Compound winter low wind and cold events impacting the French electricity system: observed evolution and role of large-scale circulation

Response to reviewers

We would like to thank both reviewers for their helpful comments and suggestions, which greatly helped to improve the manuscript. Their comments are shown below in black, with our responses in blue. In response to the major and minor points raised by both reviewers, we have added a Supplementary Materials document to the manuscript. Additionally, we made some aesthetic adjustments to the figures to improve their clarity.

Reply to reviewer 1:

Line 39. Onshore wind power capacity will increase to 30-39GW also by 2035? Please specify it.

Yes, wind power capacity is planned to increase to 30-39GW by 2035 according to RTE's scenarios (RTE, 2023). We clarified this in the manuscript at L.42-44:

"Onshore wind power capacity is planned to increase from 20GW in 2022 to 30-39GW by 2035 and substantial additional offshore wind farms are also planned, with a total projected capacity of 18GW by 2035 compared to 0.5GW in 2022 (RTE, 2023)."

Line 110. Is MERRA interpolated to ERA5 resolution of 0.25º?

Thanks for raising this question. MERRA-2 was not interpolated on the ERA5 grid before the calculation of our indices. Reviewer 2 also raised some comments regarding the interpolation scheme (nearest neighbor vs. bilinear) used to calculate our indices. In order to address these comments, we have conducted a series of sensitivity tests. These tests show that our indices are not affected by the interpolation scheme. Therefore, interpolating MERRA-2 to ERA5 should not affect our results. Here are our responses to the comments from Reviewer 2:

"To test whether the interpolation method has an influence on our indices, a bilinear interpolation scheme was used to interpolate 100-m wind speed at wind turbine locations, and near-surface temperature at each city coordinates, for ERA5, MERRA-2 and E-OBS datasets. As the reviewer suggests, the near-surface temperature is adjusted to each station altitude prior to the bilinear interpolation for the calculation of the temperature index. The results were compared to those obtained using the nearest neighbor interpolation, as described in the article. The figure below shows a general good match between the results obtained with the two interpolation methods, for the temperature index in ERA5, MERRA-2 and E-OBS, as well as the wind capacity factor index for ERA5 and MERRA-2. This suggests that the interpolation method has only a minimal impact on the findings of this study.

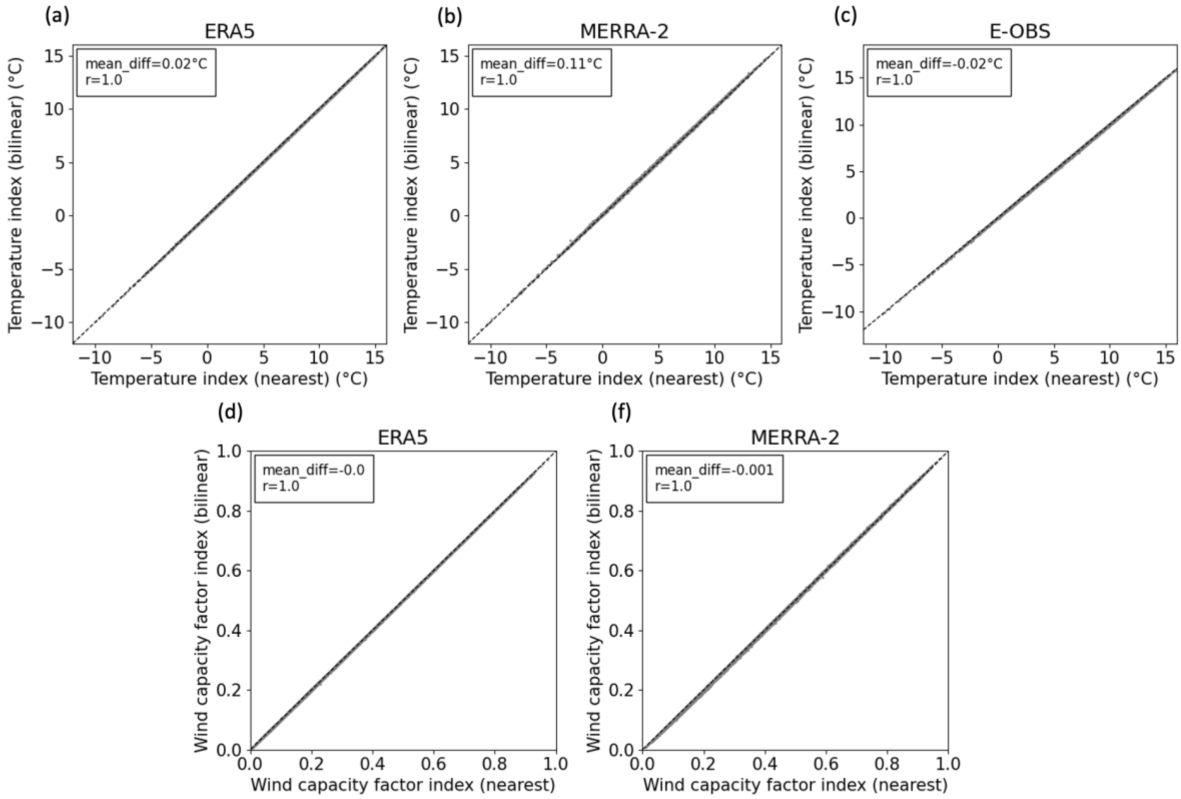

Figure R2.1: Temperature index as calculated with near-surface temperature interpolated using the nearest neighbor method (X-axis) versus the bilinear interpolation (Y-axis) at each station for (a) ERA5 (b) MERRA-2 and (c) E-OBS datasets for the winters of the 1950-2022 period. Wind capacity factor index as calculated with wind speed interpolated with the nearest method (X-axis) against as calculated with bilinear interpolation (Y-axis) at each wind farm for (d) ERA5 and (f) MERRA-2 datasets for the winters of the 1950-2022 period. The mean difference and the correlation coefficient between the two interpolation methods are shown in the top left corner.”

Lines 162-164: Figures 1 and 2. Why not to have in the same plot wind and temperature in another plot? E.g., figure 1 a) with 2 b).

We appreciate this suggestion and have implemented the recommended modifications. The revised figures are included below:

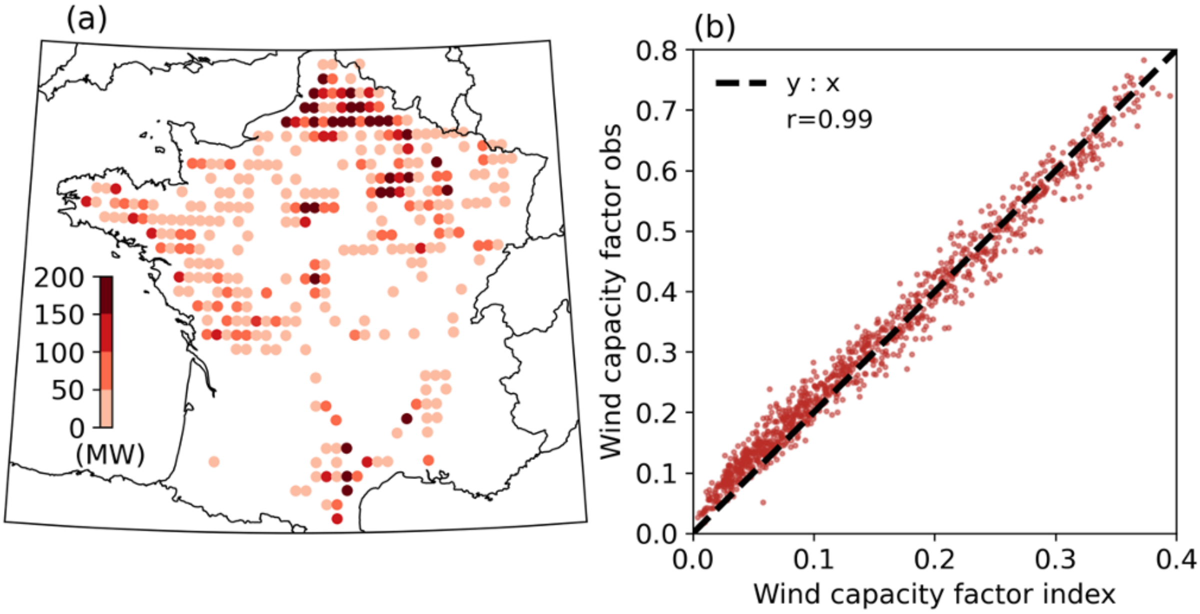

Figure 1: (a) Spatial distribution of the wind power installed capacity (MW) in France in 2021 from the WindPower.net dataset used for the calculation of the wind capacity factor index. (b) National French wind capacity factor index as calculated with ERA5 (no unit; X-axis) versus observations (no unit; Y-axis) in winter over the 2012-2020 period. The correlation coefficient is given in the top left corner, and the black dashed line represents the y:x function

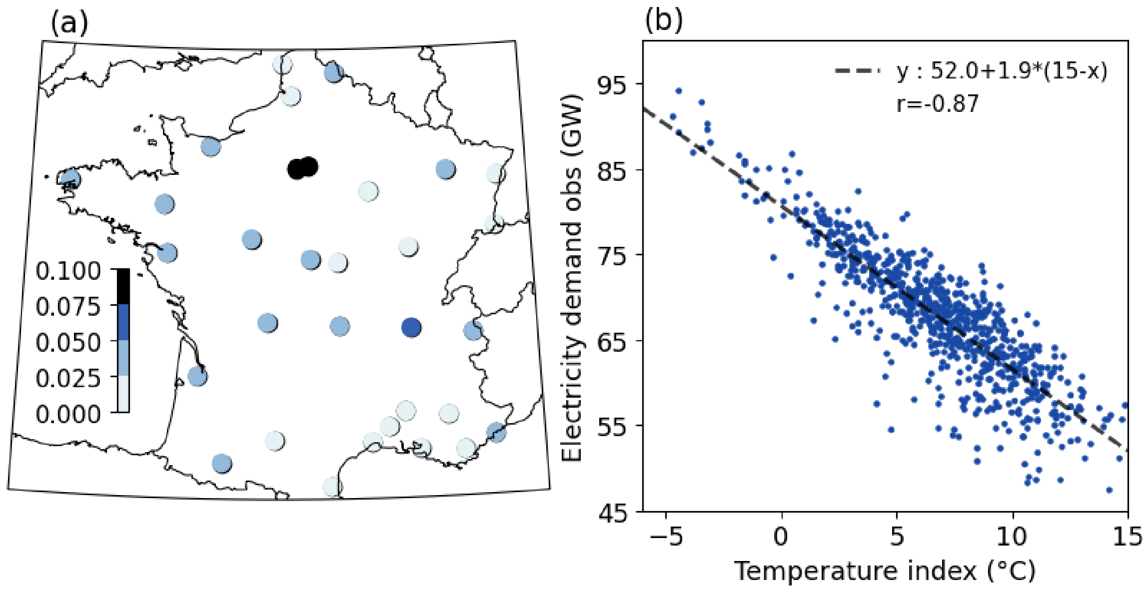

Figure 2: (a) Location of the 32 French cities and associated weights (no unit) used for the calculation of the temperature index. (b) Temperature index as calculated in ERA5 (°C; X-axis) versus observations of the electricity demand (GW; Y-axis) in winter over the 2012-2020 period, excluding week-ends and bank holidays. The correlation coefficient is given in the top right corner. The linear regression line between the temperature index and the electricity demand observations is shown by the black dashed line. The corresponding linear regression equation, in the form y=y(15°C)+a*(15°C-x), where 15°C is the threshold of residential heating and a the thermosensitivity of the electricity demand, is shown in the top right corner.

Line 180. Can the authors explain more why low wind are based on the 23th percentile? Is there any reasoning behind? I think this point is important.

We acknowledge that the explanation of our choice of the threshold needed some clarifications, and we thank the reviewer for raising this issue.

Low wind days are defined as days with an observed wind capacity factor below 0.15 (in the éCO2mix dataset, section 2.2). This value corresponds to the 23th percentile of the distribution of wind capacity factor in winter in the observations. We acknowledge that highlighting the 23th percentile threshold in the former version of the manuscript may have appeared somewhat unconventional and cherry-picked, which is less the case for the threshold 0.15. Therefore, we revised the section 2.5 “Identification of low wind days, cold days and associated compound events” at L.216-218:

“Days of low wind capacity factor (red points in Figure 3) are defined as days with an observed wind capacity factor below 0.15, corresponding to the 23th percentile of its distribution in winter.”

Additionally, we would like to inform the reviewer that, in response to comments from Reviewer 2, we have included sensitivity tests regarding the definition of compound events in the Supplementary Materials. In these tests, two alternative definitions are used and compared with the main definition. The first one tests a more extreme threshold for the wind capacity factor (i.e., 5th percentile) index compared to the temperature index (i.e., 23th percentile). The second one tests identical thresholds for both indices to define compound events (i.e., 10th percentile for both indices). These tests show limited sensitivity to thresholds for the definition of compound events, except for the long-term trend in the observed occurrence of compound events over the 1951-2022 period.

Line 263. Figure 5. Why there is not green line (E-OBS) in 5a?

There are no green lines in Figure 5a, and also Figure 5c because we only use the near-surface temperature variable from the E-OBS dataset. We chose not to use E-OBS for calculating the wind capacity factor index because (1) the E-OBS wind speed dataset only starts in 1980 and (2) the spatial coverage of the source stations is not good, especially in the early period, which is problematic for our application. Therefore, low wind days and compound events are not shown in Figure 5a and 5c for the E-OBS dataset.

Line 305. This can be explained as the compound seem to be mostly driven by cold temperatures, so their patterns are very similar.

We agree with the reviewer that the higher similarities in the composite of mean sea-level pressure anomalies between cold days and compound events (Figure 6a, b), compared to low wind days and compound events (Figure 6a, c) can be explained by the stronger link between cold days and compound events, as noted in their climatological characteristics (Figure 4) or temporal evolution (Figure 5).

This stronger link is due to the compound event definition, which is based on a more extreme threshold for cold days compared to low wind days. In response to comments from Reviewer 2 concerning the definition of compound events, we explored an additional compound event definition based on a more extreme threshold on the wind capacity factor index. While we found that the associated composite of mean sea-level pressure anomalies (red contours of Figure S3) is somewhat more similar to the composite of mean sea-level pressure anomalies for low wind days (Figure 6c), the main conclusions of this work are generally not sensitive to these thresholds. We clarified this point by adding at (L. 433-439):

"We find relatively higher similarities in the mean sea-level pressure anomalies between cold days and compound events compared to between low wind days and compound events. This can be explained by a more extreme threshold used for cold days compared to low wind days in the definition of compound events. Note that the sensitivity to thresholds used in the definition of compound events is documented in Supplementary Materials. While we find that sea-level pressure anomalies between low wind days and compound events compare better when setting a more extreme threshold for low wind days in the compound event definition, the main conclusions of this work are generally not sensitive to these thresholds (Figure S3)."

Line 403. "Overall" is repeated twice in the same sentence.

Thanks, it is corrected (L.560): "This leads to a weak decrease of 20% in the frequency of compound events."

Lines 406-407. This is not very clear, can you please clarify what do you mean with "a simple change in the frequency"?

We acknowledge that the term "simple change" was misleading and have clarified this in the revised manuscript by modifying the sentence at (L.563): "However, due to significant intra-type variability, a change in the frequency of a limited number of weather types may not capture the full range of circulation changes."

Lines 429-436. The authors state that the large-scale atmospheric circulation did not have influence in the observed decreased in the occurrence compound events, while it did in the occurrence of cold days. But, if the compound events are mostly driven by the cold days, how can the authors explain this?

Thanks for raising this question. Following a comment from reviewer 2, we performed some sensitivity tests to the parameters used in the dynamic adjustment analysis. We either found a significant decrease in the evolution of circulation-induced compound events or no trend depending on the choice of the parameters. The main conclusion from these sensitivity tests is that it is rather difficult to conclude whether or not the large-scale circulation played a role in the observed decrease in compound events because of limited robustness.

Following these sensitivity tests, we revised our choice of parameters in the dynamical adjustment analysis. With the revised parameters, the circulation-induced compound events exhibit a significant decrease (-0.14 days per decade, $p=0.04$). However, we decided to remain cautious in our conclusions as, as said in the previous paragraph, the significance of the trend of circulation-induced compound events is not robust to the methodology. Here are our revisions:

- In the abstract section at L. 25-28: "We further show that the atmospheric circulation and its internal variability are likely to play a role in the observed reduction in cold days, suggesting that this negative trend may not be entirely driven by anthropogenic forcings. It is however more difficult to conclude on the role of the atmospheric circulation in the observed decrease in compound events."
- Update of the revised dynamical adjustment parameters in the methodological section 2.7.

- In section 3.2 at L.593-601: "Interestingly, circulation-induced cold days substantially decrease (-0.40 days per decade; Table 3), although the p-value does not reach the 0.05 significance level (p-value=0.14). Large-scale circulation may therefore have contributed to more than 50% of the decline in cold days occurrence (-0.72 days per decade, Table 3) observed between 1951 and 2022, suggesting that anthropogenic forcing may not be the only driver of this trend. Similarly, circulation-induced compound events show a decrease (-0.14 days per decade, Table 3) over the 1951-2022 period (p-value=0.04). However, both the trend significance and the magnitude of the slope are sensitive to the parameters used in the dynamical adjustment (not shown). Thus, the robustness is too weak and prevents us from drawing conclusions on the role of the large-scale circulation on the decrease in compound events. Finally, there is no significant trend in the circulation-induced low wind days."
- In the conclusion section at L.677-680: "Interestingly, the large-scale atmospheric circulation shows a contribution of approximately 50% of the observed decrease in cold days over the 1951-2022 period in ERA5. [...] Finally, we cannot conclude on the role of large-scale circulation in the decrease of compound events as our methodology exhibits sensitivity to its parameters."

	Compound events	Cold days	Low wind days
ERA5	**-0.19 (0.02)**	**-0.72 (0.02)**	-0.08 (0.59)
Circulation-induced in ERA5	**-0.14 (0.04)**	-0.40 (0.14)	-0.21 (0.75)

Table 3: (first row) Trend (slope in days/decade, and associated p-value) in the frequency of low wind days, cold days, and compound low wind and cold events in winter over the period 1951-2022 in ERA5 (first row; same trend estimates as in Table 1) and in their respective circulation-induced events (second row; section 2.7). The slope is calculated with the Theil-Sen estimator and the p-value is calculated with the Mann-Kendall test. Significant trends with $p<0.05$ are shown in bold.

Line 434. Where is -0.87 in table? This must be a mistake, please correct it.

As described in our reply to the previous comment, please note that we have made some changes to the dynamic adjustment parameters following a comment from reviewer 2. We changed Table 3 accordingly in the main text. The revised Table 3 is included in the response to the previous comment.

Line 473-474. Can you be more specific?

We clarified this sentence and revised the main text at L. 681-686 :

"Assuming that observed changes in the large-scale circulation are mainly driven by internal climate variability (Shepherd, 2014), these results suggest that, over the last few decades, climate variability likely reinforced the long-term decline in cold events in response to warming. This may not continue in the near future, potentially leading to a temporary increase in the occurrence of cold events."

Lines 487- 490. I would also add to this multifaceted problem the changes in the demand patterns and therefore, the changes in the compound events. Here, compound events are limited to cold days and low production. But if the demand increases in summer due to higher temperatures, this variability in compound events would change as well.

Thanks, this suggestion was also raised by Reviewer 2. We have added an additional discussion in the conclusion about future changes in demand patterns. Here is the section available at (L. 696-708):

"With the anticipated rapid growth of onshore and offshore wind farms, the impact of low wind conditions on power system risks is likely to increase and to become a greater threat alongside cold temperature conditions. As climate change reduces the frequency of cold events (Seneviratne, 2021), future risks to the French power system may be more evenly spread throughout the winter season, rather than being concentrated primarily in January and February as it is currently (RTE, 2023, §6.2.5.3). In addition, changes in electricity demand patterns are also anticipated. During summer, increased electricity demand is expected due to higher use of air conditioning in France. However, the risks for the French power system during summer are expected to be limited thanks to higher solar power production and power system flexibilities (RTE, 2023, §6.2.5.3). How the risk on the adequacy between electricity generation and demand associated with compound events will evolve in the next few decades is therefore multifaceted, depending on future levels of installed wind power capacity, changes in demand patterns, and climate change. We plan to address some of these questions in future work using climate projections from the latest Couple Model Intercomparison Project Phase 6."

References

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RTE (Réseau de transport d'électricité). Bilan prévisionnel, édition 2023. Futurs énergétiques 2050. 2023-2035 : première étape vers la neutralité carbone.

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