Climate Change

Copernicus Climate Change Service (C3S)

Energy Seminar

Climate Data and Bias Adjustment

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Letizia Lusito | Inside Climate Service

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Copernicus Climate Change Service (C3S) Energy Seminar: Climate Data and Bias adjustment

OUTLINE

Motivation: the C3S Enhanced Operational Global Service for the Energy Sector and the need for

- climate data
- bias adjustment

Climate data:

- HIST: the ERA5 system
- SEAS: overview of the C3S and CMCC systems
- PROJ: the CMPI6 experiment and overview of projection models

Bias adjustment (b.-a.)

- Delta approach
- Quantile matching (QM)
- CDF-transform (CDFt)

Results from Lot1

- Bias adjustment of HIST ERA5 wind speed and GWA
- Evaluation of bias adjusted datasets

Conclusions and future outlook

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Climate Data and Bias adjustment: the need for climate data

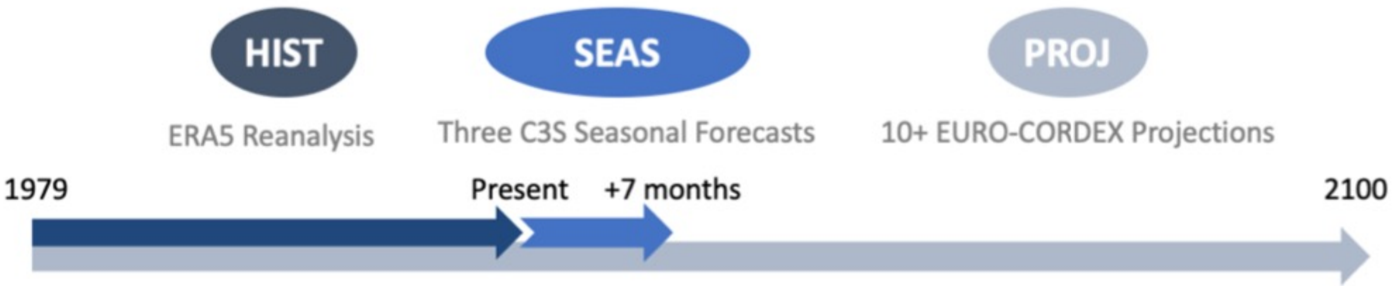
CHALLENGE/MOTIVATION

Climate Indicators

Major transformations in the ENERGY sector:

- increasingly higher share of power supply from variable renewable energy (RE) sources, (wind and solar)[1]
- taking place against a variable and changing climate

***C3S Enhanced Energy* operational service**:
to deliver an enhanced operational energy service at the global scale covering data about the **past climate**, **multi-model seasonal forecast** and **multi-model climate projections**



[1]most of the electricity production sector should be decarbonized by 2050 in order to fulfil the 2°C/1.5°C, warming target of the international agreements.

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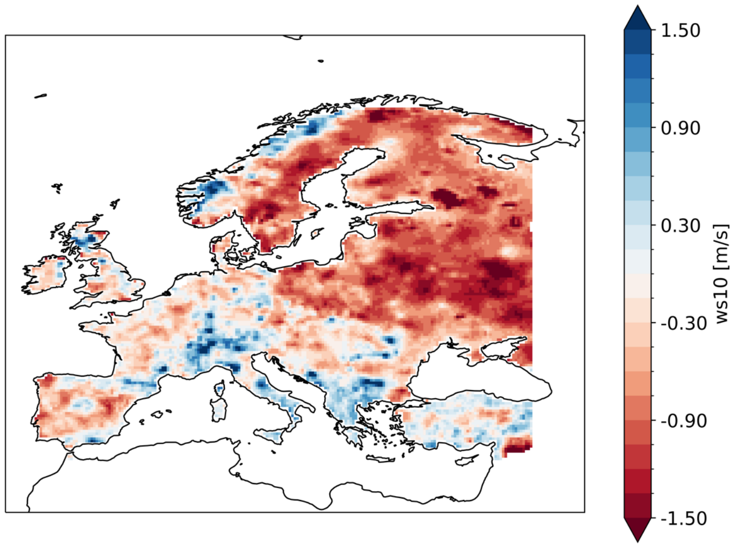
CHALLENGE/MOTIVATION

Fully physically based climate simulation chain formed by **General Circulation Models (GCMs) dynamically downscaled through Regional Climate Models (RCMs)**, are powerful tools for describing general climate conditions,

Their direct use in climate change impact or adaptation studies, risk assessment or other analyses requiring climate projections at a regional or local scale is still **challenging**.

These data present **systematic biases** (systematic model errors caused by imperfect conceptualization, discretization, coarse representation of regional features, and spatial averaging within model grid cells) when compared to observations.

Bias adjustments: the most adopted method to provide 'corrected' climate scenarios; it consists in the application of different post-processing techniques or adjustments that bring the models towards the observed climatology/other observational climate datasets.
This statistical post-processing step adjusts **selected statistics** (mean, variance, distribution) of the so-called "raw" model simulations to better match observed time series over the reference period (Bartok et al., 2019).



Bartók, Tobin, Vautard, Vrac, Jin, Levavasseur, Denvil, Dubus, Parey, Michelangeli, Troccoli, Saint-Drenan, A climate projection dataset tailored for the European energy sector, Climate Services, Volume 16, 2019, 100138, ISSN 2405-8807,https://doi.org/10.1016/j.cliser.2019.100138.

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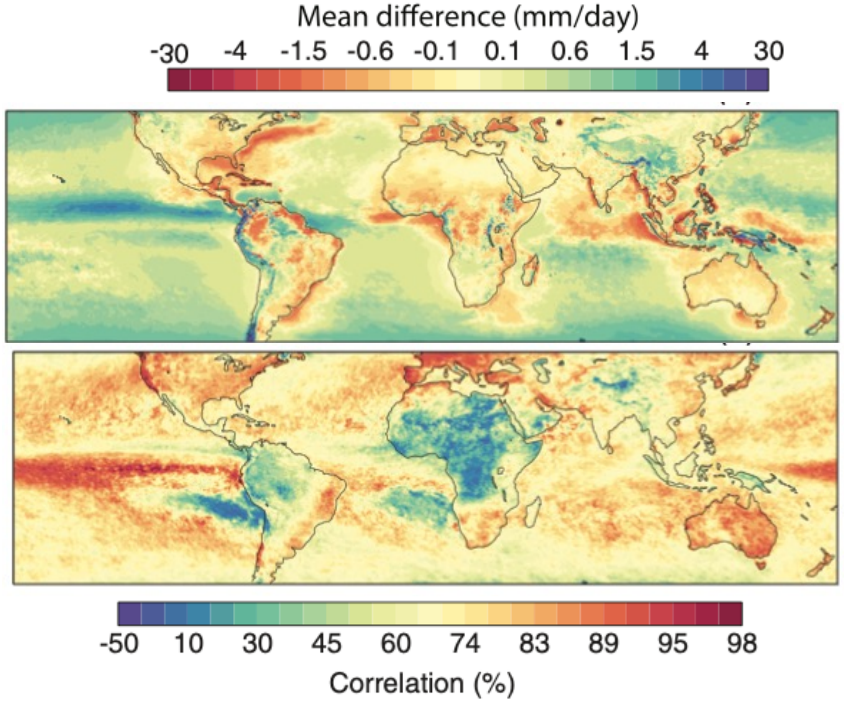
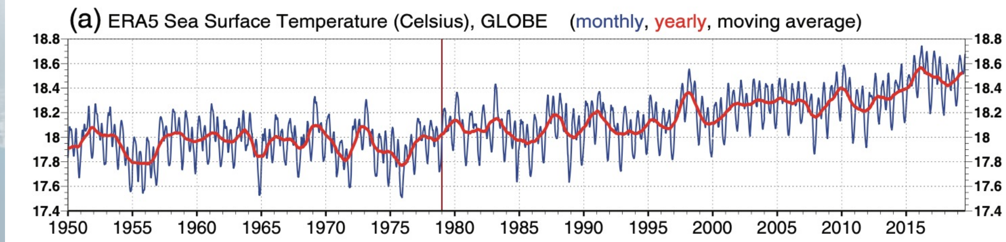
The ECMWF Reanalysis v5 (ERA5)

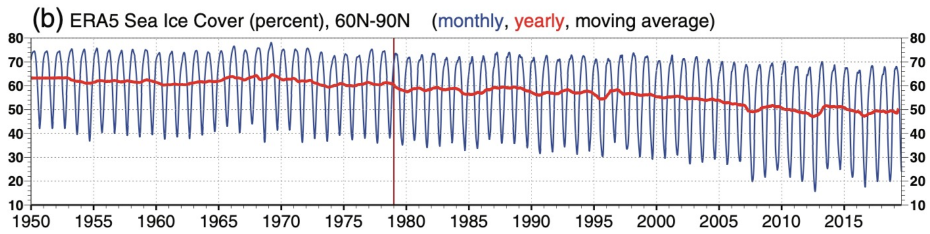
the fifth generation ECMWF atmospheric reanalysis of the global climate,



Detailed record of the global atmosphere, land surface and ocean waves from 1950 onwards. Covering the Earth on a 31 km grid and resolving the atmosphere from the surface up to a height of 80km (137 levels).
Based on the Integrated Forecasting System (IFS) Cy41r2 with a Data Assimilation methodology, based on a hybrid incremental 4D-Var system (12 variables).

Ensemble component (1+9 members) which provide **background-error estimates** for the deterministic system, allowing for the estimation of uncertainties for all variables at reduced spatial and temporal resolutions (3-hourly and half the spatial resolution).





Hersbach, Bell, Berrisford, et al. The ERA5 global reanalysis. *Quarterly Journal of Royal Meteorological Society* 2020; 146: 1999– 2049. https://doi.org/10.1002/qj.3803

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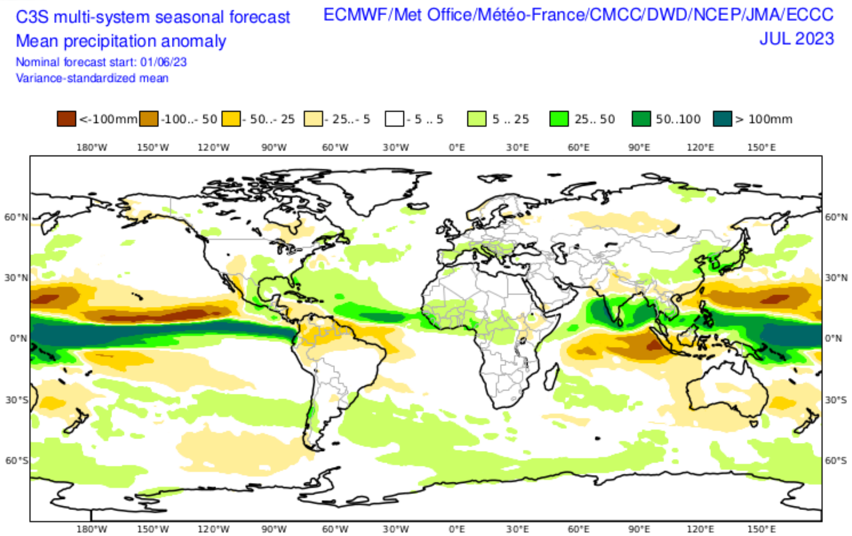
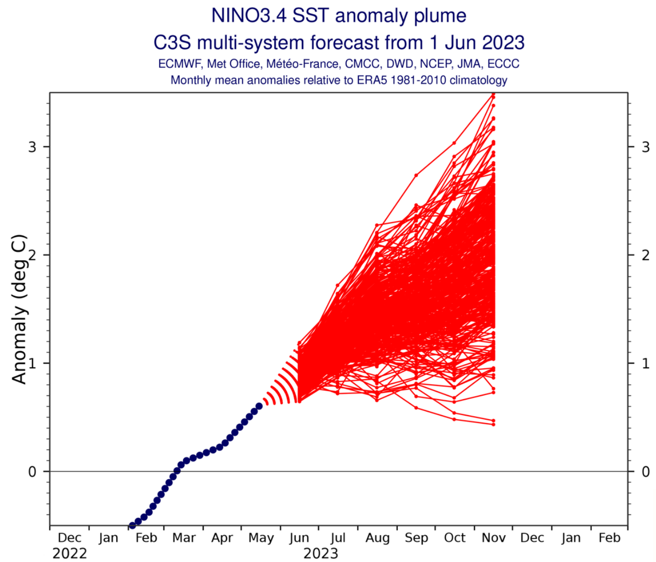
The C3S ensemble global seasonal forecast system.

Ensembles of simulations of possible weather scenarios: probabilities of how likely it is that a season will be wetter, drier, warmer or colder compared to the average for that period of the year. This is possible because some components of the Earth system, patterns such as El Niño, La Niña, the North Atlantic Oscillation (NAO) and others, evolve more slowly than the “chaotic” atmosphere, and in a rather predictable, so their influence on the atmosphere can be anticipated.

Combination of individual forecasts produced by eight global leading centres that are joined in a **single multi-system seasonal forecast**, to compensate for some of the systematic errors each of the model has.





Prediction systems: ECMWF, The Met Office, Météo-France, the German Weather Service (DWD), CMCC, the US National Centers for Environmental Prediction, NCEP, Japan Meteorological Agency (JMA) and Environment and Climate Change Canada (ECCC).

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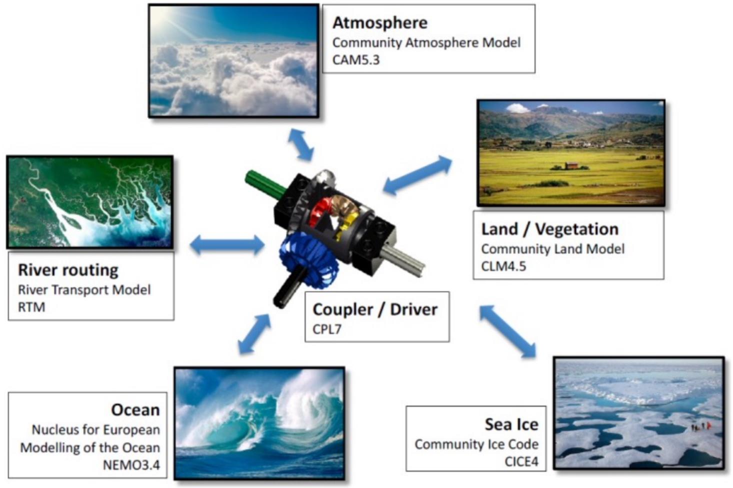
The CMCC Seasonal Prediction System model CMCC-SPS3.5

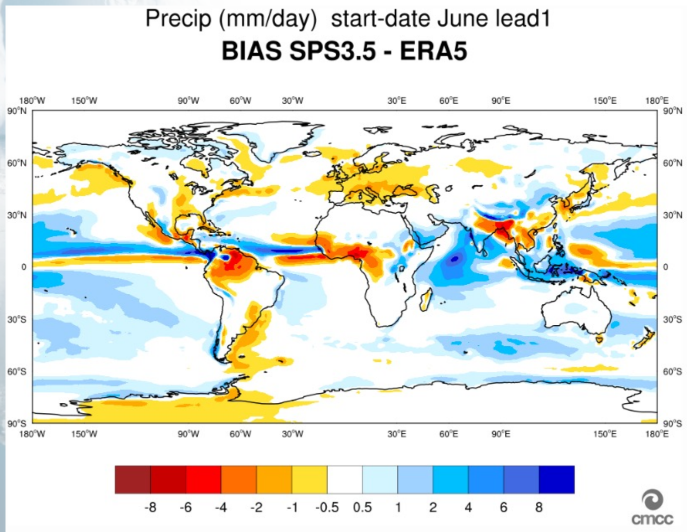
Coupled Model: several independent but fully coupled model components simultaneously simulating the Earth's atmosphere, ocean, land, sea ice and river routing, together with a central coupler/driver component for data synchronization and exchange

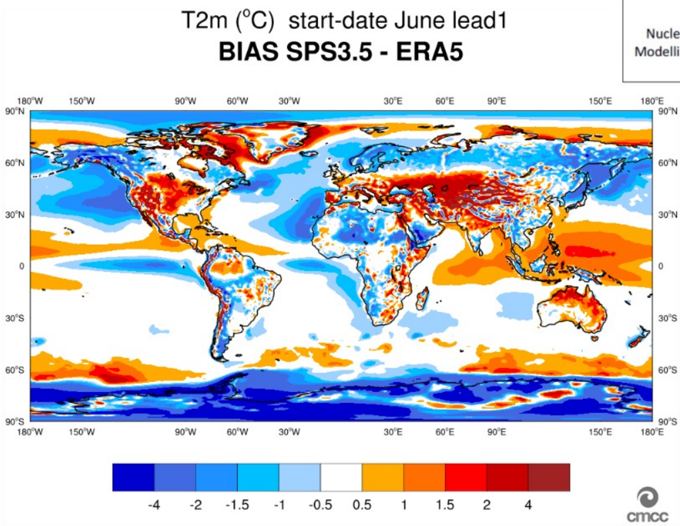
Operated monthly in Ensemble seasonal mode (**6-month predictions**)

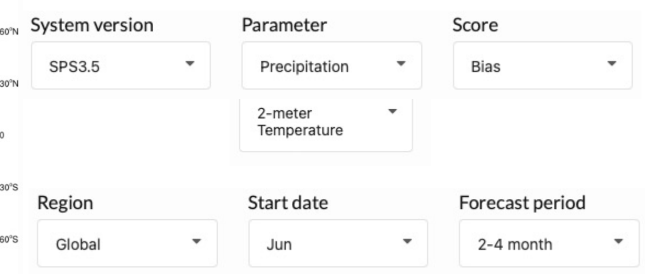
Monthly **ensemble hindcasts** (1993-2016) for performance evaluation and bias adjustments to operational forecasts

Forecast **ensemble size**: 50 in operational, 40 in hindcast mode









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Gualdi et al (2020) CMCC Technical Note RP0288 DOI: https://doi.org/10.25424/CMCC/SPS3.5

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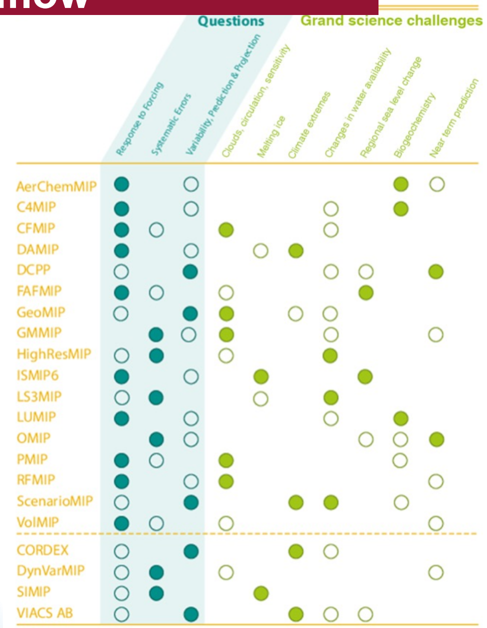
Climate Data and Bias adjustment: the PROJ climate streamflow

The World Climate Research Programme (WCRP) Working Group on Coupled Modelling oversees the Coupled Model Intercomparison Project, which is now in its 6th phase (CMIP6).

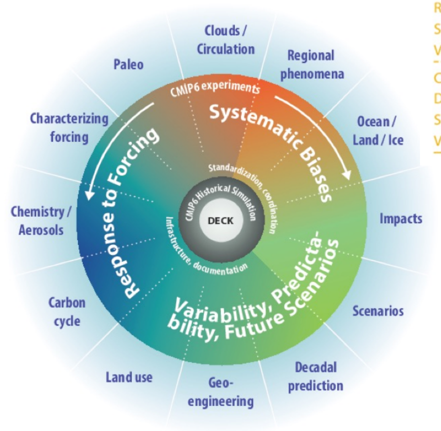


DECK four baseline experiments:

(a) a historical Atmospheric Model Intercomparison Project (*amip*) simulation,
(b) a pre-industrial control simulation (*piControl* or *esm-piControl*),
(c) a simulation forced by an abrupt quadrupling of CO2 (*abrupt-4×CO2)* and
(d) a simulation forced by a 1%yr−1 CO2 increase (*1pctCO2*).

historical simulation (*historical* or *esm-hist*) that spans the period of extensive instrumental temperature measurements from 1850 to the present.

Experiment short name	CMIP6 label	Experiment description	Forcing methods	Start year	End year	Minimum no. years	Major purpose
AMIP	*amip*	Observed SSTs and SICs prescribed	All; CO_2 concentration prescribed	1979	2014	36	Evaluation, variability
Pre-industrial control	*piControl* or *esm-piControl*	Coupled atmosphere–ocean pre-industrial control	CO_2 concentration prescribed or calculated	n/a	n/a	500	Evaluation, unforced variability
Abrupt quadrupling of CO_2 concentration	*abrupt-4×CO2*	CO_2 abruptly quadrupled and then held constant	CO_2 concentration prescribed	n/a	n/a	150	Climate sensitivity, feedback, fast responses
1 % yr^{-1} CO_2 concentration increase	*1pctCO2*	CO_2 prescribed to increase at 1 % yr^{-1}	CO_2 concentration prescribed	n/a	n/a	150	Climate sensitivity, feedback, idealized benchmark
CMIP6 historical simulation							
Past ~ 1.5 centuries	*historical* or *esm-hist*	Simulation of the recent past	All; CO_2 concentration prescribed or calculated	1850	2014	165	Evaluation



Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

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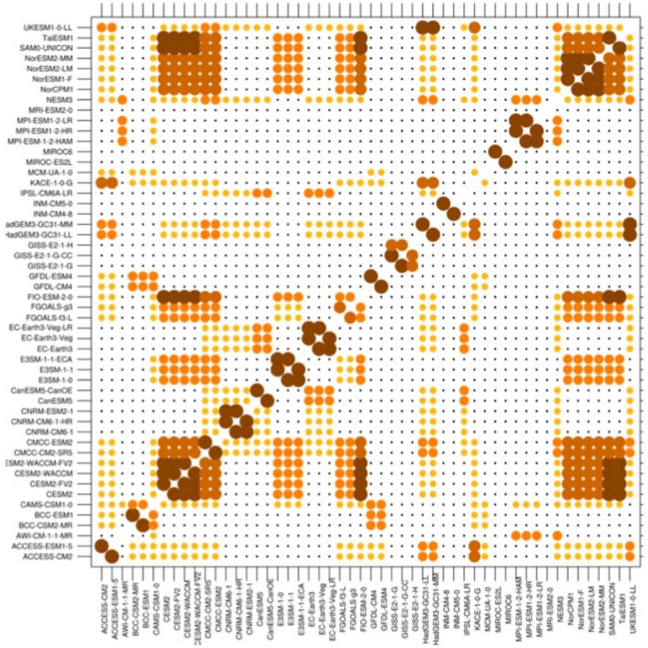
Climate Data and Bias adjustment: the PROJ climate streamflow

CMIP6 projection models to be delivered within C3S-Energy
Model selection based on: components independence, availability of reasonable horizontal and temporal resolution, maximum variability in the Equilibrium Climate Sensitivity (ECS)



4 Shared Socio-economic Pathways (SSPs)

Best case: delivery of 12 datasets (3 models x 4 scenarios)
Conservative case: delivery of 9 datasets (2 models x 4 scenarios)

Model	Variant	Horizon. res.	Temporal res.	Scenarios					ECS (˚C)
CMCC-CM2-SR5	r1i1p1f1	100 km	03hr	historical	ssp126	ssp245	ssp370	ssp585	3.52
EC-Earth3-Veg	r1i1p1f1	100 km	03hr	historical	ssp126	ssp245	ssp370	ssp585	4.31
MPI-ESM1-2-HR	r1i1p1f1	100 km	03hr	historical	ssp126	ssp245	ssp370	ssp585	2.98

Boé, J., Terray, L. Projections climatiques globales de nouvelle génération : résultats sur la France et éléments pour la sélection des modèles, CERFACS Report for EDF, 2023

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Climate Data and Bias adjustment: overview/summary of climate data

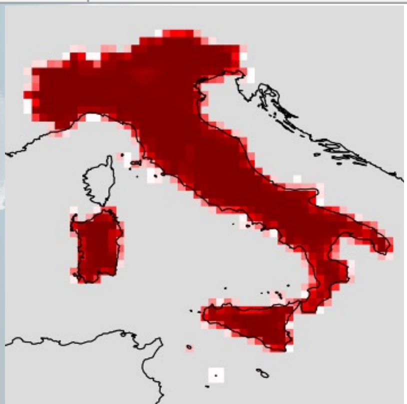
VARIABLES

Temperature| Precipitation| Wind Speed | Solar radiation at surface | Mean sea level pressure |Relative humidity | Wind direction

Historical	
Year 1	• ERA5 extended to rest of the globe, back to 1950, and to near real time • Bias adjustment of wind speed • Assessment of available variables • Investigate use of ERA5 Land for land-based indicators
Year 2	• New variables e.g. RH, WD, MSLP • Bias adjustment of variables identified as requiring it • Possible use of ERA5 Land, which could be used also for projection downscaling and wind and solar power indicators
Year 3	• Tools such as bias adjustment made available on CDS toolbox • Investigate use of updated/new historical datasets

Seasonal Forecasts	
Year 1	• Current system (3 models: ECMWF, MF and UKMO) from European to global domain • Bias adjustment using ERA5, with adjusted wind speed, and current QM approach • Refine validation metrics
Year 2	• Add two additional models (e.g. DWD, CMCC), on global domain • Adjust other variables than wind speed based on adjusted ERA5 • Investigate feasibility of spatial and temporal downscaling (similarly to projections)
Year 3	• Develop multi-model products • Tools such as bias adjustment and downscaling made available on CDS toolbox

Projections	
Year 1	• Process CMIP6 models, a selection of around 10, at 1° spatial, and monthly averages, two scenarios • Bias adjustment using ERA5, with adjusted wind speed, refining adjustment method • Refine model selection method
Year 2	• Downscaling to produce higher spatial (e.g. 1/4°) and temporal (e.g. hourly) resolutions • Adjust other variables than wind speed based on adjusted ERA5 • Introduce new variables (e.g. RH, WD, MSLP) • Develop set of validation tools
Year 3	• Develop multi-model products • Tools such as bias adjustment and downscaling made available on CDS toolbox



SPATIAL AGGREGATION

Computed using the Natural Earth10 **shapefiles as reference** (commonly used boundaries for the global domain) and float masks.

Available for two main levels: country (or **ADM0**) and sub-country (or **ADM1**) (varying in resolution depending on the continent).

Flexible tool, allowing to combine shapefiles from different sources, e.g. ADM1 for countries outside of Europe with NUTS2 for European countries.

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The Delta Change or Change factor method (abb. Delta Method) for B.-A.

- Method that performs the adjustment of a "source" dataset, based on a reference/target dataset (e.g., observations or long-term (30-year) mean of a climate variable for projection models) simply calculating the change factors (or anomalies or deltas) from the averaged datasets:
- The averages of the source and reference/target dataset are matched by performing a scaling adjustment of the source dataset with the delta factors so that the average of the adjusted source dataset is equal to the average of the reference dataset (Navarro-Racines et al., 2020).
- The time series adjustment for temperature is computed as a difference between the prediction/projection and the climatology of the hindcasts/historical run while the time series adjustment for precipitation, solar radiation and wind speed are computed as a ratio (or percentage).

$$F = \frac{< PROJ >}{< ERA5 >} \qquad PROJ_{B.A.} = \frac{PROJ}{F}$$

where the <> brackets indicate the temporal average in a common “calibration” period
The delta factors are calculated separately for each grid point/hour and month

Navarro-Racines, C., Tarapues, J., Thornton, P. *et al.* High-resolution and bias-corrected CMIP5 projections for climate change impact assessments. *Sci Data* **7**, 7 (2020). https://doi.org/10.1038/s41597-019-0343-8

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Climate Data and Bias adjustment: the quantile matching method for B.-A.

The Quantile Matching (QM) Method for B.-A.

an application of the probability integral transform that is designed to adjust the distribution of modelled data, such that it matches observed climatologies by mapping the modelled cumulative distribution function (CDF) of the variable of interest onto the observed CDF

It attempts to find a transformation h of a modelled variable Pm such that its new distribution equals the distribution of the observed variable P_o :

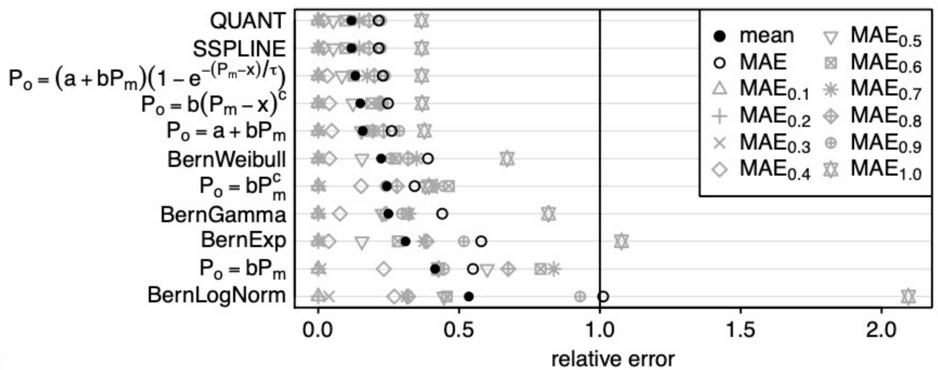
$$P_o = h(P_m)$$

If the distribution of the variable of interest is known, the transformation h is defined as:

$$P_o = F_O^{-1}(F_m(P_m))$$

QM can be achieved by:

- using theoretical distributions to represent the CDFs (distribution derived transformations), e.g. mixture of Bernouilli/Gamma etc.
- parametric transformations, e.g. $P_o = b\, P_m$; . $P_o = a+b\, P_m$
- non parametric transformations, e.g. empirical quantile mapping: the empirical CDFs for both the modelled and observed variables are approximated using tables of the empirical percentiles. Values in between the percentiles are approximated using linear interpolation.



Gudmundsson, L., Bremnes, J.B., Haugen, J.E., Engen Skaugen, T., 2012. Technical note: downscaling RCM precipitation to the station scale using quantile mapping—a comparison of methods. Hydrol. Earth Syst. Discuss. 9, 6185–6201, http://dx.doi.org/10.5194/hessd-9-6185-2012.

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Climate Data and Bias adjustment: the CDF-transform (CDFt) for B.-A.

The CDFt Method for B.-A.

A probabilistic downscaling method where the relationship between statistical properties (i.e. probabilistic) between a target (or reference such as observations or RCMs) and a source (biased projection model or GCMs) datasets are modelled, typically the CDFs.

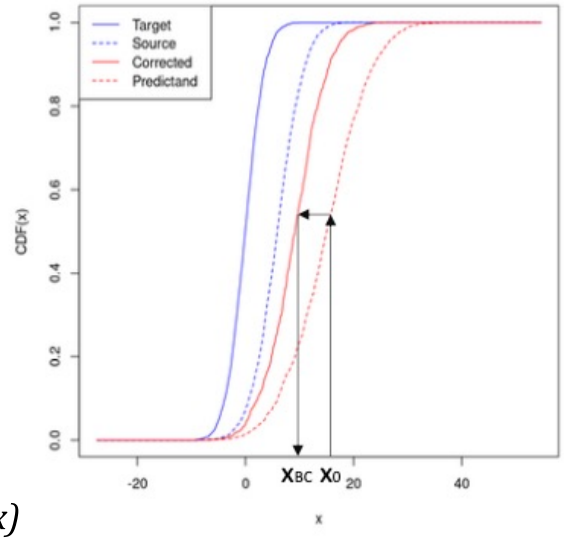
No assumption on the shape of the relationship to be modelled, or on the family of the CDFs, but rather non-parametric correspondences between the predictor and predictand CDFs are used

There exists a transformation T allowing to ''translate'' the CDF of a source variable into the CDF representing the reference climate variable.

$$T\left(F_{Gh}(x)\right) = F_{Sh}(x)$$

with $F_{Sh}(x)$ being the CDF of the reference data for the calibration (h, historical) period and $F_{Gh}(x)$ the CDF of the source/to-be-adjusted for the calibration period.

Thus, T can be used to model the relationship between $F_{Sf}(x)$ and $F_{Gf}(x)$, *i.e.*, same CDFs but for a future (different) period, assuming that $F_{Gf}(x)$ is known in the following way:



$$T(u) = F_{Sh}\left(F_{Gh}^{-1}(u)\right) \quad F_{Sf}(x) = T\left(F_{Gf}(x)\right) \quad F_{Sf}(x) = F_{Sh}\left(F_{Gh}^{-1}\left(F_{Gf}(x)\right)\right)$$

Michelangeli, Vrac, Loukos (2009) Probabilistic downscaling approaches: Application to wind cumulative distribution functions. Geophysical Research Letters, 36, L11708, <doi:10.1029/2009GL038401>

Vrac, Drobinski, Merlo, Herrmann, Lavaysse, Li, Somot (2012) Dynamical and statistical downscaling of the French Mediterranean climate: uncertainty assessment. Nat. Hazards Earth Syst. Sci., 12, 2769-2784, www.nat-hazards-earth-syst-sci.net/12/2769/2012/, <doi:10.5194/nhess-12-2769-2012>.

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The CDF-t Method for B.-A.

The estimates of F_{Sh} , F_{Gh}^{-1}, F_{Gf}, are empirically modelled respectively from the historical observations and the historical and future large-scale simulated data.
Combining them according to

$$F_{Sf}(x) = F_{Sh}\left(F_{Gh}^{-1}\left(F_{Gf}(x)\right)\right)$$

the estimator of F_{Sf} can be calculated

Difference between QM and CDFt
CDFt takes into account the change in the large-scale CDF from the historical to the future time period,
QM only projects the simulated large-scale values onto the historical CDF to compute and match quantiles.

QM cannot provide local-scale quantiles outside the range of the historical observations (limitation for a changing climate context), whereas CDFt allows one to overcome this problem by taking advantage of the simulated future large-scale CDF.

Michelangeli, Vrac, Loukos (2009) Probabilistic downscaling approaches: Application to wind cumulative distribution functions. Geophysical Research Letters, 36, L11708, <doi:10.1029/2009GL038401>
Vrac, Drobinski, Merlo, Herrmann, Lavaysse, Li, Somot (2012) Dynamical and statistical downscaling of the French Mediterranean climate: uncertainty assessment. Nat. Hazards Earth Syst. Sci., 12, 2769-2784, www.nat-hazards-earth-syst-sci.net/12/2769/2012/, <doi:10.5194/nhess-12-2769-2012>.

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Climate Data and Bias adjustment:

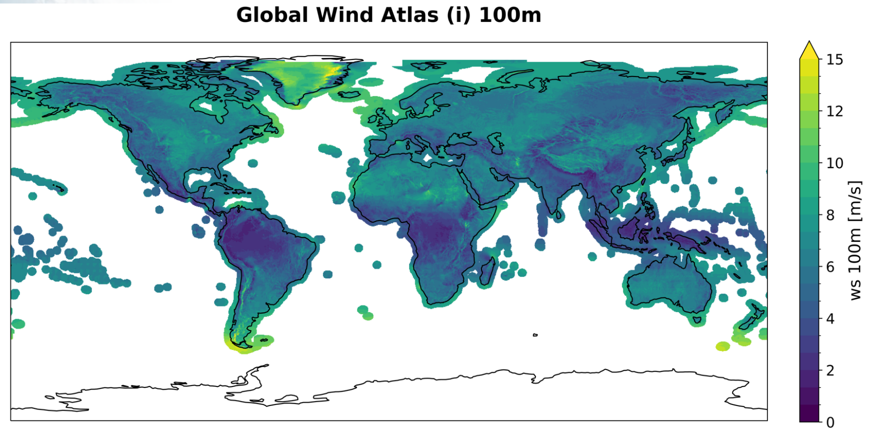
Bias Adjustment for C3S-Energy: METHODOLOGY

HIST streamflow

wind speed at 10 m/ 100 m adjusted by means of the delta method using the Global Wind Atlas, version 3 (GWA3) as reference

GWA is the only global wind speed reference dataset that is available globally

For the time being, only wind speed means are available in the GWA dataset therefore only delta method (based on means) is feasible; QM/CDF-t need long time series in order to calculate quantiles/cdfs.



GWA3:

- available at 250 m resolution globally
- up to **200** km offshore
- at 5 heights: 10, 50, 100, 150 and 200 m
- based on 10 years of simulations 2008:2017
- publicly available on the web

https://globalwindatlas.info

Murcia, J. P., Koivisto, M. J., Luzia, G., Olsen, B. T., Hahmann, A. N., Sørensen, P. E., Als, M. “Validation of European-scale simulated wind speed and wind generation time series”, Applied Energy, vol. 305, 117794 (2022) https://doi.org/10.1016/j.apenergy.2021.117794

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Bias Adjustment for C3S-Energy: RESULTS

HIST streamflow:

wind speed at 10 m/ 100 m adjusted by means of the delta method using the Global Wind Atlas, version 3 (GWA3) as reference

$$F = \frac{GWA}{< ERA5 >}$$

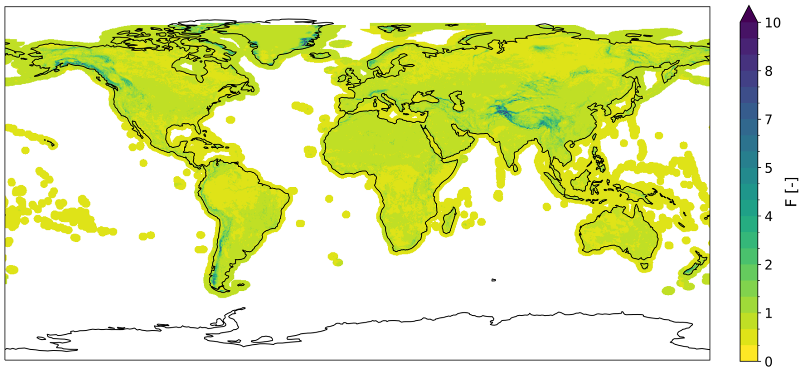
where <ERA5> indicates the ERA5 mean wind speed over the GWA reference period, 2008-2017

$$WS^{h=10,100}_{i,b.a.} = WS^{h=10,100}_{i} * F^{h=10,100}$$

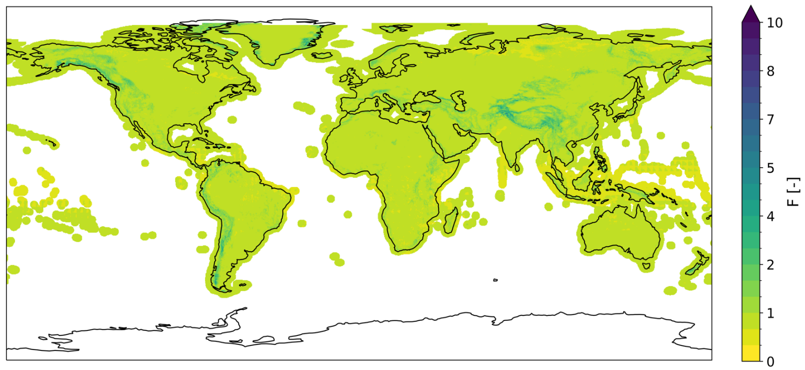
Table 3.1: Change factor minimum, maximum and mean values for heights corresponding to 10 m and 100 m

Height	Minimum	Maximum	Mean
10 m	0.4	18.0	1.0
100 m	0.6	8.1	1.2

Change factor ws 10m



Change factor ws 100m



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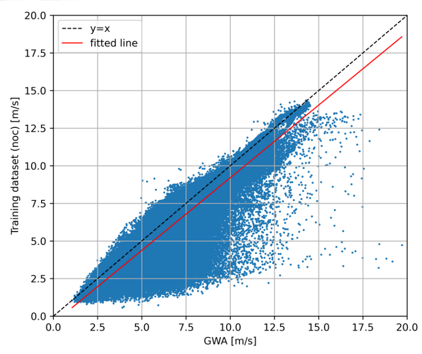
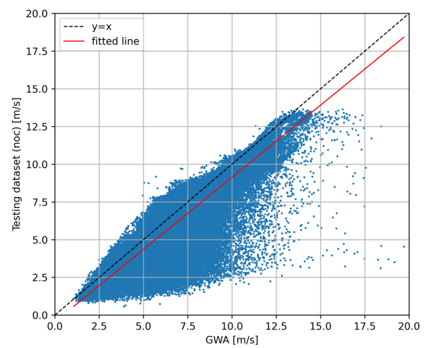
Climate Data and Bias adjustment:

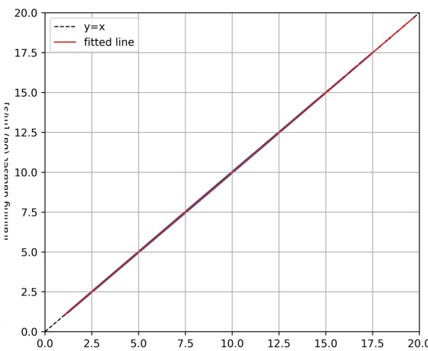
Bias Adjustment for C3S-Energy: VERIFICATION

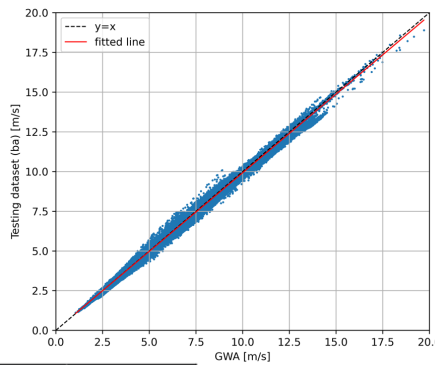
HIST streamflow: wind speed at 10 m/ 100 m adjusted by means of the delta method using the Global Wind Atlas, version 3 (GWA3) as reference

- train_ba: bias-adjusted mean wind speed over the period 2008-2017
- test_ba: bias-adjusted mean wind speed over the period 1971-2000
- train_noc: original mean wind speed over the period 2008-2017
- test_noc: original mean wind speed over the period 1971-2000









Height	ERA5 Dataset	Slope (95%)	Intercept (95%)	R^2	RMSE
100m	Testing (ba)	0.99016 +/- 0.00023	0.01936 +/- 0.00159	0.99448	0.1613
	Testing (noc)	0.95719 +/- 0.00142	-0.43792 +/- 0.01005	0.80920	1.2107
	Training (ba)	0.99941 +/- 0.00001	0.00280 +/- 0.00005	0.99999	0.0050
	Training (noc)	0.96585 +/- 0.00143	-0.45543 +/- 0.01011	0.81012	1.1901

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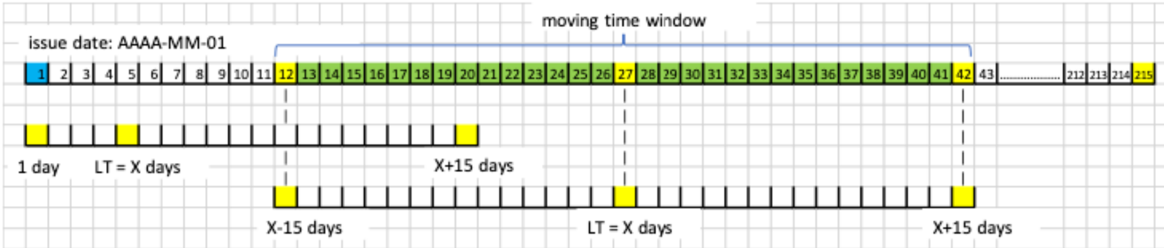
Climate Data and Bias adjustment:

Bias Adjustment for C3S-Energy
SEAS streamflow



B.A. METHODOLOGY:
delta method for the adjustment of GHI, CDFT for 10 m wind speed, precipitation and temperature

TARGET	SOURCE	PREDICTAND
B.C. ERA5 for month MM (1980-2021)	HINDCAST of moth MM (1993-2016)*	FORECAST of month MM (current year)

- Bias correction is applied on each single member as soon as the monthly forecast (forecast of month MM) is downloaded
- Forecasts have a lead time of 7 months (215 timesteps for daily var.)
- The correction will be done for each time-step considering a moving time window of 31 days**
- Source CDF will be built on data from all hindcast members

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Bias Adjustment for C3S-Energy
PROJ streamflow

B.A. METHODOLOGY:
delta method for the adjustment of GHI, CDFT for 10 m wind speed, precipitation and temperature

TARGET	SOURCE	PREDICTAND
ERA 5	PROJ MODELS	PROJ MODELS
1985-2014	1885-2014	2015-2100
BA wind speed	historical scenario	ssp126
ORIG precipitation		ssp245
ORIG solar radiation		ssp370
ORIG temperature		ssp585

- Adjusting by month and by hour
- Adjusting 10 years at a time
- Moving window of 20 years, following the schema 5+10+5

PROGRAMME OF THE EUROPEAN UNION Copernicus Europe's eyes on Earth IMPLEMENTED BY ECMWF ICS Inside Climate Service

Conclusions and future outlook

- Service well underway: the 1st year milestone is approaching
- Improvement of climate data and relative toolbox applications strongly based on the continuous engagement and feedback with users and stakeholders communities
- 2023 achievements:
    - Extension of the historical data period back to 1950
    - Updating of the bias adjustment procedure
    - Implementation of updated operational processing chain, service operations and quality control
    - PROJ/SEAS data streams soon to be initiated

If you are interested, more at ICEM:

- Identifying Gaps in Meteorology Knowledge Required to Further Develop Wind Energy (S.H. Haupt, 27/06)
- MIA: A flexible data-driven system for climate impact modelling applied for subseasonal-to- seasonal prediction of renewable energy in Brazil (G. Perez, 27/06)
- Energy Pathways to 2050 – Evolution in weather-related risks to France's power system (B. Jourdier, 29/06)
- Adaptation of the French Transmission Network to Climate Change – The case of underground lines resilience to extreme heat
- (L. Dubus, 29/06)
- A climate change compatible approach and database for energy systems prospective studies in Europe (L. Stoop, 29/06)

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BACKUP

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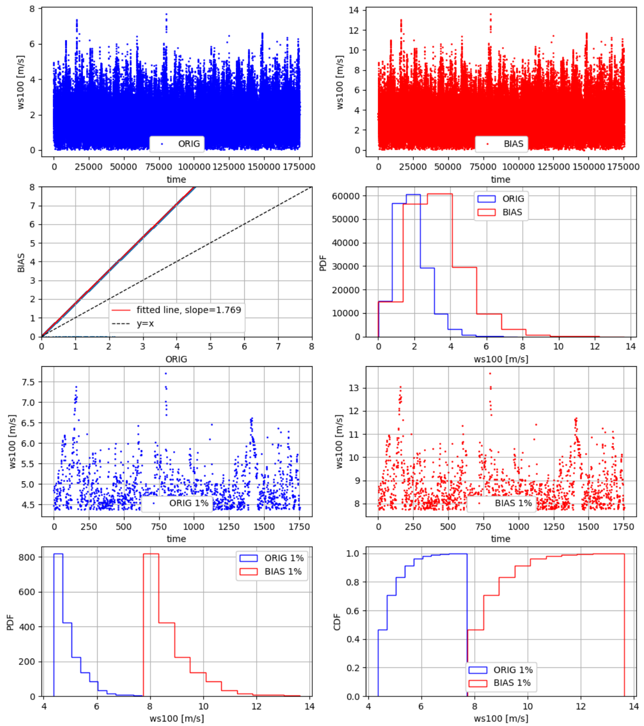
Climate Data and Bias adjustment:

Bias Adjustment for C3S-Energy: VERIFICATION

HIST streamflow: wind speed at 10 m/ 100 m adjusted by means of the delta method using the Global Wind Atlas, version 3 (GWA3) as reference

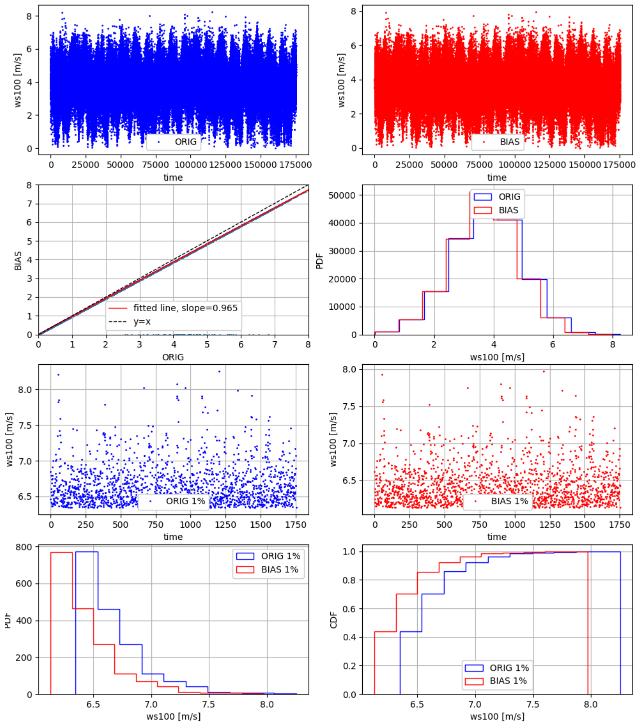


6.75 °E, 46.0 °N

ERA5	F	Regression Slope	99% Quantile
10 m noc	1.881	1.88090	2.657
10 m ba			4.998
100 m noc	1.768	1.76857	4.379
10 m ba			7.742

52.0 °W, 1.0 °N

ERA5	F	Regression Slope	99% Quantile
10 m noc	0.617	0.609	4.018
10 m ba			2.475
100 m noc	0.966	0.965	6.347
10 m ba			6.130



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Climate Data and Bias adjustment:

The **Sixth Phase of the Coupled Model Intercomparison Project (CMIP6)** was organized by the World Climate Research Programme (WCRP). The WCRP coordinates the efforts of partners and modelling groups participating in CMIP. Over time, as participation in CMIP increased and the number and complexity of climate models expanded, the need for increasingly detailed and organized experiments led to CMIP becoming an integrated framework within which a number of individual Model Intercomparison Projects (MIPs) are organized. MIPs are sets of experiments and simulations designed to test and compare specific aspects of climate models. Each individual MIP lays out an experimental design aimed at improving understanding of:

- important physical processes in the climate system; or
- the response of the climate system to external drivers (such as increasing greenhouse gases).

CMIP6 comprises 23 individual MIPs. Future climate change simulations are coordinated within 'ScenarioMIP' for which approximately 30 climate models contributed results. Additionally, the Diagnostic, Evaluation and Characterization of Klima (DECK) experiments are central to CMIP6 as they involve the historical simulations (1850–near present) that allow evaluation of the model's simulation of past climate. While MIPs are given priority by CMIP, and organizations can participate in as many or few as they are able, the DECK experiments are mandatory for any model to enter into the CMIP. The schematic below illustrates the complex and interconnected nature of CMIP6.

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Climate Data and Bias adjustment:

SSPs

SSP1 Sustainability - Taking the green road (low challenges to mitigation and adaptation)

- The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries.
- Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being.
- Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries.
- Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2 Middle of the road - (medium challenges to mitigation and adaptation)

- The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns.
- Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations.
- Global and national institutions work toward but make slow progress in achieving sustainable development goals.
- Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines.
- Global population growth is moderate and levels off in the second half of the century.
- Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3 Regional rivalry - A rocky road (high challenges to mitigation and adaptation)

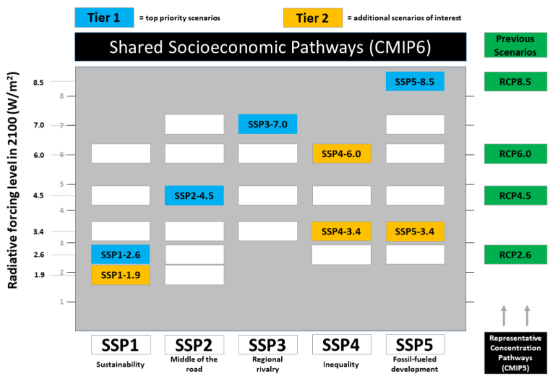
- A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues.
- Policies shift over time to become increasingly oriented toward national and regional security issues.
- Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development.
- Investments in education and technological development decline.
- Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time.
- Population growth is low in industrialized countries and high in developing countries.
- A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4 Inequality - A road divided (low challenges to mitigation, high challenges to adaptation)

- Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries.
- Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy.
- Social cohesion degrades and conflict and unrest become increasingly common.
- Technology development is high in the high-tech economy and sectors.
- The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

SSP5 Fossil-fueled development - Taking the highway (high challenges to mitigation, low challenges to adaptation)

- This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development.
- Global markets are increasingly integrated.
- There are also strong investments in health, education, and institutions to enhance human and social capital.
- At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world.
- All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century.
- Local environmental problems like air pollution are successfully managed.
- There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.



Shared Socio-economic Pathways and year 2100 radiative forcing combinations used in ScenarioMIP.

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