Climate Change

C3S Energy Webinar
GLOBAL CLIMATE INDICATORS

23rd April 2024

Processing methodologies and selected examples of global climate indicators for the C3S Global Energy Climate Service

Letizia Lusito
Inside Climate Service

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Outline

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

- Climate indicators
- Wind profile power law for the wind speed scaling

Global climate indicators, their utility, applications and examples:

- Historical climate
- Seasonal forecasts
- Climate projections

Bias adjustment (b.-a.) methods, applications and examples:

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

Conclusions and future outlook

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Wind profile power law for the wind speed scaling

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Wind speed scaling

The need for wind speed scaling:
wind speed measurements are traditionally available (anemometers installation heights) or referred to the standard height of **10 m** above ground level in order to clear the measurements from the effects of terrain, buildings, surroundings (open ground)

https://library.wmo.int/viewer/41755/download?file=wmo-td_452_en.pdf&type=pdf&navigator=1

Wind speed scaling for the energy sector

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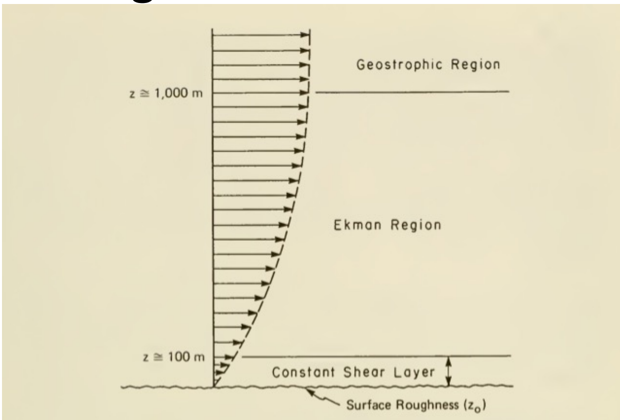
How can we use the 10 m winds to determine wind speeds at the heights relevant for wind turbines?



Winds are driven by large-scale pressure gradients in the atmosphere :

- (> 1000 m or so above the surface) winds are driven mainly by geostrophic balance between Coriolis and local pressure gradient forces.
- (< 1000 m) frictional effects distort the wind field; wind speed and direction become dependent upon elevation above the mean surface, roughness of the surface, air-sea temperature differences

Wind profile (or shear) power law

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https://en.wikipedia.org/wiki/Hornsea_Wind_Farm

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Wind shear power law

The **wind profile power law** is a relationship between the wind speeds v_r at one (reference) height z_r and the wind speed v at another height z.

$$\frac{v}{v_r} = \left(\frac{z}{z_r}\right)^{\alpha}$$

The exponent α is an empirically derived coefficient that varies dependent upon the stability of the atmosphere. For neutral stability conditions, it is approximately 1/7 = 0.143.

Application

The wind shear exponent α can be used to estimate the vertical wind profile and derive wind speed information at different heights above ground in context and applications connected to the energy sector, e.g., wind farms modelling and climate modelling for RE resources assessments.

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Wind speed scaling for the energy sector

In the C3S Energy contracts, a location dependent exponent is computed to account for local features as represented by the model (ERA5). Temporal variations are accounted for too, by stratifying α according to the time of day and month.

ERA5 ws @ 100 m, 0.25° horizontal resolution, hourly resolution

2011-2021

$$\alpha = \frac{\ln v_2 - \ln v_1}{\ln h_2 - \ln h_1}$$

ERA5 ws @ 10 m, 0.25° horizontal resolution, hourly resolution

2011-2021

The power law exponent will be used to derive the climate indicator “wind speeds at 100 m” when not directly available, e.g., for CMIP6 projections, for seasonal forecast and, for coherence, also for the past climate data (1950-2023)

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Global climate indicators, their utility, applications and examples

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Historical Climate Indicators

Based on **ECMWF Reanalysis v5 (ERA5)**

Climate reanalyses combine past observations with models to generate consistent time series of multiple climate variables.

The most relevant climate indicators for the Energy Sector have been processed in a more ready-to-use formats by the C3S Energy Team

- Temperature
- Precipitation
- Wind speed at 10/100 m AGL
- Wind direction at 10/100 m AGL
- Solar radiation at Surface

Climate Indicators

Spatial resolution:

- Gridded level (NetCDF format) covering the entire Globe
- Aggregated information at ADM0/ADM1 level

Temporal resolution:

daily, soon to be hourly (except Precipitation)

ERA5 is the latest climate reanalysis produced by ECMWF, providing hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty.

ERA5 data are available in the Climate Data Store on regular latitude-longitude grids at 0.25° x 0.25° resolution, with atmospheric parameters on 37 pressure levels.

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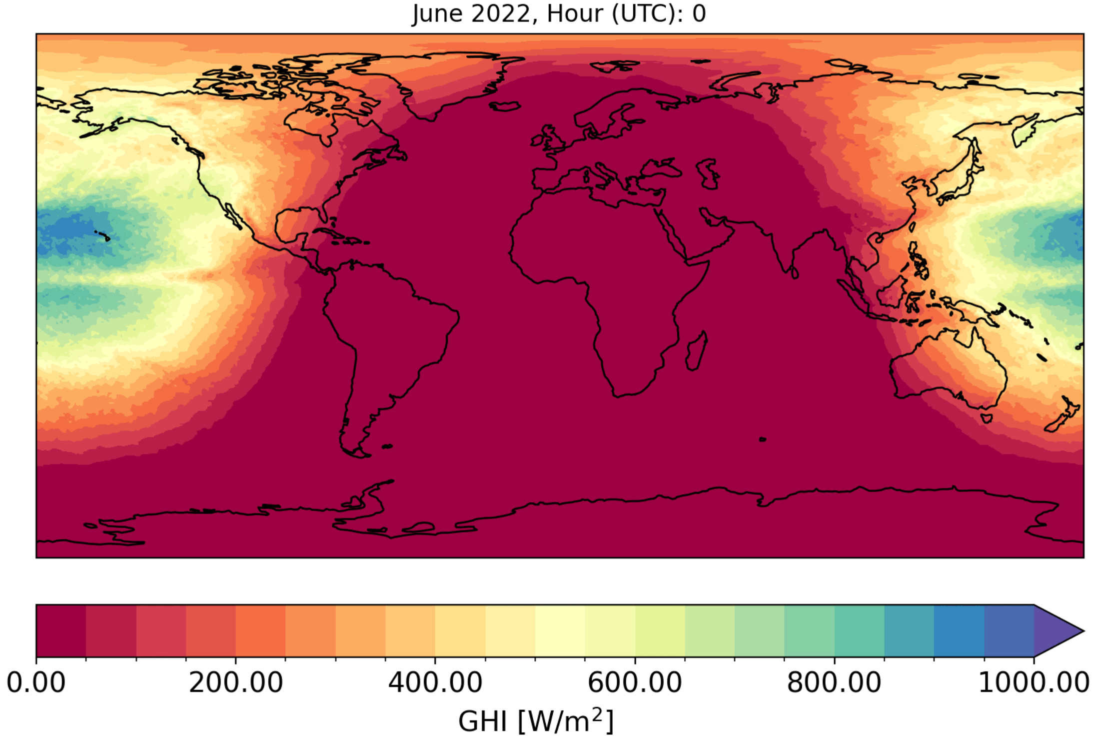
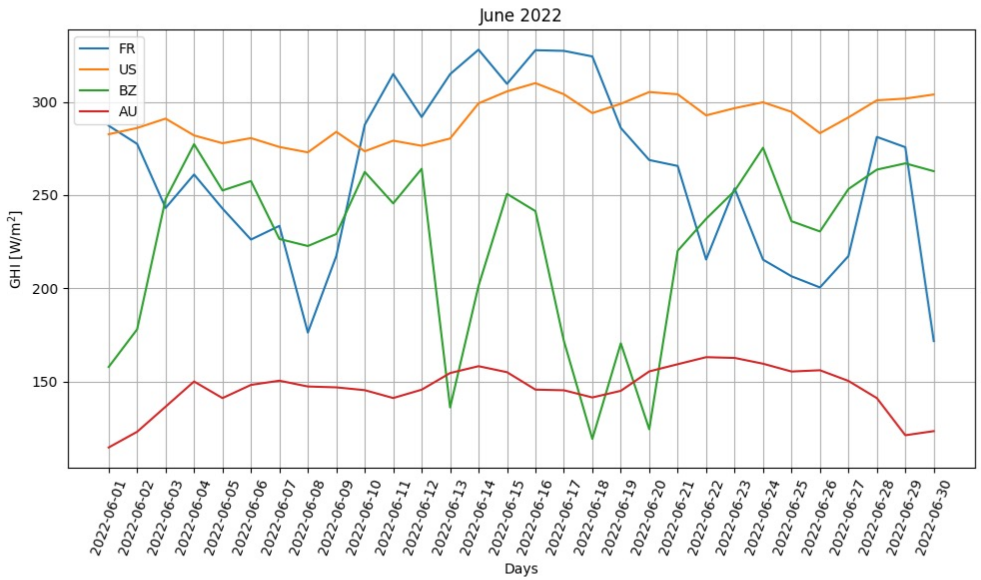
Historical Climate Indicators

Selected examples:

- maps from gridded products : useful to compare climate indicators across geographical areas/selected locations over a certain period of time, e.g. for resource assessments
- time series from aggregated products : useful to compare climate indicators across countries over a certain period of time





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Seasonal forecast climate indicators

Seasonal forecast models for the C3S2 Energy community

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 evolve more slowly than the "chaotic" atmosphere in a predictable way.

Model	Original spatial res.	Ensemble Members	Initialisation Approach	Lead time	Link to institutions
ECMWF SYS 5.1	1° x 1°	25 hindcasts 51 forecasts	Burst	215 days	https://www.ecmwf.int/en/forecasts/documentation-and-support/long-range
CMCC SYS 3.5	1° x 1°	40 hindcasts 50 forecasts	Burst	6 calendar months	https://sps.cmcc.it
DWD SYS 2.1	1° x 1°	30 hindcasts 50 forecasts	Burst	6 calendar months	https://www.dwd.de/EN/ourservices/seasonals_forecasts/start.html

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Seasonal forecast climate indicators

Application: Seasonal forecast climate indicators for the C3S2 Energy community (other models follow the same schema)

Variable	Time period	Source	Temporal resolution	Type	Units
Temperature (TA)	Hindcasts: 1993-2016 Forecasts: From 2023-01	ECMWF SYS 5.1	Gridded: 6 hours ADMO: 1 month	Instantaneous	°K
Precipitation (TP)	Hindcasts: 1993-2016 Forecasts: From 2023-01	ECMWF SYS 5.1	Gridded: 1 day ADMO: 1 month	Daily cumulated	m
Solar Radiation at Surface (GHI)	Hindcasts: 1993-2016 Forecasts: From 2023-01	ECMWF SYS 5.1	Gridded: 1 day ADMO: 1 month	Daily mean	W m^{-2}
Wind speed 10 m (WS10)	Hindcasts: 1993-2016 Forecasts: From 2023-01	ECMWF SYS 5.1	Gridded: 6 hours ADMO: 1 month	Instantaneous	m^{-1}
Wind speed 100 m (WS100)	Hindcasts: 1993-2016 Forecasts: From 2023-01	ECMWF SYS 5.1	Gridded: 6 hours ADMO: 1 month	Instantaneous	m^{-1}

Climate Projections

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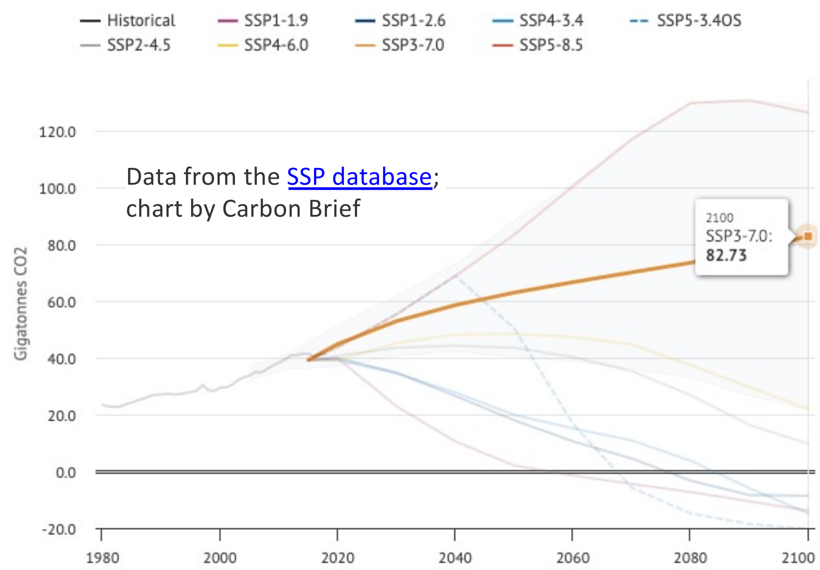
The World Climate Research Programme (WCRP) Working Group on Coupled Modelling oversees the **Coupled Model Intercomparison Project, which is now in its 6th phase (CMPI6)**

- For climate model improvements
- For support national and international assessments of climate change.

SSP	Scenario	Estimated warming (2041–2060)	Estimated warming (2081–2100)	Very likely range in °C (2081–2100)
SSP1-1.9	very low GHG emissions: CO_2 emissions cut to net zero around 2050	1.6 °C	1.4 °C	1.0 – 1.8
SSP1-2.6	low GHG emissions: CO_2 emissions cut to net zero around 2075	1.7 °C	1.8 °C	1.3 – 2.4
SSP2-4.5	intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0 °C	2.7 °C	2.1 – 3.5
SSP3-7.0	high GHG emissions: CO_2 emissions double by 2100	2.1 °C	3.6 °C	2.8 – 4.6
SSP5-8.5	very high GHG emissions: CO_2 emissions triple by 2075	2.4 °C	4.4 °C	3.3 – 5.7

CO2 emissions in CMIP6 scenarios



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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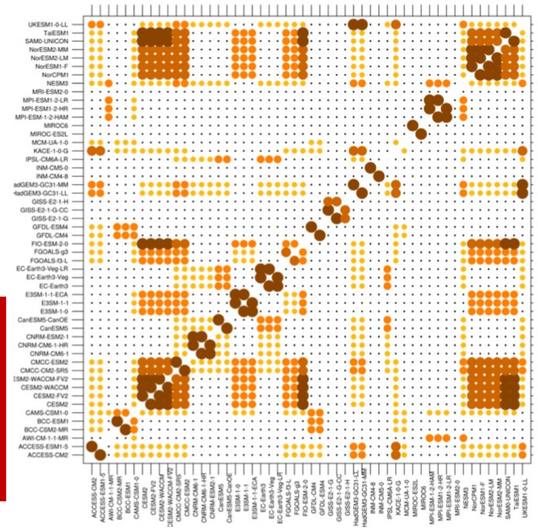
Climate Projections

Application: CMIP6 projection models to be delivered within C3S-Energy

Selection based on model components independence, availability of reasonable horizontal and temporal resolution, maximum variability in the Equilibrium Climate Sensitivity (ECS)



C3S2 Energy selection:
(data further interpolated at 0.25°x 0.25° horizontal resolution, daily resolution)

Model	Time resolution	Spatial resolution	Scenarios	Variant label	Calendar
CMCC-CM2-SR5	3 hours	100 km	historical, ssp245, ssp370	r1i1p1f1	365_day
EC-Earth3	3 hours	100 km	historical, ssp245, ssp370	r1i1p1f1	proleptic_gregorian
MPI-ESM1-2-HR	3 hours	100 km	historical, ssp245, ssp370	r1i1p1f1	proleptic_gregorian
BCC-CSM2-MR	3 hours	100 km	historical, ssp245, ssp370	r1i1p1f1	365_day

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

Climate Projections

Climate projections indicators

Variable	Time period	Source	Temporal Resolution	Spatial Resolution	Spatial Aggregation	Units
Temperature (TA)	2015-2065	CMIP6 4 models x 2 SSPs	daily for gridded data and ADM0, monthly for ADM0/ADM1	0.25° x0.25°	Gridded & ADM0, ADM1	°K
Precipitation (TP)						M
Wind speed 10 m (WS10)						m s^{-1}
Wind speed 100 m (WS100)*						m s^{-1}
Solar Radiation at Surface (GHI)						W m^{-2}

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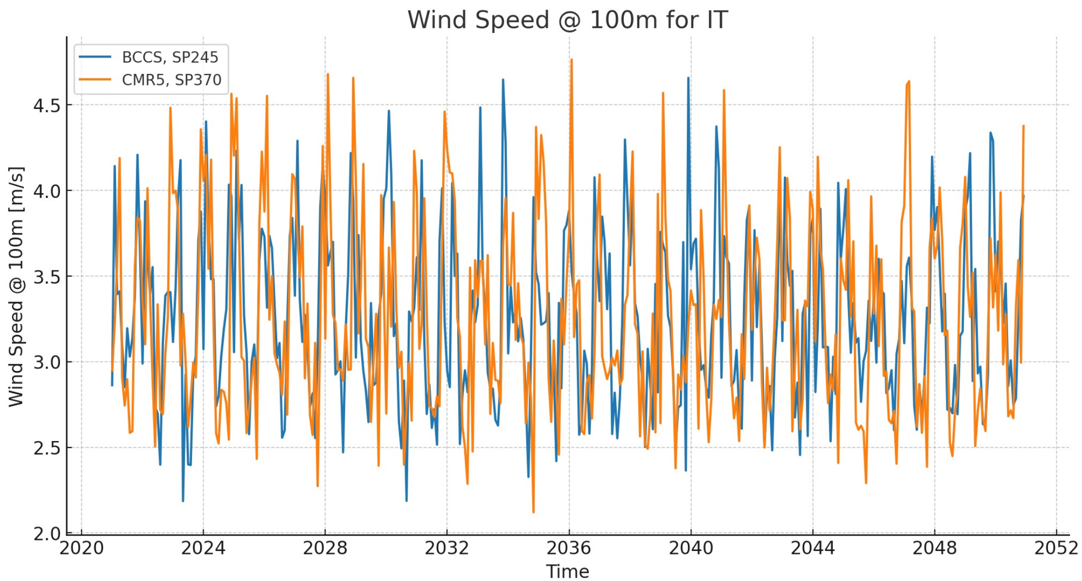
Indicators in the Projection Stream

Selected examples: time series for a particular Country for combinations of models/scenarios: useful to compare the influence of scenarios, fixing a model or to compare the projections offered by different models and have a better estimation of the uncertainty



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Bias adjustment (b.-a.) methods, applications and examples

The need for the bias adjustment

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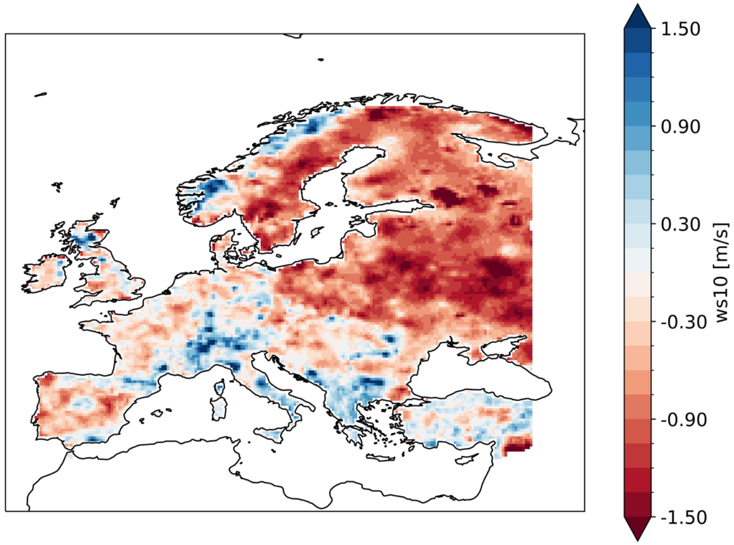
Fully physically based climate simulation chain formed by **General Circulation Models (GCMs) dynamically downscaled through Regional Climate Models (RCMs)**, are powerful tools for describing general climate conditions,

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 **calibration of an empirical transfer function between simulated and observed distribution over a historical period that can be used to adjust the climate model output over a future period.**

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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Chang

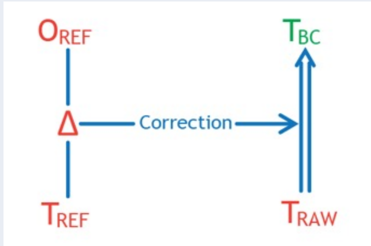
Overview of bias adjustment methods

Delta

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

$$PROJ_{B.A.} = \frac{PROJ}{F}$$

Adjustment of a "source" dataset, based on a target variable simply calculating the change factors (or anomalies or deltas) from the averaged datasets
The averages of the source and target dataset are matched by performing a **scaling adjustment** of the source dataset with the delta factors



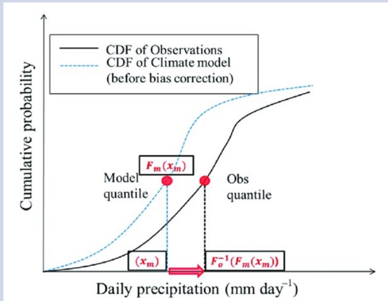
Navarro-Racines, C., Tarapues, J., Thornton, P. *et al.* High-resolution and bias-corrected CMIP5 projections for climate change impact assessments. *Sci Data* **7**, 7 (2020). https://doi.org/10.1038/s41597-019-0343-8

Quantile mapping

$$P_o = h(P_m)$$

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

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



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.

CDFt

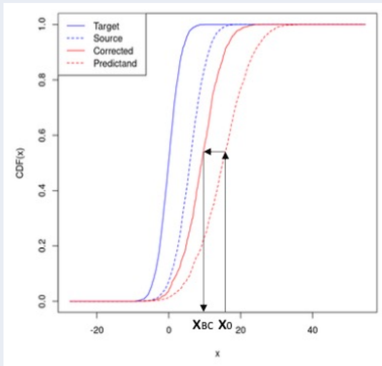
$$T(F_{Gh}(x)) = F_{Sh}(x)$$

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

$$F_{Sf}(x) = T\left(F_{Gf}(x)\right)$$

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

A probabilistic downscaling method: statistical properties (CDFs) between a target and a source (biased projection model or GCMs) datasets are modelled.
Non-parametric correspondences between the predictor and predictand CDFs.
$F_{Sh}(x)$ the CDF of the target 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.



Michelangeli, Vrac, Loukos (2009) Probabilistic downscaling approaches: Application to wind cumulative distribution functions. Geo. Res. 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<doi:10.5194/nhess-12-2769-2012>.

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Bias-adjustment methods for C3S Energy

Variable	Seasonal Forecasts	Climate Projections
TA	**Quantile mapping** with ERA5 as reference	Moving windows **Cumulative Distribution Function transform (CDFt)** with ERA5 as reference
TP	**Quantile mapping** with ERA5 as reference	**Cumulative Distribution Function transform (CDFt)** with ERA5 as reference
WS10	**Quantile mapping** with ERA5 as reference	**Cumulative Distribution Function transform (CDFt)** with bias adj. ERA5 as reference
GHI	**Quantile mapping** with ERA5 as reference	**Delta method** with ERA5 as reference

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Bias-adjustment methods for C3S Energy

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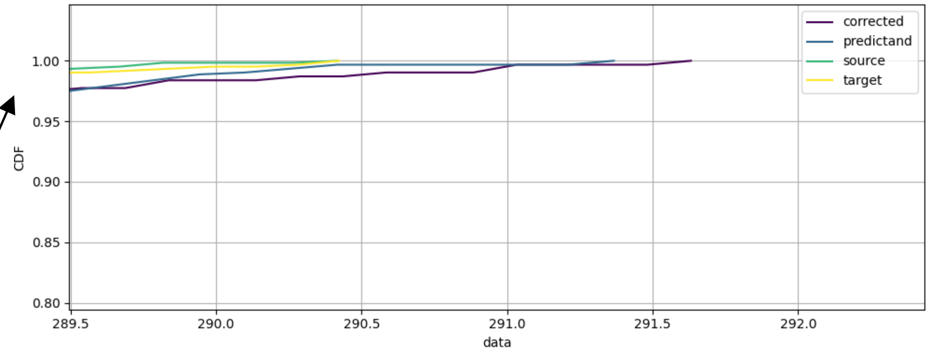
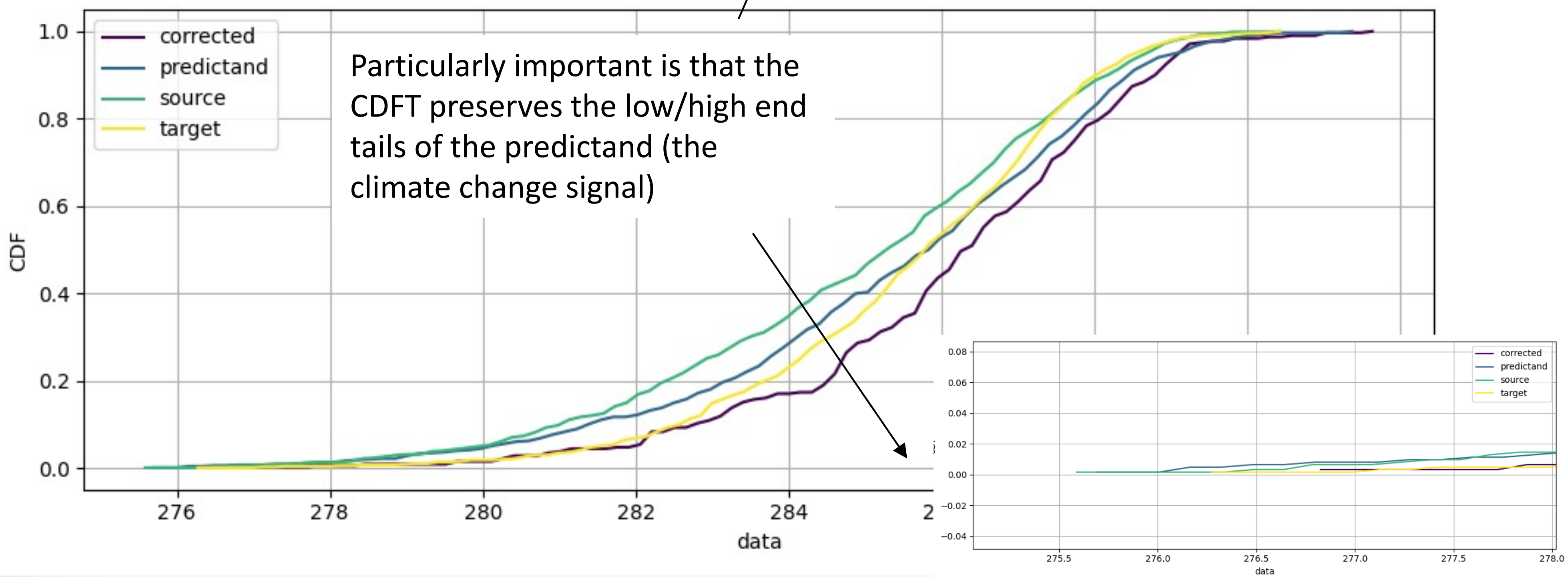
Selected examples: CDFT in action

Source: 1995-2014 AWCM hist CMIP6 projection TA
Target: 1995-2014 ERA5 TA
Predictand: 2015-2034 AWCM SSP 245 CMIP6 projection TA
Corrected: 2025-2034 AWCM SSP 245 CMIP6 projection TA



Particularly important is that the CDFT preserves the low/high end tails of the predictand (the climate change signal)



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Conclusions and future outlook

Added value of the C3S2 Energy contract:

- **wind shear power law** used to derive wind speeds at height relevant for the wind power simulations, also for climate projections, where they are not normally available to user communities
- **bias adjustment** used to minimize biases in climate projections making them useful to renewable energy assessments but preserving the climate change trends
- improvement in the delivery of climate indicators strongly based on the **continuous engagement and feedback** with users, stakeholders and ECMWF/CDS communities

- **Next steps:**
  - Further assessment of ERA5 and CMPI6 climate indicators
  - Publication of data and procedures
  - Further engagement with users/stakeholders and training activities

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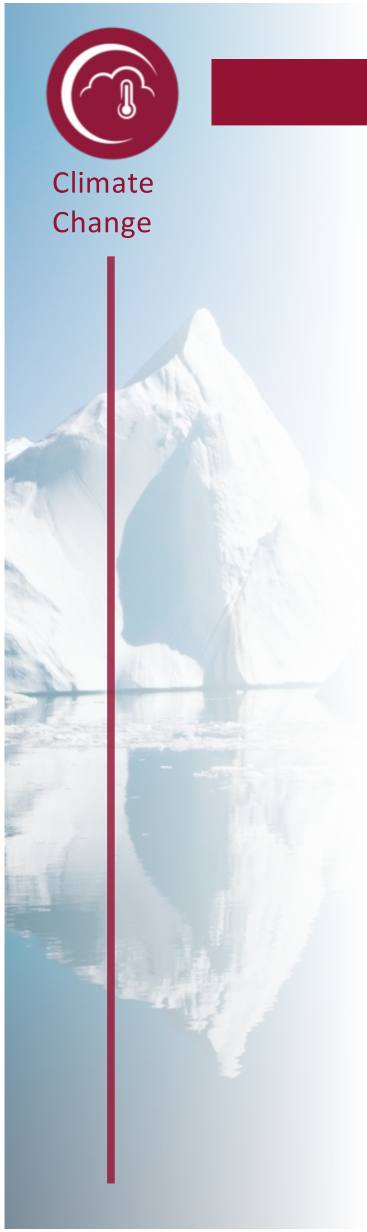

BACKUP

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BIAS ADJUSTMENT

Process of reducing biases in climate models at post processing phase

Even though climate models (CMs), both regional and global, have gained impressive skill in recent decades, model errors and biases do still exist. Model biases are systematic differences between the simulated climate statistic and the corresponding real-world statistic over a historic period where observations exist (Maraun 2016).

These biases could be due to inaccurately resolved topography of the model, due to misrepresentation of convection processes, due to misplacement of large scale processes such as the midlatitude circulation or many other factors. These model errors then manifest as discrepancies in the values and statistical properties of meteorological variables.

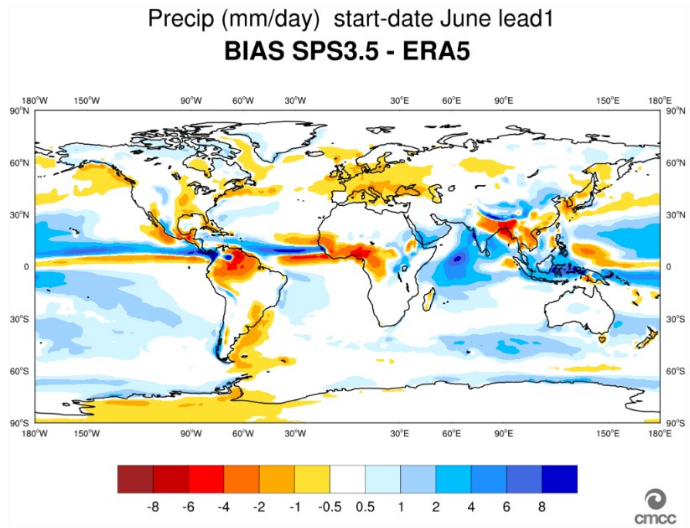
Bias adjustment' methods, which have now become a standard pre-processing step for climate impact studies, calibrate an empirical transfer function between simulated and observed distribution over a historical period that can be used to adjust the climate model output over a future period.

Climate Change

Seasonal Forecasts

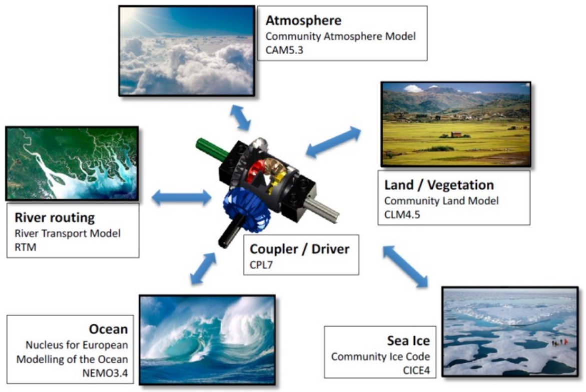
Simulations of possible weather scenarios: probabilities of how likely it is that a season will be wetter, drier, warmer or colder compared to the average for that period of the year. This is possible because some components of the Earth system evolve more slowly than the “chaotic” atmosphere in a predictable way.

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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The need for climate data

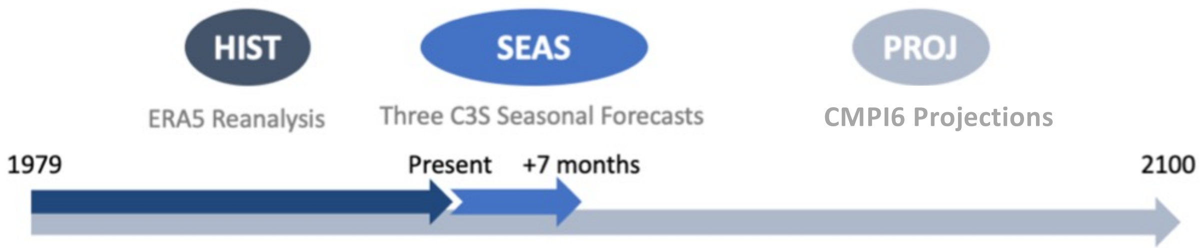
The need for climate data

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 forecasts** 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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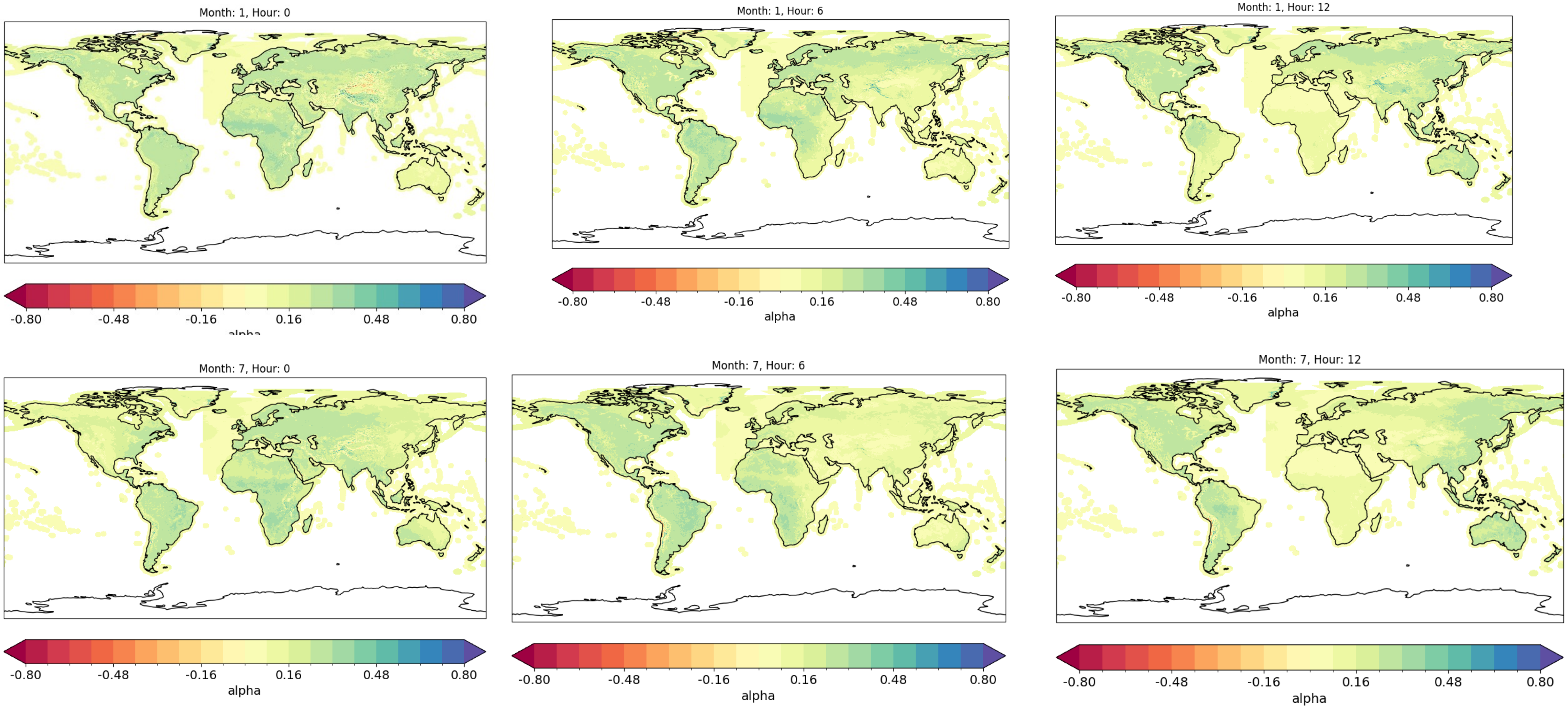
Wind speed scaling for the energy sector



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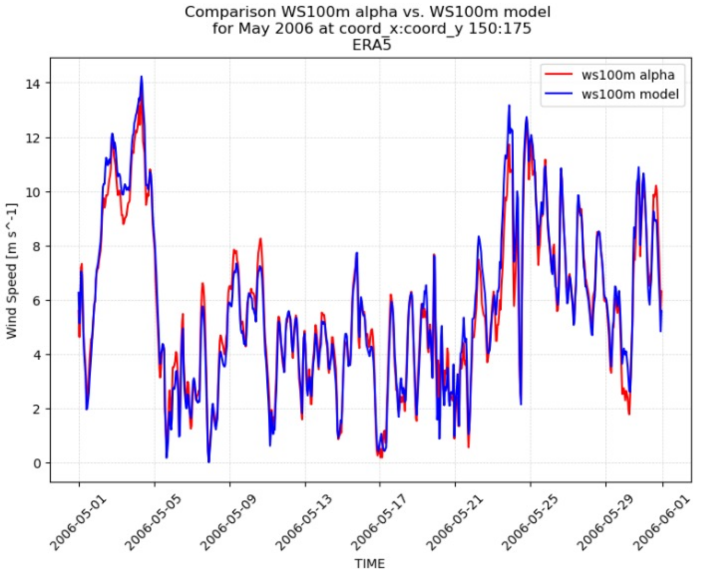
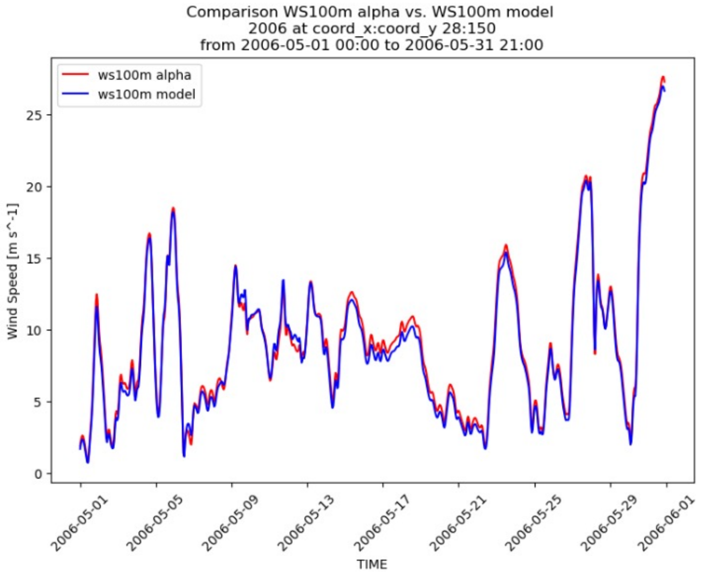
Use of the α exponent in C3S Energy

Validation





The power law exponent will be used to derive the climate indicator "wind speeds at 100 m" when not directly available, e.g., for CMIP6 projections, for seasonal forecast and, for coherence, also for the past climate data (1950-2023)

Climate Projections

Climate Change

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)**

a collaborative framework designed to improve knowledge of climate change since 1995.

It is developed in phases to foster the climate model improvements but also to support national and international assessments of climate change.

SSP	Scenario	Estimated warming (2041–2060)	Estimated warming (2081–2100)	Very likely range in °C (2081–2100)
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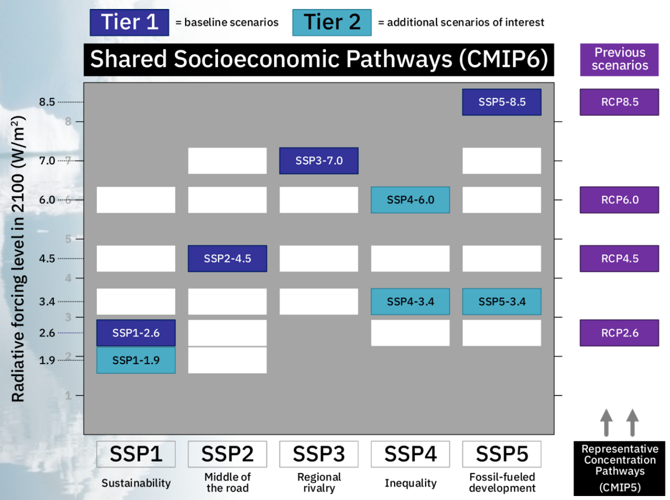

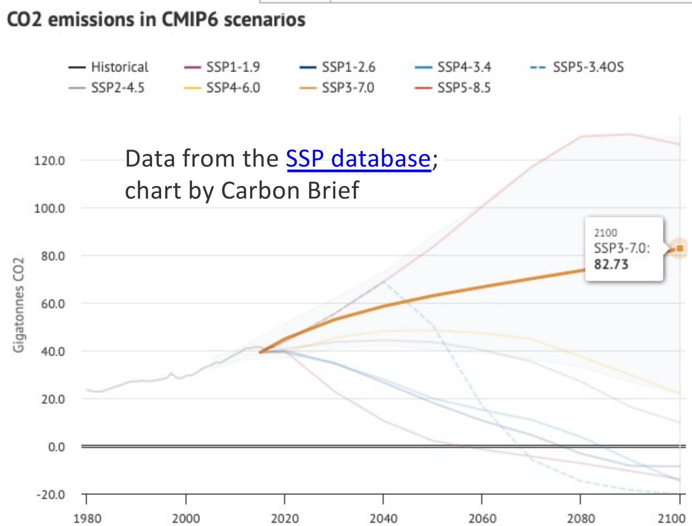

Coupled models are computer-based models of the Earth's climate, in which different parts (such as atmosphere, oceans, land, ice) are "coupled" together, and interact in simulations.

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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