of snowfall to rainfall in the original GCM data is preserved, based on the bias-corrected rainfall data.

9.1.3. Other variables

Monthly values of the other variables that are also subject to positivity constraints are corrected in a multiplicative way as described above for precipitation. The only exception is wind. In the case of wind, the magnitude of wind is corrected using the multiplicative algorithm. The individual wind components are then derived by preserving the direction of the original GCM data.

9.2. Adjustment of the daily variability

As described above, we adjust neither the monthly variability of the temperature information in absolute terms, nor the monthly variability of the other variables in relative terms. However, we do adjust the daily variability around the monthly mean values as described below. The method is similar to the correction of the daily variability in Haerter et al. (2011).

9.2.1. Temperature

The daily variability of the temperature data is simply adjusted to reproduce the variability of the observed data. The data is processed as follows:

1. Subtract the monthly means from both data sets.
2. Multiply the residual daily variations by a constant month and grid point specific factor, thereby matching the variance of the simulations to the variance of the observations.
3. These bias corrected daily variations are afterwards added to the bias corrected monthly means provided by the GCM.

9.2.2. Precipitation

For precipitation we again adopt a multiplicative approach, which adjusts the relative variability. The data is processed as follows:

1. Normalize the daily precipitation data from the GCM and the Watch data set by dividing by their monthly mean values. The daily variability of dry months, specified by a certain threshold, is not modified.

2. After normalization of the wet months, map the distribution of the simulated data to the distribution of the observed daily data using a transfer function [as introduced by Piani et al. (2010) and applied to the non-normalized data within Water-MIP]. The transfer function corrects both the frequency of dry days as well as the distribution of the precipitation intensity to the observed statistics.

3. For the future projections, apply the generated transfer functions to the normalized daily precipitation of wet months.

4. Multiply the transferred data by the bias corrected monthly mean values. By ensuring the mean value of the transferred normalized daily data is equal to one (by simply dividing by the associated mean value) we ensure that the corrected monthly mean values are preserved when factoring in the daily variability.

9.2.3. Other variables

For the other variables we also use the same multiplicative approach as for precipitation. However, in these cases the situation is simplified as it usually does not require a treatment of months or days with mean values of zero.

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