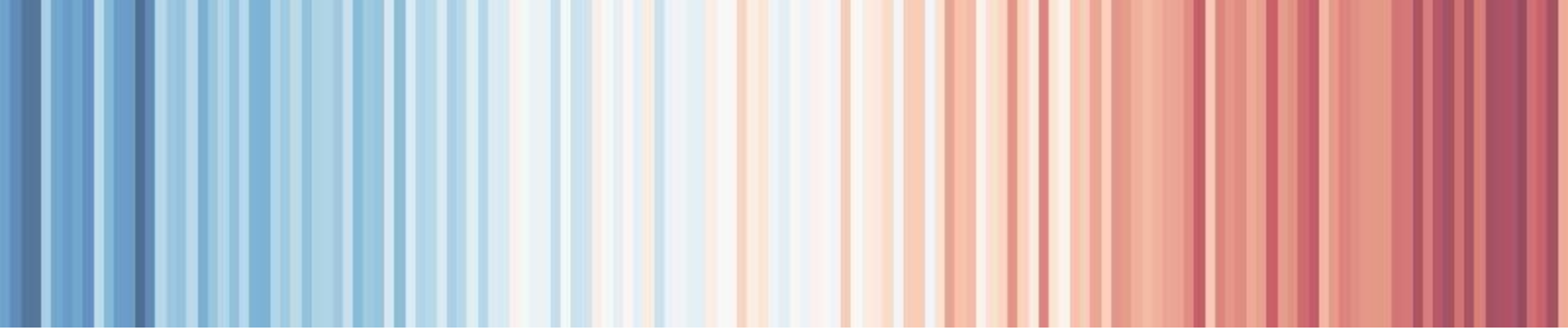

Einbindung von zeitreihenbasierten Klimamodelldaten in den Standortbewertungsprozess

Fraunhofer Institut für Windenergiesysteme - IWES

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KliWiSt

GERICS Climate Service Center Germany

Eine Einrichtung des Helmholtz-Zentrums Hereon

hereon

Fraunhofer IWES

Motivation

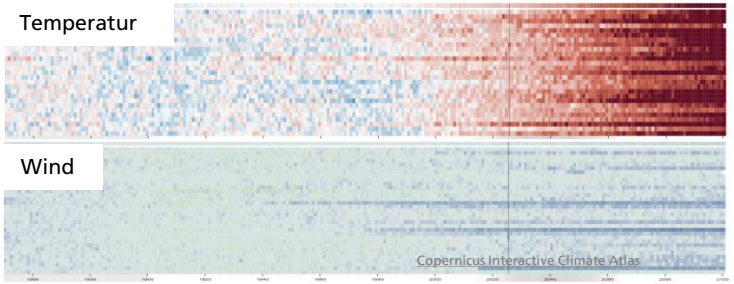
Zeitreihenanalyse Klimamodelldaten

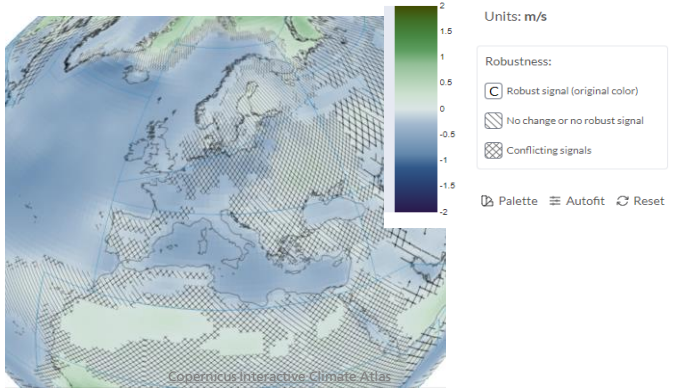
- State-of-the-Art (TR6):
  Annahme von Persistenz (+ mögliche Unsicherheit)

- **Noch gültig?**
  - Zeitpunkt der Erzeugung (e.g. Tageszeit oder Saison) wird im Energiesystem relevanter

- **Ansätze zur Verbesserung?**
  - Einbindung von Klimaprojektionen in den Standortbewertungsprozess
  - Zeitreihenanalyse anstatt Korrektur von Mittelwerten

  → Datenbasierte Unsicherheitsanalysen
  → Analysen von Tages- und Jahresgängen möglich





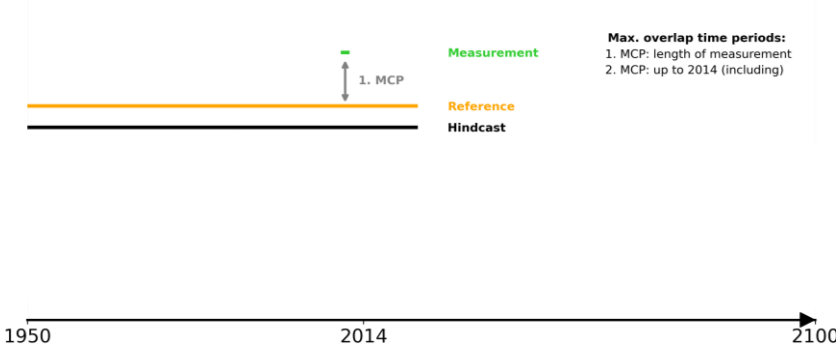
Methodik

Methodik

Klimamodelldaten in der Standortbewertung

Basis: State-of-the-Art method to predict hindcast wind speed
(using Measure-Correlate-Predict (MCP) Methodology)

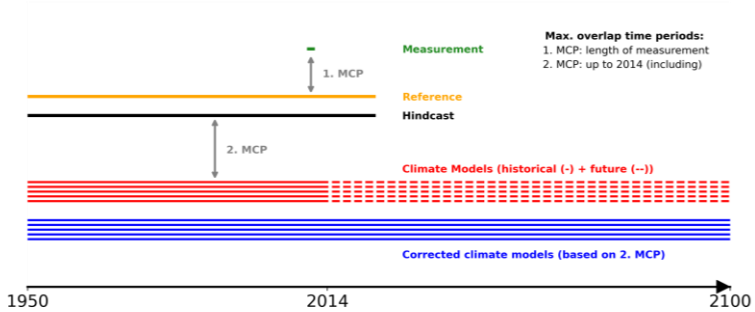
- Input:
  - **Kurzfristige Standortdaten (One-year measurement)**
  - **Langfristige Modelldaten (z.B. Reanalysis)**
- Output:
  - **Hindcast:** Prediction of wind speeds of the past
    - Including: Site specific wind characteristics and long-term wind variability
- Method:
  - Statistical relationship (correlation): e.g. linear regression



Methodik

Klimamodelldaten in der Standortbewertung

- Input:
  - **Hindcast**
  - **Ensemble of climate models (historical: 1950 – 2014)**
- Output:
  - **Corrected climate models (ensemble)**: Prediction of the wind climate from past to future (1950 – 2100)
- Method to link input data:
  - Statistical relationship (correlation): e.g., linear Regression
    - **Issue**: Time inconsistency between Hindcast and climate models data sets



Issue: Excurse – Weather forecast VS Climate model

Initial value – Boundary value problem

Weather Model/Reanalysis ! Connection not time consistent ! **Climate Model**

- Short-term predictions (**hours to days**)
- High precision thanks to accurate **initial conditions**

- Long-term trends and averages (**decades to centuries**)
- Focus on **boundary conditions** and **external drivers** (e.g., CO_2 emissions, solar cycle, Ocean currents, Weather Systems (e.g. NAO))

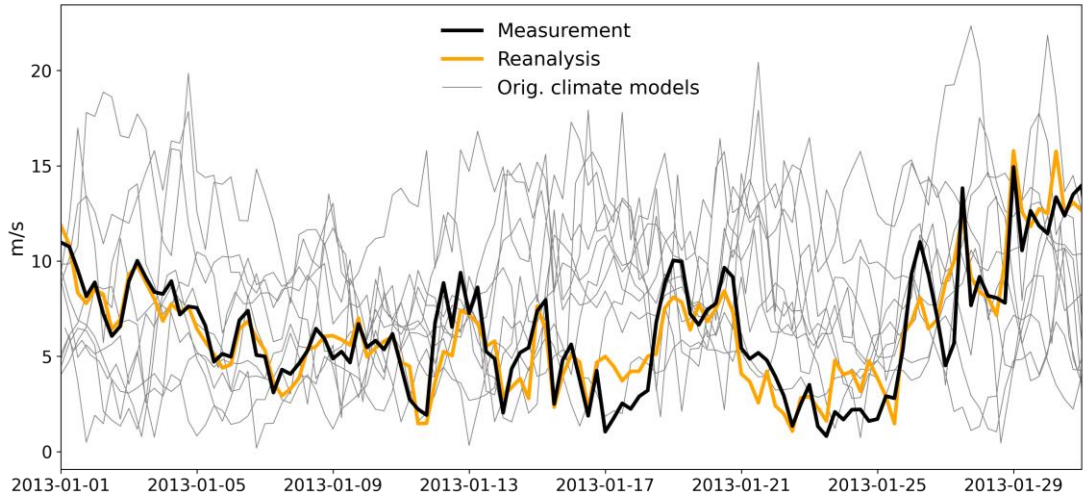
The uncertainties in the initial conditions grow strongly over longer periods of time, which makes it impossible to make precise long-term predictions based on initial values alone.

!!! Climate model data represent averages/trends/statistical values **BUT NOT** a precise prediction for a certain time step !!!

Problem: Excurse – Weather forecast VS Climate model

Visualization

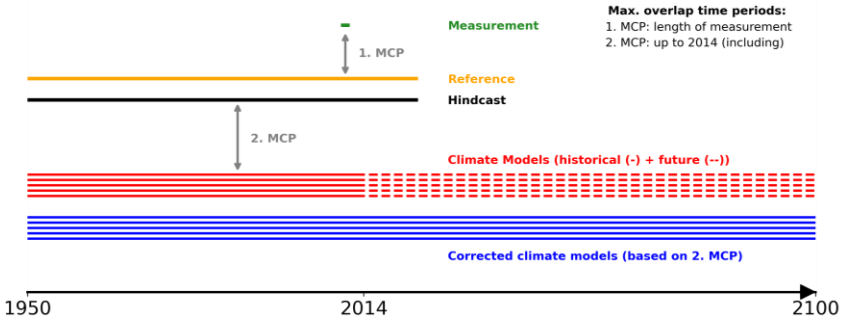
- Weather model/reanalysis:
  - Exact values at the specified time steps!
- Climate models:
  - Represent the probabilistic value of the time step based on the surrounding decades!



Solution

Handling climate model data in wind resource assessment

- Input:
  - **Hindcast**
  - **Ensemble of climate models (historical: 1950 – 2014)**
- Output:
  - **Corrected climate models (ensemble)**: Prediction of the wind climate from past to future (1950 – 2010)
- Method to link input data:
  - Statistical relationship (correlation): e.g., linear Regression
    - Solution: Methods that do not require time consistency



Standorte und Datensätze

- 7 Standorte mit öffentlich verfügbaren Messdaten
- 10 Klimamodelle
- Horizontale Auflösungen: 100 – 250 km
- 2 Szenarien (Focus zur Entwicklung auf SSP5-8.5)

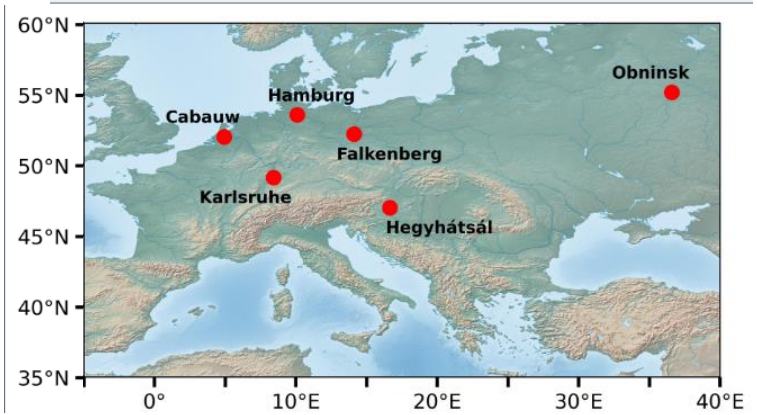


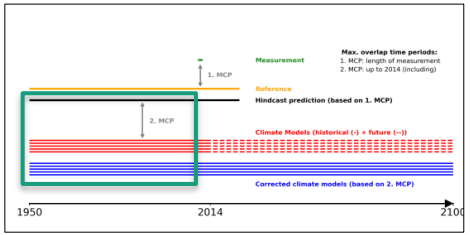
Table 2. Summary of the used global climate models with their characteristics and the approx. height (a.g.l.) of the used model-level or height above terrain.

Model	Scenarios	Horizontal grid (nominal) resolution	lev coordinate	approx. height	Reference
MPI-M-ESM1-2-HR	ssp2-4.5, ssp5-8.5	0.9375° x 0.935° (100 km)	hybrid sigma pres	145 m	Müller et al. (2018)
MPI-M-ESM1-2-LR	ssp2-4.5, ssp5-8.5	1.8750° x 1.865° (250 km)	hybrid sigma pres	144 m	Mauritsen et al. (201
IPSL-CM6A-LR	ssp2-4.5, ssp5-8.5	2.5° x 1.27° (250 km)	? pressure	95 m	Boucher et al. (2020)
CanESM5	ssp2-4.5, ssp5-8.5	2.8125° x 2.79° (500 km)	hybrid sigma pres	125 m	Swart et al. (2019)
ACCESS-CM2	ssp245, ssp5-8.5	1.25° x 1.875° (250 km)	hybrid height [m]	76.6 m	Ziehn et al. (2020)
CMCC-CM2-SR5	ssp245, ssp5-8.5	1.25° x 0.940° (100 km)	hybrid sigma pres	199 m	Cherchi et al. (2019)
CMCC-ESM2	ssp245, ssp5-8.5				
EC-Earth3	ssp245, ssp5-8.5	(100 km)	hybrid sigma	66 m	Döscher et al. (2022)
NorESM2-MM	ssp2-4.5, ssp5-8.5	1.25° x 0.942° (100 km)		62 m	Seland et al. (2020)
NorESM2-LM	ssp245, ssp585	2°x 2° (atm) (250 km)	62 m		
MIROC6	ssp245, ssp585	1.4° x 1.4° (250 km)		108 m	Tatebe et al. (2019)

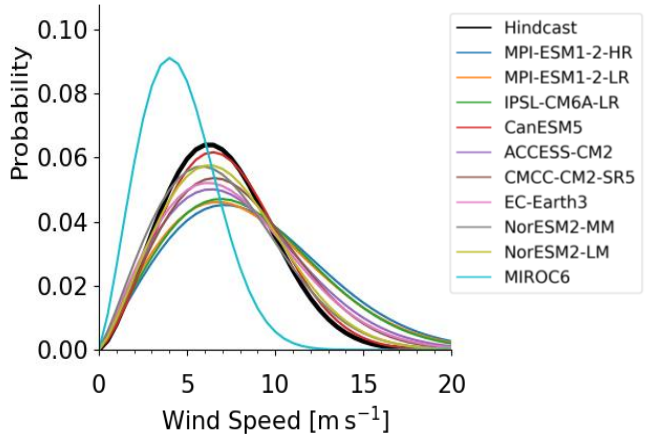
Validierung

Historical: Validation

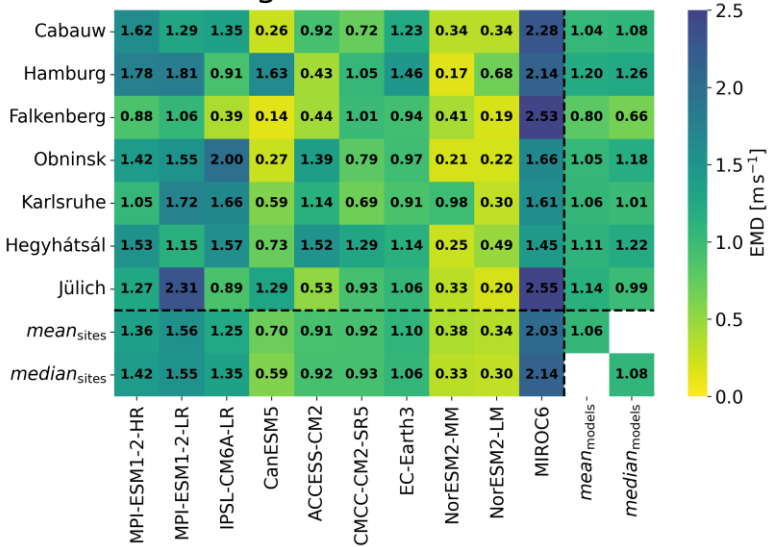
Earth Mover's Distance



- Earth Mover's Distance (EMD): Here measure of similarity of two histograms

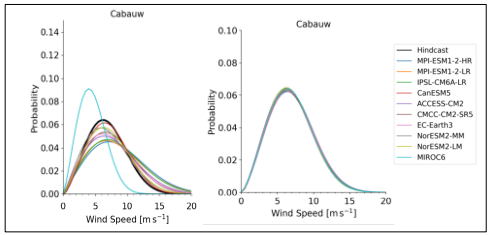


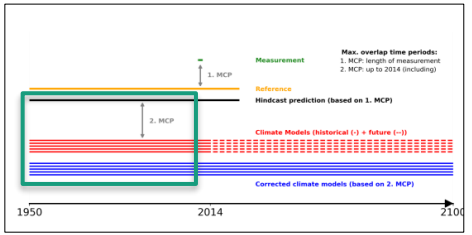
Original climate models



Historical: Validation

Wind Speed Distribution: Orig. vs Corr. CMs





Original climate models

	MPI-ESM1-2-HR	MPI-ESM1-2-LR	IPSL-CM6A-LR	CanESM5	ACCESS-CM2	CMCC-CM2-SR5	EC-Earth3	NorESM2-MM	NorESM2-LM	MIROC6	$mean_{models}$	$median_{models}$
Cabauw	1.62	1.29	1.35	0.26	0.92	0.72	1.23	0.34	0.34	2.28	1.04	1.08
Hamburg	1.78	1.81	0.91	1.63	0.43	1.05	1.46	0.17	0.68	2.14	1.20	1.26
Falkenberg	0.88	1.06	0.39	0.14	0.44	1.01	0.94	0.41	0.19	2.53	0.80	0.66
Obninsk	1.42	1.55	2.00	0.27	1.39	0.79	0.97	0.21	0.22	1.66	1.05	1.18
Karlsruhe	1.05	1.72	1.66	0.59	1.14	0.69	0.91	0.98	0.30	1.61	1.06	1.01
Hegyhátsál	1.53	1.15	1.57	0.73	1.52	1.29	1.14	0.25	0.49	1.45	1.11	1.22
Jülich	1.27	2.31	0.89	1.29	0.53	0.93	1.06	0.33	0.20	2.55	1.14	0.99
$mean_{sites}$	1.36	1.56	1.25	0.70	0.91	0.92	1.10	0.38	0.34	2.03	1.06	
$median_{sites}$	1.42	1.55	1.35	0.59	0.92	0.93	1.06	0.33	0.30	2.14		1.08

EMD [m s^{-1}]: 0.0, 0.5, 1.0, 1.5, 2.0, 2.5

Corrected climate models

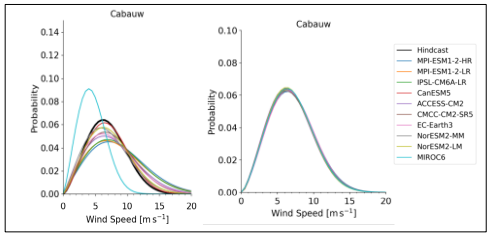
	MPI-ESM1-2-HR	MPI-ESM1-2-LR	IPSL-CM6A-LR	CanESM5	ACCESS-CM2	CMCC-CM2-SR5	EC-Earth3	NorESM2-MM	NorESM2-LM	MIROC6	$mean_{models}$	$median_{models}$
Cabauw	0.20	0.04	0.14	0.11	0.06	0.11	0.20	0.08	0.03	0.07	0.10	0.09
Hamburg	0.08	0.09	0.14	0.12	0.06	0.12	0.17	0.06	0.06	0.08	0.10	0.09
Falkenberg	0.03	0.08	0.05	0.06	0.08	0.07	0.09	0.03	0.06	0.09	0.06	0.07
Obninsk	0.05	0.09	0.06	0.08	0.06	0.12	0.04	0.08	0.08	0.11	0.08	0.08
Karlsruhe	0.12	0.04	0.07	0.08	0.05	0.06	0.11	0.07	0.03	0.06	0.07	0.07
Hegyhátsál	0.06	0.10	0.06	0.08	0.13	0.10	0.05	0.07	0.07	0.12	0.08	0.08
Jülich	0.17	0.04	0.10	0.11	0.04	0.10	0.18	0.09	0.05	0.06	0.10	0.10
$mean_{sites}$	0.10	0.07	0.09	0.09	0.07	0.10	0.12	0.07	0.05	0.09	0.08	
$median_{sites}$	0.08	0.08	0.07	0.08	0.06	0.10	0.11	0.07	0.06	0.08		0.08

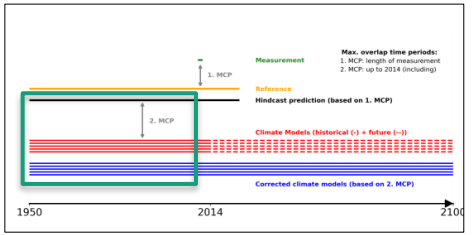
EMD [m s^{-1}]: 0.00, 0.05, 0.10, 0.15, 0.20, 0.25

Einfluss der Korrektur

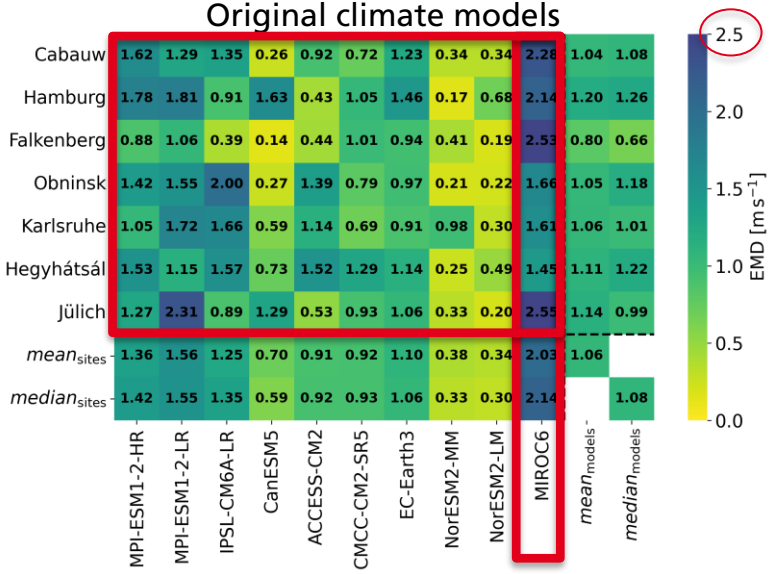
Historical: Validation

Wind Speed Distribution: Orig. vs Corr. CMs

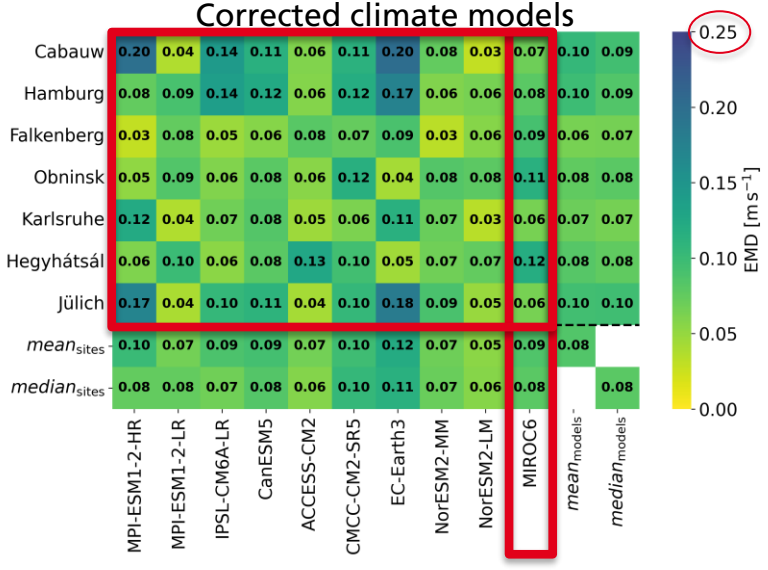




Original climate models



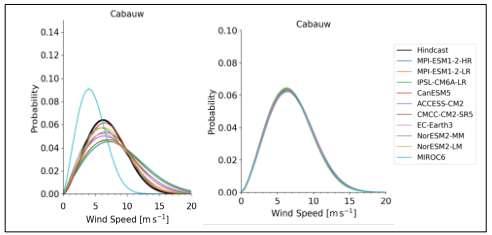
Corrected climate models

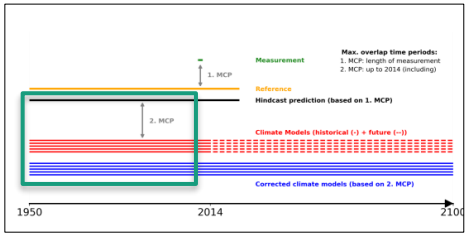


Site and model dependent

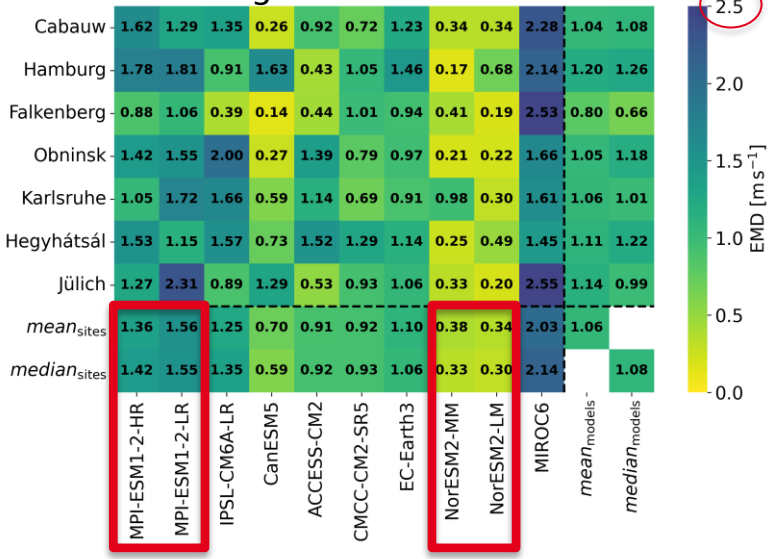
Historical: Validation

Wind Speed Distribution: Orig. vs Corr. CMs

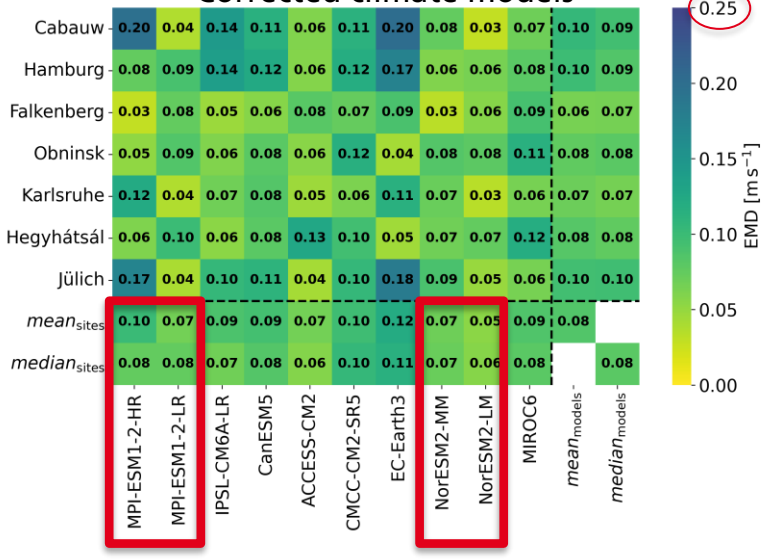




Original climate models



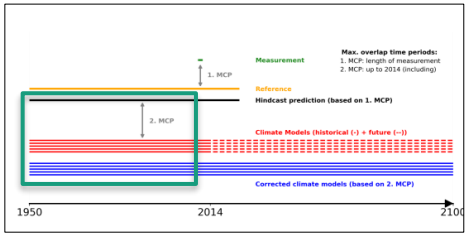
Corrected climate models



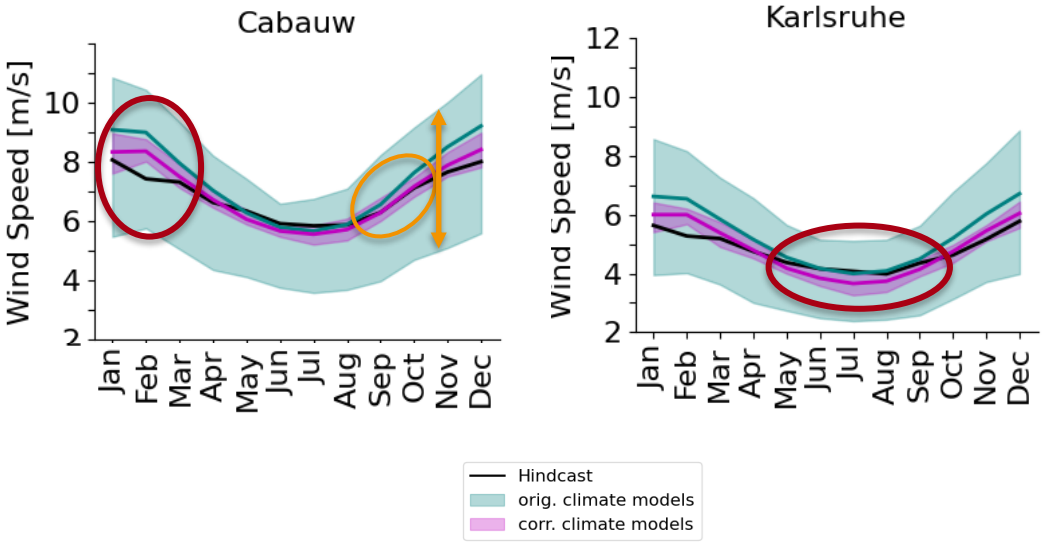
Correction beneficial regardless of model resolution

Historical: Validation

Seasonal cycle



- Improvement:
  - High agreement of corrected ensemble mean
  - Reduction of ensemble spread
  - Greatest adjustment: Winter
- Further improvements:
  - Including more small scaled processes: downscalings/regional models



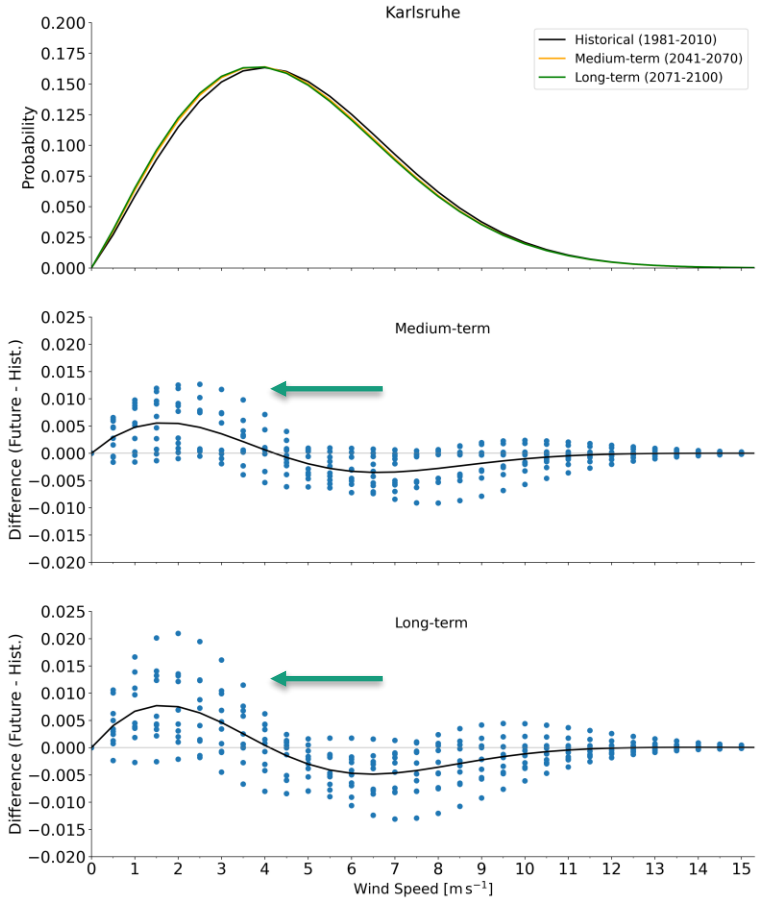
Ergebnisse

Future Wind Ressource

Karlsruhe: Historical – medium – long-term

Worst-Case-Scenario (SSP5-8.5)

- Minor differences between historical and future
- More frequent: Low wind speeds (< 4 m/s)
  - More frequent shutdowns
- Less frequent: 5 – 10 m/s
- Ensemble spread: Slightly higher for long-term



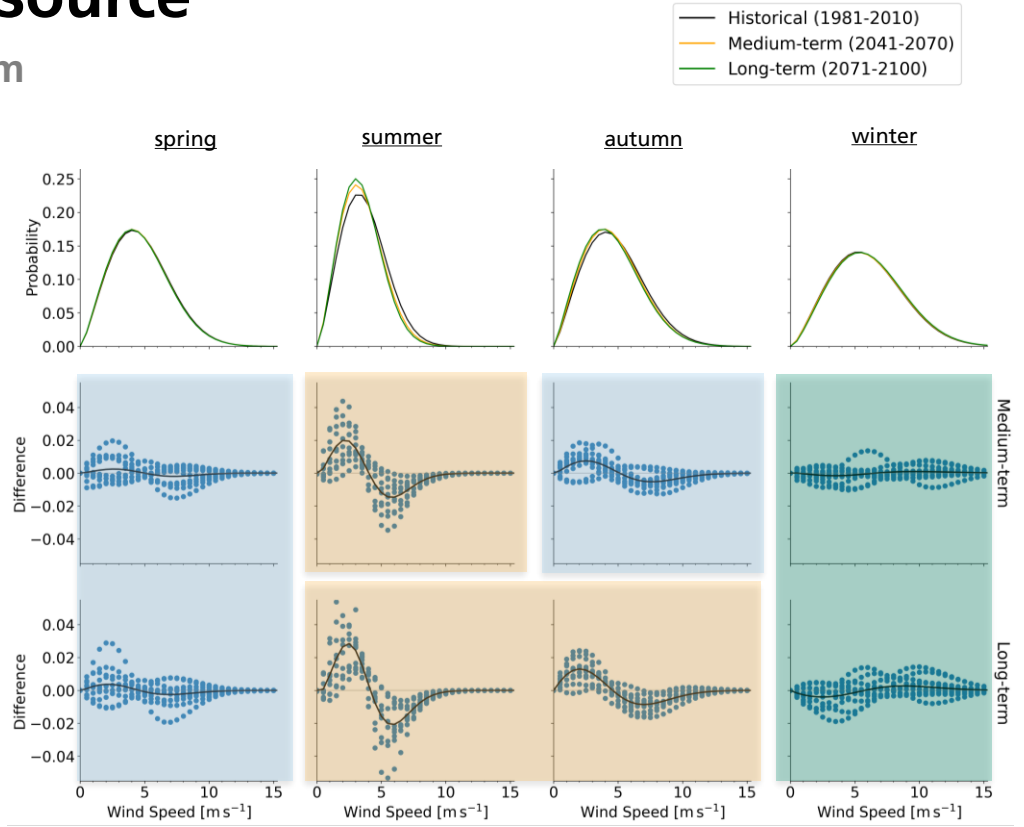
Seasonal Future Wind Ressource

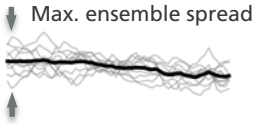
Karlsruhe: Historical – medium – long-term

Worst-Case-Scenario (SSP5-8.5)

- Difference: Future – Historical
- Degree of deviation varies by season
- Partly conflicting signals:

Wind speed change	Higher to lower	Lower to higher
Clear signal	Summer Autumn + long-term	
Conflicting signal	Spring Autumn + medium-term	Winter + (medium)/long-term

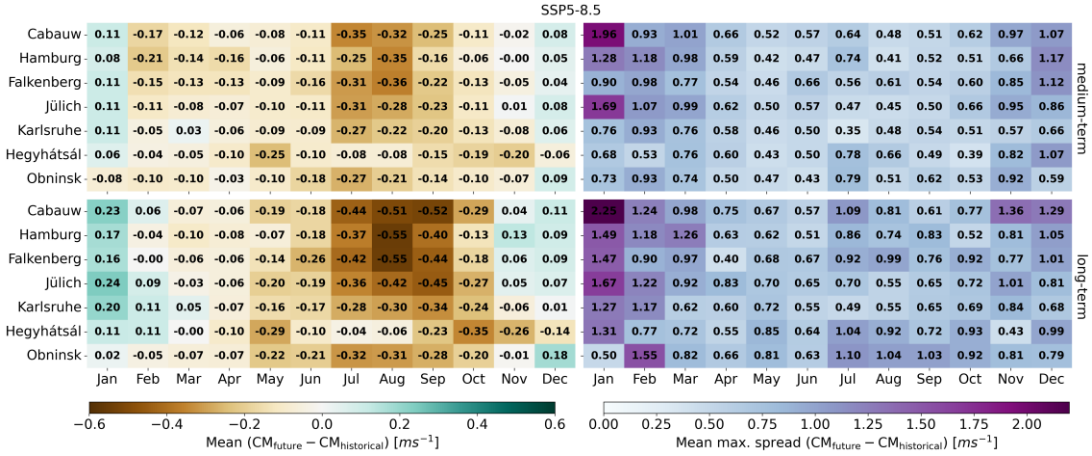




Monthly Future Wind Resource

Monthly difference + Uncertainty

- Decrease in summer at most sites
  + low ensemble spread
- Increase in winter months
  + higher ensemble spread
- Local impacts:
  - E.g. Hegyhátsál: Decrease in autumn – impact Alps?
- Intensification (most cases) from
  - medium to long-term
  - moderate to worst case scenario

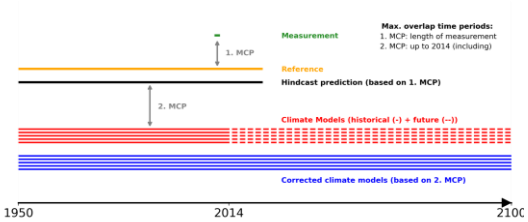


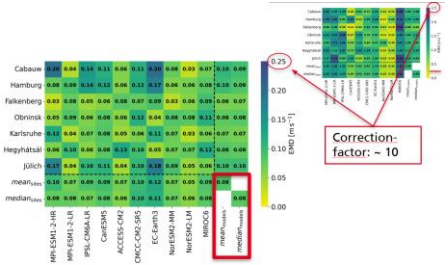
Zusammenfassung

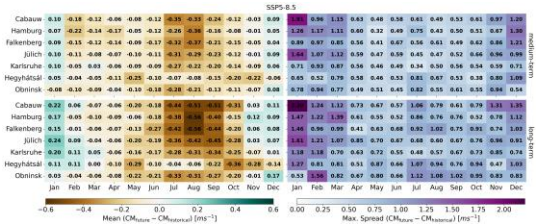
- **Workflow Entwickelt** to **incorporate climate models** at a **specific site**
  - High resolution: **6 hourly** instead of daily/monthly/annual means
  - Beneficial correction: **High agreement** with site data and **reduced ensemble spread**
  - **Method** can be used with **every climate model** data set **on any site**

- Future wind speed changes:
  - **Tendency to lower wind speeds** at some sites in **summer** months
  - Conflicting signals (higher uncertainty) in winter months

- Further improvement: Usage of downscaling/regional climate models
  - **CMIP6 downscaled models** (in preparation) will provide hourly resolution







Vielen Dank für die Aufmerksamkeit

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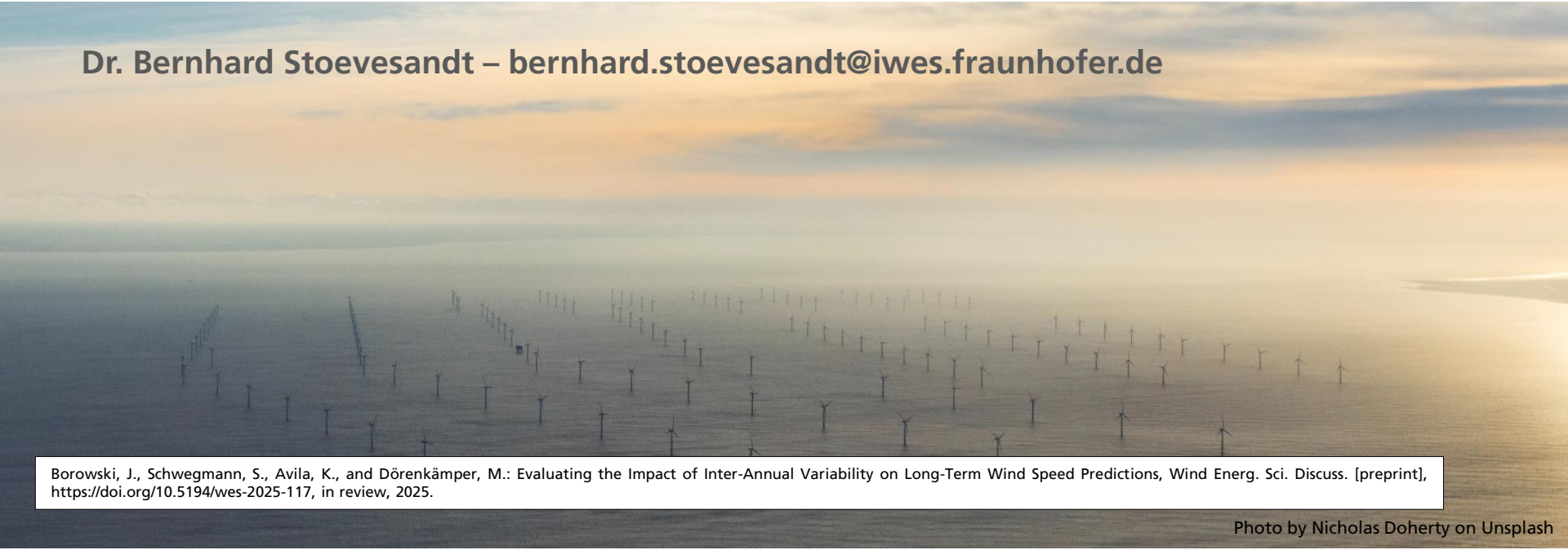

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