Process-based climate change assessment for European winds using EURO-CORDEX and global models

Jan Wohland
Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Hamburg, Germany
E-mail: jan.wohland@env.ethz.ch

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Abstract
Wind energy is an important pillar of decarbonization strategies and potentially vulnerable to climate change. Existing wind climate change assessments rely on climate models but a systematic investigation of the global-to-regional climate modeling chain is missing. In this study, I highlight key limitations, namely (a) the differing representation of land use change in global and regional climate models which compromises comparability, and (b) the consistency of large-scale features along the global-to-regional climate modeling chain. To this end, I analyze the large European Coordinated Downscaling Experiment (EURO-CORDEX) ensemble (rcp85: N = 49; rcp45: N = 18; rcp26: N = 22) along with the driving global models (rcp85: N = 7; rcp45: N = 5; rcp26: N = 7), finding evidence that climate change reduces mean wind speeds by up to $-0.8 \text{ m s}^{-1}$ (offshore) and $-0.3 \text{ m s}^{-1}$ (onshore). I provide physical explanations for these changes by identifying two key drivers. First, onshore wind speeds drop in the driving global models in regions and scenarios with strong land use change but show no drop in EURO-CORDEX where land use is held constant. Second, offshore wind reductions follow decreases in the equator-to-pole temperature gradient remarkably well with correlations reaching around 0.9 in resource-rich European countries like Ireland, the United Kingdom and Norway, implying that arctic amplification is a severe risk for European offshore wind energy. My results suggest that earlier conclusions of negligible climate change impacts on wind energy might be premature if either land use changes strongly or polar amplification is at or above the range sampled in global climate models.

1. Introduction
To decarbonize the energy system and reach climate neutrality within a few decades, we need to substantially expand carbon-free power generation (United Nations Environment Programme 2019). While renewables are primarily a means to mitigate climate change, their weather dependence also makes them vulnerable to climatic changes (IPCC 2022). Concretely, deploying wind parks to curb greenhouse gas emissions can be risky if human interference alters the wind resource and its variability. To incorporate these risks into real-world decisions we need to quantify them: by how much can we expect wind speeds to change as a consequence of climate change?

The quantification of climate change impacts is usually based on climate model outputs from the Climate Modeling Intercomparison Project, which is currently in its sixth phase (CMIP6, Eyring et al. 2016). When relatively fine-scale features matter, for instance, in the vicinity of coasts or in complex terrain, global climate models are often insufficient and higher resolution models are required. Such data is available through the Coordinated Downscaling Experiments (CORDEX, Jacob et al. 2014, 2020) that provide a protocol for regional modeling groups to downscale global climate simulations in a consistent and inter-comparable manner. The increased resolution comes with a cost: publication of CORDEX downscalings lags the CMIP publication by a few years because of the organizational and computational challenges involved. This is why current regional climate change assessments, including this study, rely on downscaled CMIP5
simulations despite the availability of the newer CMIP6 dataset.

Given the importance of wind energy, many climate change assessments have already been published. In a recent review summarizing the state of the field, Pryor et al (2020) argue that it remains unknown whether climate change causes winds to increase or decrease, indicating a need for improved understanding of the physical mechanisms. Most published primary literature is based on extrapolated 10 m wind speeds (e.g. Hueging et al 2013, Tobin et al 2015, 2016, 2018, Wohland et al 2017, Karnauskas et al 2018, Bartók et al 2019, Jerez et al 2019, Soares et al 2019, Bloomfield et al 2021) despite the fact that existing wind turbines are substantially higher with normal hub heights in the range of 100 m to 150 m. This suboptimal choice is, however, dictated by data availability as hub height winds have generally not been saved in the past, causing a mismatch between energy sector needs and data provision by the climate modeling community (Craig et al 2022). Even though pressure level wind components are typically available and they are sometimes used to complement near-surface assessments (e.g. Gonzalez et al 2019), the lowermost level is too high for wind energy assessments in CMIP5 (usually 925 hPa or 850 hPa, corresponding to around 750 m or 1500 m). In other words, the fraction of the boundary layer that is of relevance for wind energy, has been poorly represented in the list of variables that were archived for EURO-CORDEX and CMIP5. Having said that, improvements exist in CMIP6, where 100 m wind speeds are archived and used (Hahmann et al 2022), and similar plans exist for the new generation of EURO-CORDEX downscalings.

Joining the academics listed above, practitioners also raise concerns about climate change impacts on energy. For instance, the European Network of Transmission System Operators identifies climate change impacts on system adequacy as one key challenge that will be addressed in upcoming adequacy forecasts (ENTSO-E 2020). In a corresponding invitation to tender, the European Centre for Medium Range Weather prediction (ECMWF) requires the inclusion of at least 10 EURO-CORDEX models spanning the entire 21st century for multiple future scenarios in the Pan-European Climate Database for the energy sector (ECMWF 2022).

Within this context of increasing attention directed at climate change risks for wind energy, this study has two goals. First, it addresses mean wind speed changes along the global-to-regional climate modeling chain, to illuminate the effects that current regional climate models have on the wind resource. Second, it suggests physical explanation for the reported signals and discrepancies, thereby providing an additional layer of reasoning beyond mere data analysis.

2. Methods and data

I compare changes in wind speeds between the end of the 21st century (01.01.2080-01.01.2100) versus the end of the historical period in the climate model simulations (01.01.1985-01.01.2005). The 20 year window was chosen as it represents a typical lifetime of wind parks (Ziegler et al 2018) and smooths out shorter-term variability that can mask potential climate change signals. Statistical significance of changes in the ensemble mean is assessed using a two-sided t-test with the null hypothesis that the changes have a mean of zero and a confidence level of 95%.

2.1. Regional and global climate model inputs from EURO-CORDEX, CMIP5, CMIP6

The analysis is based on the large EURO-CORDEX ensemble, and comprises all simulations that provide monthly mean 10 m wind speeds (variable name sfcWind). Only one realization per combination of global (GCM) and regional climate model (RCM) is considered to avoid over-weighting individual models that downscaled many CMIP5 realizations. Per default, I choose the r1i1p1 realization with the exception of EC-EARTH where r1i1p1 was not available and I use r7i1p1 instead. The number of available downscalings varies with scenario. RCP85 stands out with more than twice as many ensemble members (49) than rcp45 (18) and rcp26 (22).

To analyze the effect of downscaling, I also evaluate the driving CMIP5 models (i.e. those global models that were downscaled in EURO-CORDEX). The Norwegian model NorESM1-M does not provide 10 m wind speeds but only reports instantaneous wind components on pressure levels. Due to a lack of comparability, NorESM1-M is thus excluded from the CMIP5 analysis but downscaled EURO-CORDEX data based on this particular model is explored. Similar to EURO-CORDEX, the ensemble of driving GCMs from CMIP5 is largest for rcp85 (7) and smallest for rcp45 (5), while in contrast to CMIP5 rcp26 also has seven ensemble members.

To ensure that the relatively small CMIP5 ensemble described above is representative for the full CMIP5 ensemble, essential parts of the analysis are repeated with the full CMIP5 ensemble (rcp2.6: N = 20; rcp4.5: N = 29; rcp8.5: N = 28). Moreover, results are compared to the CMIP6 ensemble (SSP1-26: N = 27; SSP2-45: N = 31; SSP3-70: N = 29; SSP5-85: N = 32) to ensure that updates in the model code and resolution of the global models, as well as scenario modifications, do not invalidate the presented results.

2.1.1. Grids

I use EURO-CORDEX simulations at the highest available resolution (0.11° or around 12 km). Most models provide data on the so called EUR-11 grid, a
standard rotated polar coordinate system defined by WCRP (2015). I bi-linearly remap those few models using different grids onto the EUR-11 grid. Moreover, I bilinearly remap the CMIP5 and CMIP6 global model simulations onto a regular grid with 1.5° increments in the latitudinal and 1.75° increments in the longitudinal direction. For grid box based comparisons, land use data is remapped conservatively to the same grid.

I also report wind changes per country, both onshore and offshore, derived by computing the spatial mean over a country’s territory. In this process, I use Exclusive Economic Zones (EEZs) from Flanders Marine Institute (2020) to define potential offshore domains for each country (see SI figure G1).

2.2. Land use change data
Changes in onshore wind speeds are compared to vegetation changes in the Land Use Harmonization dataset (LUH1; Hurtt et al 2011) that is used in CMIP5. As in Wohland et al (2021b), I evaluate the sum of primary and secondary land as a proxy for land use change, where ‘secondary refers to land previously disturbed by human activities and recovering, while primary refers to land previously undisturbed’ (Hurtt et al 2011). While this proxy does not capture the plurality of approaches taken by different modeling groups to ingest LUH data into climate models (Lawrence et al 2016), it is justified in hindsight because it explains a large portion of the change signal and makes sense physically.

The focus on primary-plus-secondary land changes implies that the different contributions from changes in cropland, pasture and urban areas are not individually studied. Urban is neglected because urban areas occupy a significantly lower fraction of the global land area than any of the other land-use types (see figure 9 in Hurtt et al). Since all land use types have to sum to 100% of land area, it follows that any change in primary-plus-secondary land corresponds to an equal change of opposite sign in cropland-plus-pasture. Further separation between cropland and pasture did not appear beneficial for the large-scale assessment carried out in this study. Nevertheless, this separation and the inclusion of urban areas is likely very important in more local assessments carried out in future studies.

2.2.1. Equator-to-pole temperature gradient
The temperature gradient between equator and pole is considered as one proxy for the strength of the large-scale circulation that is driven by differential heating of Earth’s surface (e.g. Wallace and Hobbs 2006). It is here defined as

\[ \Delta T_{\text{gradient}} = T_{\text{equator}} - T_{\text{pole}}, \]

where \( T_{\text{equator}} \) is the zonal mean 2 m temperature (\( T_s \)) averaged over 10° S to 10° N and \( T_{\text{pole}} \) is the zonal mean 2 m temperature averaged over 70° N to 90° N. Defined this way, the equator-to-pole gradient is positive. I report changes in the gradient as

\[ \Delta T_{\text{gradient, future}} = T_{\text{equator}} - T_{\text{pole}}, \]

Since the pole wars more strongly than the equator, changes in this temperature gradient are negative, with greater absolute changes in the strong climate change scenarios.

3. Results and discussion

Offshore wind speeds decrease both in the global CMIP5 and the downscaled EURO-CORDEX data at the end of the 21st century and the magnitude of this decrease scales with the emission scenario (figure 1). While the mitigation scenario rcp26 features only modest reductions that rarely exceed \(-0.3 \text{ m s}^{-1}\) and are generally indistinguishable from zero south of England, stronger reductions occur almost everywhere under the strong climate change scenario rcp85. The intermediate rcp45 also features intermediate offshore wind reductions, supporting the idea that wind speed changes scale with the amount of greenhouse gas forcing. A noticeable exception to general decrease exists in the Barents Sea close to Russia’s north-western coast, where wind speeds increase (CMIP5 and EURO-CORDEX) as well as in the northern part of the Baltic (EURO-CORDEX only). These increases are likely related to sea-ice loss and resultant drops in surface roughness that causes higher near-surface wind speeds. The fact that only EURO-CORDEX captures this effect in the Northern Baltic is an indication of added value in the downsampling because the small spatial extent of this watermass means that it is only crudely captured in global models.

Onshore wind speeds evolve differently and document major discrepancies between the global and regional models. In the global CMIP5 models, changes are weak in rcp26, strong in rcp45 and intermediate in rcp85. By contrast, the regional EURO-CORDEX models show essentially no onshore wind speed changes in any scenario. The discrepancy is most pronounced in rcp45, where CMIP5 features a strong reduction in Eastern Europe and Western Russia with amplitudes exceeding \(-0.5 \text{ m s}^{-1}\) (figure 1(b)) and EURO-CORDEX shows no signal at all (figure 1(c)). Moreover, CMIP5 documents widespread reductions between \(-0.1 \) and \(-0.2 \text{ m s}^{-1}\) in rcp85 that are not paralleled in EURO-CORDEX. Another noteworthy discrepancy occurs in England under rcp26 where wind speeds increase in CMIP5 and decrease in EURO-CORDEX.

In brief, the regional and global models agree on offshore reductions while they disagree onshore.

Decomposing the CMIP5 ensemble mean by analyzing models separately reveals that most models
support the ensemble mean results while highlighting that inter-model spread can be substantial. While, for example, all CMIP5 models feature offshore decreases in rcp85 (SI figure B3), the amplitude of the signal and the extent of the affected area varies considerably. HadGEM2-ES and MIROC5 are at the upper end of the spectrum, showing reductions in essentially all European offshore areas that exceed $-0.7 \text{ m s}^{-1}$. By contrast, the signal is much weaker in IPSL-CM5A-MR. Similarly, the onshore wind reduction in Eastern Europe exists in four out of five models, yet with varying amplitudes in the range between $-0.2 \text{ m s}^{-1}$ and $-0.8 \text{ m s}^{-1}$ (figure B2).

Evaluating the EURO-CORDEX wind changes per GCM-RCM combination shows that the GCM exerts stronger control than the RCM, in line with the results presented in Vautard et al. (2021). This importance of the GCM can either imply that the fluxes into the regional modeling domain constrain the RCMs strongly or that the prescribed sea surface temperatures from the GCM synchronize low-frequency wind variability in the RCMs (e.g. Keenlyside et al. 2015, Farneti 2017), suggesting that the separation of model uncertainty and internal variability is complicated (Hawkins and Sutton 2009). For example, HadGEM2-ES was downscaled by ten different RCMs under rcp85 and always features wind reductions in the North-Western end of the domain (SI figure B6). By contrast, the 8 NorESM1-M downscalings consistently feature small increases in the same region. This discrepancy even occurs when the same RCM is used to downscale HadGEM2-ES and NorESM1-M. Nevertheless, most of the 49 GCM-RCM combinations agree on wind reductions offshore, although some point towards localized increases north of the UK. With respect to the onshore signal in rcp4.5, some EURO-CORDEX simulations project weak wind speed reductions (SI figure B5) but the signals are weak and do not occur consistently across the ensemble and thus do not manifest in the ensemble means.

The remainder of this paper aims at explaining the onshore discrepancy between EURO-CORDEX and CMIP5 by investigating land use change as one driver of change (3.1), documenting the scale of expected onshore and offshore changes on a country level (3.2), and evaluating the role of the equator-to-pole gradient as a second driver of change (3.3). Owing to the very good correlations between equator-to-pole temperature gradient changes and offshore wind changes, the last part will be complemented with an analysis of the full CMIP5 and CMIP6 ensembles.

### 3.1. Driver for onshore signal: land-use change

The CMIP5 onshore signal correlates very well with the land use change forcing (figure 2). Comparing the land use change maps, to the wind change maps (figure 1) reveals some striking similarities. Most importantly, the strong land use change in Eastern Europe and Russia in rcp4.5 coincides with the pronounced reduction in winds. This link is physically plausible since recovering vegetation increase surface roughness locally and reduces near-surface wind speeds. Albeit less pronounced, similar features exist in the other scenarios as well. In rcp2.6, the wind increase in England is accompanied by a reduction in primary and secondary land. Large parts of the Atlantic coast, penetrating a few hundred kilometers inland, experience both reductions in winds and increases in primary plus secondary land in rcp8.5.
Figure 2. Land use change in the LUH1 dataset and its correlation with CMIP5 onshore wind changes. The headings in the upper subplots denote the scenario names (rcp2.6, rcp4.5, rcp8.5) along with the Integrated Assessment Model that was used in constructing the scenario (IMAGE, MINICAM, MESSAGE). Each point in the lower scatter plot corresponds to one grid cell and different colors denote different scenarios. Locations where the change in primary plus secondary land was essentially zero (i.e., less than 1%) are excluded. Land use change is measured in the fraction of a grid cell: a value of 1 means that 100% of a cell’s area has experienced a change, a value of 0 means no change within a cell.

These similarities manifest in a high pattern correlation of $r = -0.75$ (figure 2(d)) between land use change and wind change. As noted already in Wohland et al. (2021b), this analysis documents that the land use forcing is strongest in rcp4.5, questioning the default assumption of higher signal-to-noise ratios in rcp8.5.

In summary, CMIP5 onshore wind changes are closely linked to the land use forcing, raising the question why similar signals do not exist in EURO-CORDEX. The answer is simple: Land use is kept constant in current EURO-CORDEX downscalings. In fact, the required high resolution forcing datasets have only recently been developed (Hoffmann et al. 2021) and were simply not available by the time CMIP5 was downscaled. Moreover, including varying land-use in the CORDEX downscalings is currently explored in a Flagship Pilot Study (Rechid et al. 2017, Davin et al. 2020) and it is currently unclear whether CMIP6 downscalings will account for varying land use. This shortcoming in current EURO-CORDEX simulations has implications for impact modelers. Even though the scenarios share the same name in CMIP5 and EURO-CORDEX, they do not share all forcings. While the greenhouse gas evolution is identical, the lower boundary condition over continents is not, with significant implications for wind speeds—and presumably other near-surface variables—in some locations. As a consequence, assessments exclusively relying on EURO-CORDEX can underestimate risks in line with studies evaluating other surface variables like radiation, temperature and precipitation (e.g. Boé et al. 2020, Gutiérrez et al. 2020). In the example studied here, EURO-CORDEX creates the questionable impression that no risk exist for 20 years mean onshore winds in disarray with the global models. In the interest of transparency and to avoid misinterpretation, I argue that the data providers should flag diverging forcings as clearly as possible while working towards better aligned global and regional climate simulations.

3.2. Country-level assessments

In order to illuminate the expected changes within different jurisdictions, I provide a per country breakdown of expected wind speed changes separately for onshore (figure 3) and offshore regions (figure 4).

As expected, there is a substantial discrepancy between EURO-CORDEX and CMIP5 in particular onshore in rcp45 and rcp85 (figure 3). EURO-CORDEX generally projects small changes in the range between $-0.06$ m s$^{-1}$ and $+0.06$ m s$^{-1}$ in most countries, except some countries with long coastlines like Portugal, Spain or Norway. By contrast, CMIP5 wind speeds decrease by more than $-0.06$ m s$^{-1}$ in all but five (six) countries in rcp45 (rcp85) and decreases
Figure 3. Wind speed change breakdown per country—onshore. Values are ensemble mean wind speed changes averaged over all grid boxes within a country. Statistically significant changes are in bold font (95% significance threshold).

Figure 4. Wind speed change breakdown per country—offshore. Values are ensemble mean wind speed changes averaged over all grid boxes within a countries’ exclusive economic zone. Statistically significant changes are in bold font (95% significance threshold).
are greater than $-0.18 \text{ m s}^{-1}$ in six (five) countries. Values reported for individual small countries (like Luxembourg or Cyprus) have to be interpreted carefully in the CMIP5 ensemble because the extent of these countries is smaller than a typical grid box in CMIP5. Nevertheless, CMIP5 produces a large-scale decline in onshore winds that is moreover backed up by physical reasoning, thus providing evidence that these results are not an artefact of limited model resolution.

Offshore, there is good agreement between CMIP5 and EURO-CORDEX in resource-rich countries like Ireland, the United Kingdom and Norway and a reduced discrepancy overall. Wind speed increases in EURO-CORDEX in areas with complex coasts and adjacent mountains like Bulgaria and Croatia might point to added value of downscaling as the relevant local circulations are likely much better captured. Similarly, the increases seen in Finland are likely due to an improved representation of the Northern Baltic and reduced sea-ice formation in winter. Comparing the ensemble mean changes on- and offshore reveals that the magnitudes are comparable (strongest reductions around $-0.3 \text{ m s}^{-1}$), implying that the relative changes are greater over land where mean wind speeds are lower.

### 3.3. Analyzing the full ensemble in a UK offshore case study

To assess robustness and ensemble spread, figure 5 depicts wind speed changes in all models. Here, I show an offshore example for the United Kingdom due to its large resources and plans to expand offshore wind energy. Similar plots for other resource-rich countries are in the appendix, see figures D1–D3. Wind speeds decline in the ensemble mean in all
scenarios both in CMIP5 and EURO-CORDEX but the ensemble spread is of the same order of magnitude as the signal, indicating substantial uncertainty. Compared to CMIP5, the EURO-CORDEX decline is approximately twice as strong in rcp2.6 and comparable yet weaker in the other scenarios. A clustering of the EURO-CORDEX values by driving GCM is clearly visible, again supporting the interpretation that it is mostly the choice of GCM rather than the RCM that determines expected changes in wind speeds.

Using a strict definition of robustness that requires agreement of all models on the sign of change, robust declines occur in CMIP5 in rcp4.5 and rcp8.5. They never exist in CORDEX. Nevertheless, accounting for the different ensemble sizes and considering a signal robust if at least 95% of the models agree on the sign of change, EURO-CORDEX features robust declines in all scenarios.

I report a very clear connection between UK offshore wind speed changes and the equator-to-pole temperature gradient change (figure 5(d)). This connection reconciles the large uncertainties discussed before by tracing it to a very large spread in equator-to-pole temperature gradient changes. In fact, all scenarios overlap in terms of their temperature gradient: rcp2.6 projects changes between 0 K and −4.5 K; rcp4.5 between −2 K and −6.5 K; rcp8.5 between −3.5 K and −11 K. In other words, one model projects less arctic warming in rcp8.5 than another models does in rcp2.6. Once this inter-model uncertainty in terms of the temperature gradients is addressed, however, models agree with regard to how much wind reduction is expected for a given change in the temperature gradient ($r = 0.9$). If arctic amplification, and hence the temperature gradient change, is at the upper end of the range sampled by these models as suggested by recent analysis from the Polar Amplification Intercomparison Project (Smith et al 2022), the UK could experience average offshore wind speed reductions up to $-0.6$ m s$^{-1}$. Compared against the modeled average historical wind speeds ($\approx 8$ m s$^{-1}$), this corresponds to approximately a 6% reduction, likely causing even larger drops in wind energy density due to their cubic relationship.

Since the equator-to-pole gradient is a proxy for the strength of the general circulation, this connection makes sense physically. Nevertheless, the very high correlation found here ($r = 0.9$) is remarkable since there are other phenomena that control winds around the United Kingdom which go beyond the large-scale energy imbalance of the planet.

3.4. European offshore wind speeds drop with a declining equator-to-pole gradient

The high correlation reported for the UK is not unique to that area but instead is common in European offshore areas (figure 6). A band of correlations exceeding 0.8 stretches from the Western Mediterranean over the Bay of Biscay, the Atlantic Ocean around Great Britain and along the Norwegian coast. In addition, I find correlations between 0.6 and 0.8 in all other areas suitable for European offshore wind energy excluding small domains (e.g. in the Eastern Baltic and west of Portugal). The sensitivity of wind speeds to changes in the temperature gradient usually lies in between 0.02 and 0.08 m s$^{-1}$ K$^{-1}$. That is, for values at the upper end of the sampled temperature gradient range, offshore wind speeds will drop by 0.2 to 0.8 m s$^{-1}$ depending on location, constituting a substantial reduction compared to typical mean wind speeds in the order of 6 to 10 m s$^{-1}$. In fact, the upper end of model results is more representative of the real-world evolution than the mean, according to an analysis using a large ensemble with a couple of
thousand simulations from 16 CMIP6 models (Smith et al. 2022).

To verify the robustness of these results and rule out a sampling bias, I repeated the analysis with the full CMIP5 and CMIP6 ensembles (SI figures E1 and E2). The full ensembles confirm the positive correlations between the temperature gradient and wind speed changes although correlations are lower. Very high correlations (above 0.8) only occur around the Balearic islands in CMIP5 and never in CMIP6. High correlations between 0.6 and 0.8 occur almost everywhere in the Mediterranean but only infrequently in the Atlantic and never in the North Sea in both datasets. Medium correlations between 0.4 and 0.6 occur around the British Isles (both), in the North Sea (CMIP6) and along the Norwegian coast (CMIP6). In other words, the more recent, and potentially more realistic, CMIP6 ensemble provides greater evidence for a strong role of the temperature gradient in determining wind speeds than the older CMIP5 does. Expanding the analysis to the global scale suggests that other potential offshore wind locations such as the North American Pacific coast may also be at risk if arctic temperatures increase strongly, given high to very high correlations in both CMIP5 and CMIP6 (SI figures F1 and F2).

The reported high correlations are also consistent with earlier works. For instance, Harvey et al. (2014) showed that the storm track response in CMIP5 is highly correlated with the temperature gradient, albeit at shorter timescales than those considered in this study and using temperatures further above ground. Similarly, Barnes and Polvani (2015) report high correlations between arctic amplification and zonal winds over the North America/North Atlantic region, in particular between April and August.

3.5. Comparison to multidecadal variability and implications for wind energy

The interpretation of the results of this study should take the existence of multidecadal climate variability into account because pronounced multidecadal wind variability has been documented in observations and modeling studies (e.g. Vautard et al. 2010, Zeng et al. 2019, Wohland et al. 2021b, Utrabo-Carazo et al. 2022). On a continental scale, this variability features rates of change in the order of ±0.1 m s⁻¹/decade sustained over around 2 decades. In many countries, the changes expected in the ensemble mean by the end of the 21st century are of a similar order (cf figure 3). Nevertheless, it is unlikely that those changes are caused by climate variability because (a) they occur in the mean over an non-synchronized ensemble, (b) there are physically plausible mechanisms explaining the wind changes in terms of local land use or global changes in atmospheric circulation.

Real wind parks are not built in a hypothetical ensemble mean but in the single realization of the climate system that we live in. That is, they will experience a combination of multidecadal variability and forced changes. In the near- to medium future, multidecadal climate variability will remain more important than climate change impacts regarding mean winds because the former are stronger. For instance, multidecadal wind variations cause changes in wind turbine outputs exceeding 10% in some locations in Europe (Wohland et al. 2021a).

Nevertheless, climate change does not only affect mean conditions, but also spatial patterns (e.g. Ozturk et al. 2021) and extremes (e.g. Coumou and Rahmstorf 2012), implying that the results presented here do not suggest that climate change impacts can be safely neglected for wind energy in general. By contrast, this study provides additional evidence for the need to include climate expertise and climate data into energy-system planning.

An obvious weakness of the presented results is the reliance on 10 m wind speeds. However, as argued before, it is state-of-the-art to use extrapolated wind speeds to carry out wind energy climate impact assessments and the standard methodologies leave relative changes in wind speeds untouched. This includes the methodology detailed by ECMWF (2022) that foresees to use constant power law exponents in conjunction with EURO-CORDEX 10 m wind speeds in a key dataset that informs regulatory and industry players. For instance, both the power and log laws (e.g. Emeis 2018), translate a 5% reduction in 10 m winds into a 5% reduction in hub height winds if applied using the standard assumption of time-invariant power law exponents and roughness lengths.

In addition, methodological progress at the energy-climate interface is needed to better understand the implications of the presented wind speed changes for wind energy applications. While changes in mean wind speeds are often indicative of changes in wind power potentials, there is no one-to-one relationship due to the non-linearity of power curves. Explicit calculation of wind energy potentials is challenging, however, because of systematic biases in current climate model results. These biases should be corrected before applying non-linear transformations but we lack the evidence that historical bias-corrections remain valid in the future despite thermodynamical and dynamical climatic changes. A combination of improved climate models and better understanding of the relevant processes, as discussed in this study, will help to better constrain climate risk for wind energy.

4. Conclusions

Near-surface wind speeds have been the base for most climate change impacts assessments in the wind energy sector, and thus inform key policy decisions to mitigate climate change. Evaluating the global-to-regional climate modeling chain, I showed that
EURO-CORDEX misses reductions in near-surface onshore winds that exist in the driving global models and thereby underestimates the risks of human interference with the wind climate. The critical aspect is land-use change, which forms part of the global model inputs but is not yet implemented in EURO-CORDEX climate change simulations, thus compromising comparability of scenarios with strong land-use change (e.g. rcp45). Nevertheless, I revealed that there is high agreement across global and regional climate models that offshore wind speeds will decline with climate change by up to 0.8 m s\(^{-1}\). Viewing wind speed reductions as a function of the change in the equator-to-pole temperature gradient proves useful in limiting ensemble spread: while the global models that were downscaled in EURO-CORDEX sample a large range of temperature gradient changes indicating pronounced uncertainty, they agree well on the expected wind speed change for a given temperature gradient change (correlations often exceed 0.8). In other words, European offshore winds are threatened by arctic amplification. The connection has been found to also hold in the complete CMIP5 and CMIP6 ensembles, although correlations are weaker, and it extends to areas beyond Europe such as the North American west coast.

This study underlines the need for process-based understanding of the drivers that alter wind speeds. It shows that climate change impacts on winds can be substantial while also highlighting remaining uncertainties in translating model output into actionable advice for the wind energy sector.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/record/7373229#.Y4c4633P2Uk.

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Code and data availability

The code is written in Python and is maintained on github (https://github.com/jwohland/kliwist_modelchain). The version used to generate the results presented in this paper is also archived on zenodo (https://doi.org/10.5281/zenodo.7373229). EURO-CORDEX, CMIP5 and CMIP6 input data was accessed from the German Climate Computing center and is also available via the data portals of the Earth System Grid Federation at https://esgf-data.dkrz.de/projects/esgf-dkrz/. Land Use Data is available from https://luh.umd.edu/data.shtml#LUH1_Data. Intermediate data that allows reproducing all Figures is available on zenodo (https://doi.org/10.5281/zenodo.7372998).

Conflict of interest

There are no competing interests.

ORCID iD

Jan Wohland @ https://orcid.org/0000-0001-8336-0009

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