RESPONSE TO REVIEWER RC1

May 26, 2025

Dear Editor,
we thank the Reviewer and the Editor for the time dedicated to reading and revising our manuscript. We have taken great care of answering your comments. Among all modifications, we stress the main ones here. We provide our full answer letter below.

Sincerely,
Lia Rapella,
on behalf of the authors

General comments

Comment #1

The link between the impacts of the effects of climate change and airport operations are superficial and sometimes misleading (e.g., stronger headwind actually improves airplane performance; the authors also suggest an increased risk due to increased tailwinds, which is not likely a big impact because tailwind operations are easily and commonly avoided); while wind shear in downbursts is dangerous, in extratropical cyclones wind shear typically means that the planes take off into the shear, which improves climb performance (likewise, descending into wind shear acts to increase the headwind, so it is not inherently dangerous). So, a much more nuanced analysis is needed when considering the impacts of ETCs on aircraft operations. (I'm not arguing that stronger winds don't cause disruptions, but the current argument in the manuscript is imprecise.)
My recommendation is that either the "spin" of the paper is adjusted, away from airport operations, and instead putting more emphasis on how the weather systems were affected by climate change. Alternatively, a much more detailed analysis about how climate change actually affected air travel would be needed: Given the increases of turbulence/wind speed, how many more delays happened due to climate change? What are the costs? Wouldn't this be the questions that stakeholders would be interested in?.

We agree that the target of our paper is not directly searching impacts of climate change on airports' operation, thus we will correspondingly adjust the target and writing of the paper, as suggested by

the Reviewer, in the revised version. We would like to emphasize that our analysis is indeed an obervation-based (analogues) attribution approach to investigate how the weather systems that contributed and forced to airport closures, disruptions, delays, and cancellations, have changed compared to similar synoptic-scale situations and conditions occurred in the past. This means that, although similar large-scale patterns are observed historically, their effects and impacts, as measured, among others, by changing wind patterns and intensity, wind shear and bulk wind difference, turbulence-related metrics, are now different with respect to the past, thus suggesting a possible link with anthropogenic climate change. For this reason, we focus on 4 high-impact weather events, geographically distributed over Europe, USA, and Asia, that forced airports' disruptions, to find if these impacts belongs to the same class of previously-observed ones. Indeed, a detailed analysis on impacts on air travel due to climate change would require to completely revise the focus of our paper, also adapting our methodology to changing conditions that cannot be ruled out in an objective way. For example, while we can quantify natural mode variability and/or climate change trends using indices and long-term behaviour of key meteorological parameters to introduce an attribution-based framework, widely employed into different sectors (e.g., Faranda et al., 2024), directly investigated impacts on air travel in terms of costs, delays, and weather disruptions would require to add more data, some of them not freely available or covering short time intervals to be statistically robust to assess differences among present and past conditions, as well as, to take (and model/parametrize) into account additional factors as the increased number of flights over time, significantly higher today than decades ago, the different types of aircraft employed now with respect to those used earlier. Thus, we favourably accept the suggestion of the Reviewer to adjust the wording and general organization of the paper to clearly highlight our aims.

Comment #2

Throughout the manuscript, the authors use wind shear (which should have units of 1/s rather than m/s) when I think they mean "bulk wind difference" (which has the unit of m/s).

We fully agree with the Reviewer and we will change accordingly.

Specific comments

We will implement corrections to each specific comment.

RESPONSE TO REVIEWER RC2

May 26, 2025

Dear Editor,
we thank both Reviewer and the Editor for the time dedicated to reading and revising our manuscript. We have taken great care of answering your comments. Among all modifications, we stress the main ones here. We provide our full answer letter below.

Sincerely,
Lia Rapella,
on behalf of the authors

Main comments

Comment #1

This first comment relates to the analogue method.
As I understand it, the analogue method only considers the time of maximum intensity when looking for similar cyclones in the earlier period. I wonder how different the analogues would be (and therefore also the results) if you took into account the cyclone development. In terms of impacts, particularly for precipitation, the development period of the cyclone may matter more in terms of overall similarity than only the time of maximum intensity. I assume it should not be too difficult to look for analogues at various times before maximum intensity to see if the results are sensitive to this. Finding analogues that remained similar throughout their lifecycle may find cyclones that are more representative of the cyclones from the current period.

We particularly thank the Reviewer for raising this point. It has been shown (e.g., Ginesta et al., 2024) that attribution-based results on analogues are robust also if taking into account time steps related to the cyclone development and not just the time at which the minimum in SLP is observed. However, in the revised version we will assess this point by looking also for analogues at times before and after the defined cyclone time (see Figures 1)-4).

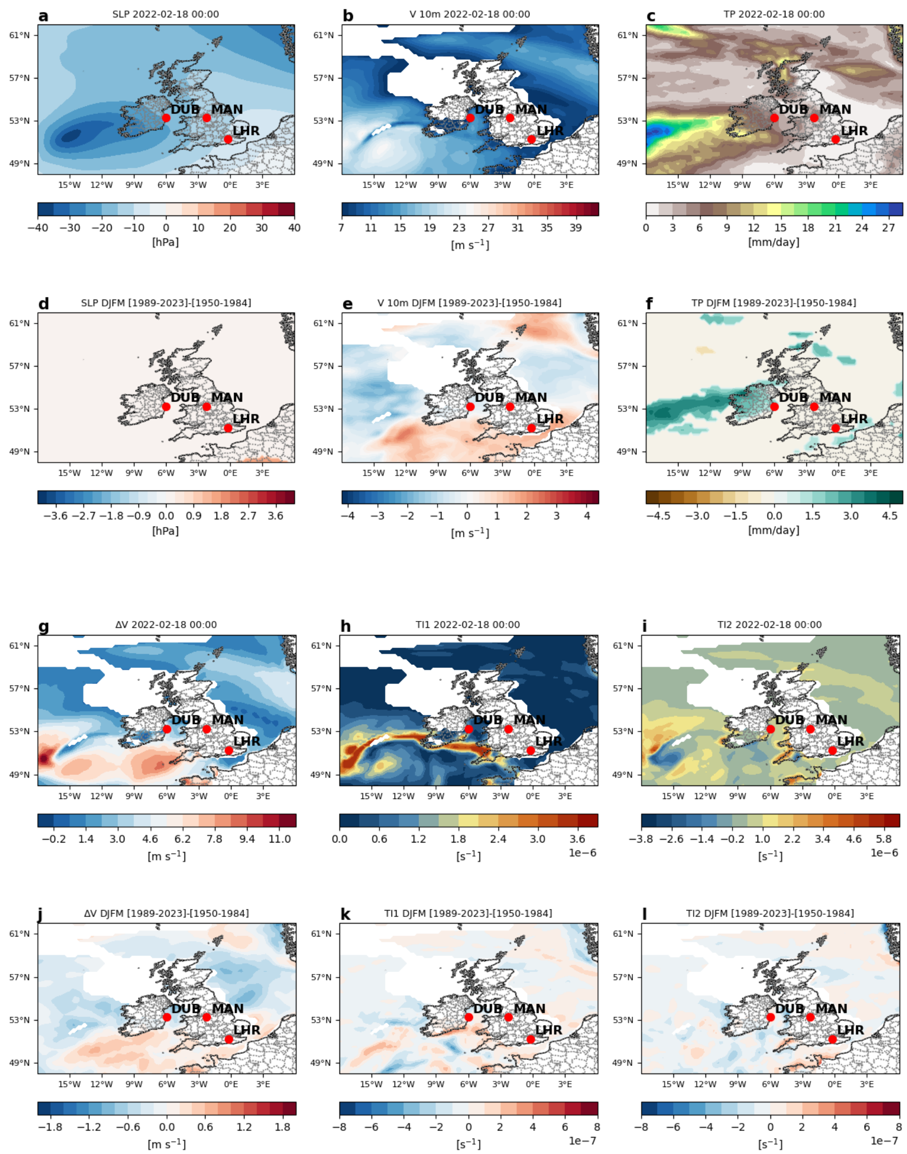

Figure 1: Analogue-based results for the Storm Eunice on 2022-02-18 00:00 (before the cyclone time). SLP **a** anomaly, V 10m **b** and TP **c**. Difference between factual [1989-2023] and counterfactual [1950-1984] period of the average SLP anomalies **d**, V 10m **e** and TP **f**. Bulk wind difference **g**, TI1 **h**, TI2 **i** and difference between factual [1989-2023] and counterfactual [1950-1984] period of the same variables ΔV **j**, TI1 **k** and TI2 **l**. In the second and fourth rows, shadings indicate significant changes. Red dots indicate major airports in the region: Dublin Airport (DUB), Manchester Airport (MAN) and Heathrow Airport (LHR).

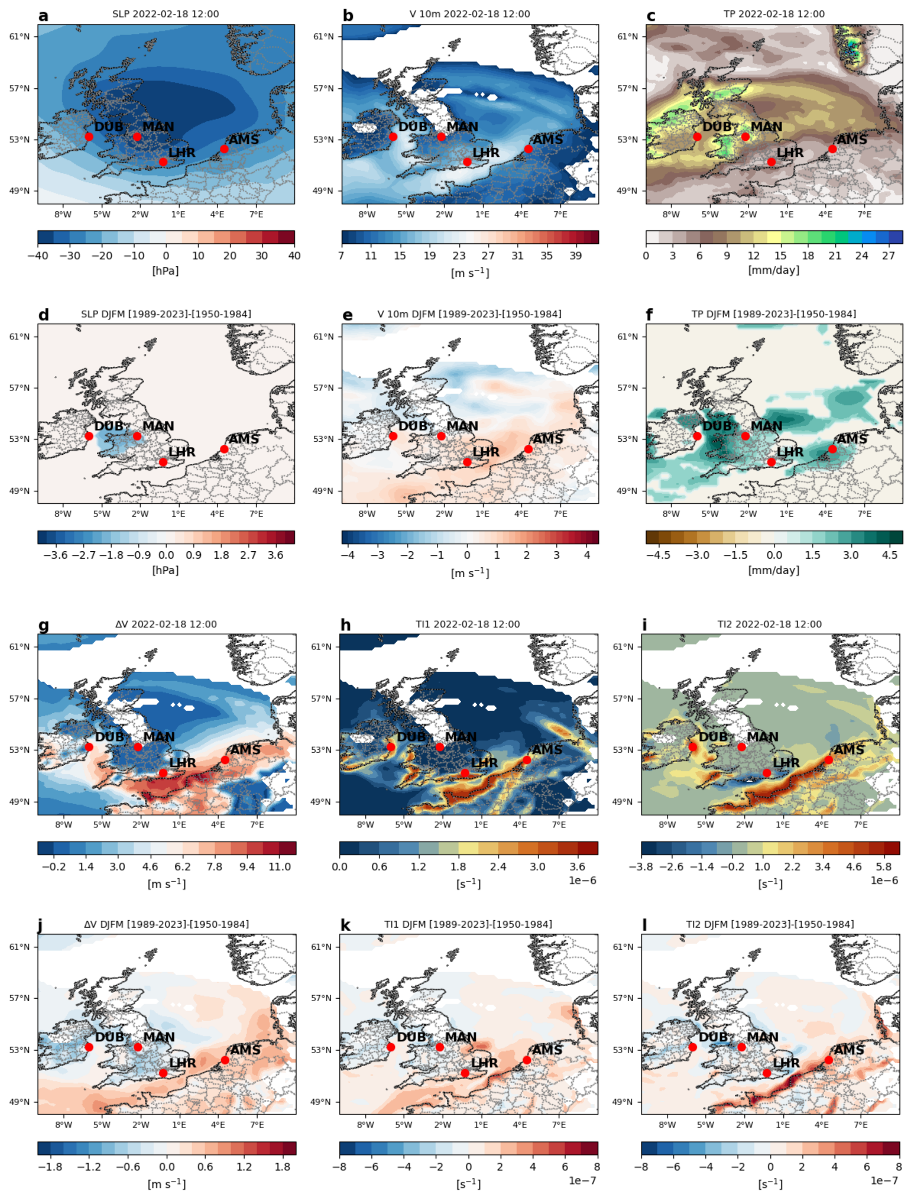

Figure 2: Analogue-based results for the Storm Eunice on 2022-02-18 12:00 (after the cyclone time). SLP **a** anomaly, V 10m **b** and TP **c**. Difference between factual [1989-2023] and counterfactual [1950-1984] period of the average SLP anomalies **d**, V 10m **e** and TP **f**. Bulk wind difference **g**, TI1 **h**, TI2 **i** and difference between factual [1989-2023] and counterfactual [1950-1984] period of the same variables ΔV **j**, TI1 **k** and TI2 **l**. In the second and fourth rows, shadings indicate significant changes. Red dots indicate major airports in the region: Dublin Airport (DUB), Manchester Airport (MAN), Heathrow Airport (LHR) and Amsterdam Airport (AMS).

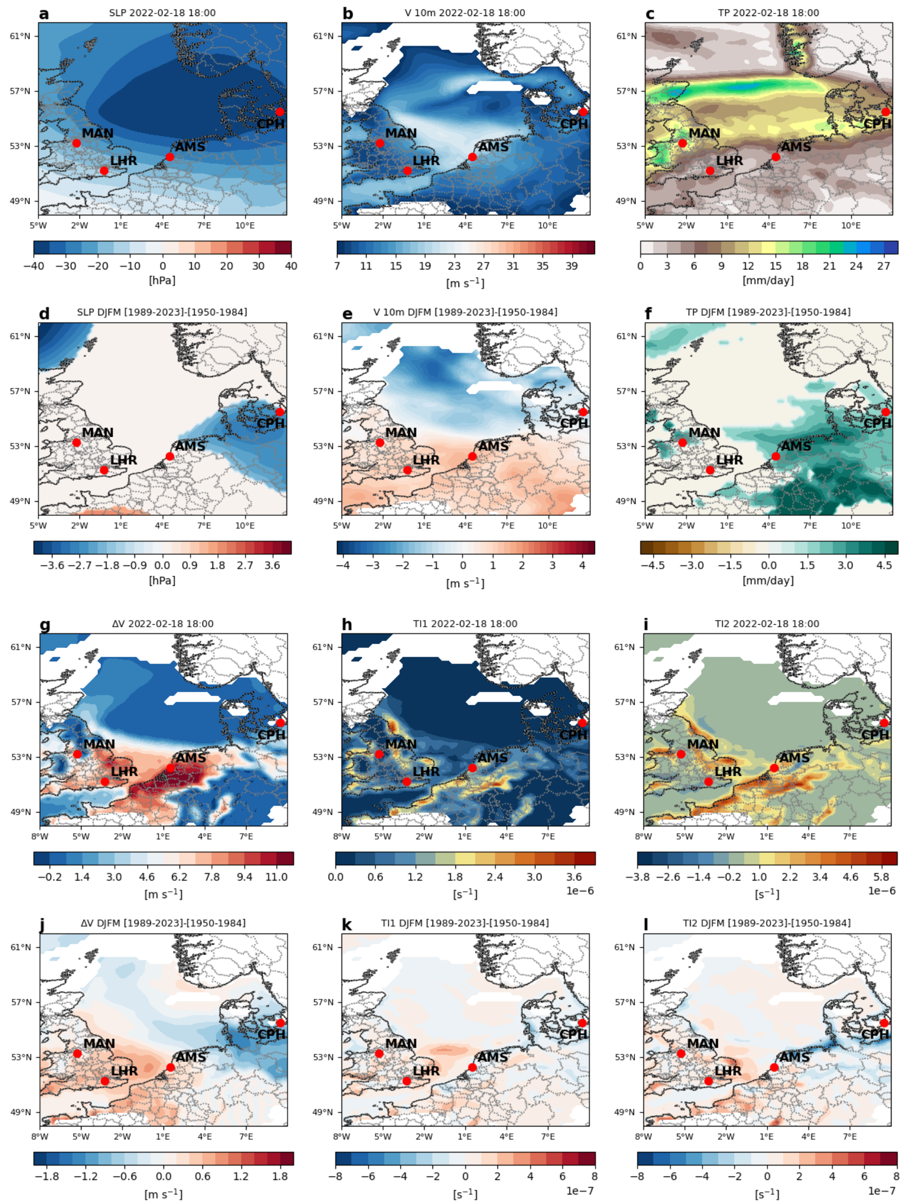

Figure 3: Analogue-based results for the Storm Eunice on 2022-02-18 18:00 (after the cyclone time). SLP **a** anomaly, V 10m **b** and TP **c**. Difference between factual [1989-2023] and counterfactual [1950-1984] period of the average SLP anomalies **d**, V 10m **e** and TP **f**. Bulk wind difference **g**, TI1 **h**, TI2 **i** and difference between factual [1989-2023] and counterfactual [1950-1984] period of the same variables ΔV **j**, TI1 **k** and TI2 **l**. In the second and fourth rows, shadings indicate significant changes. Red dots indicate major airports in the region: Manchester Airport (MAN), Heathrow Airport (LHR), Amsterdam Airport (AMS) and Copenhagen Airport (CPH).

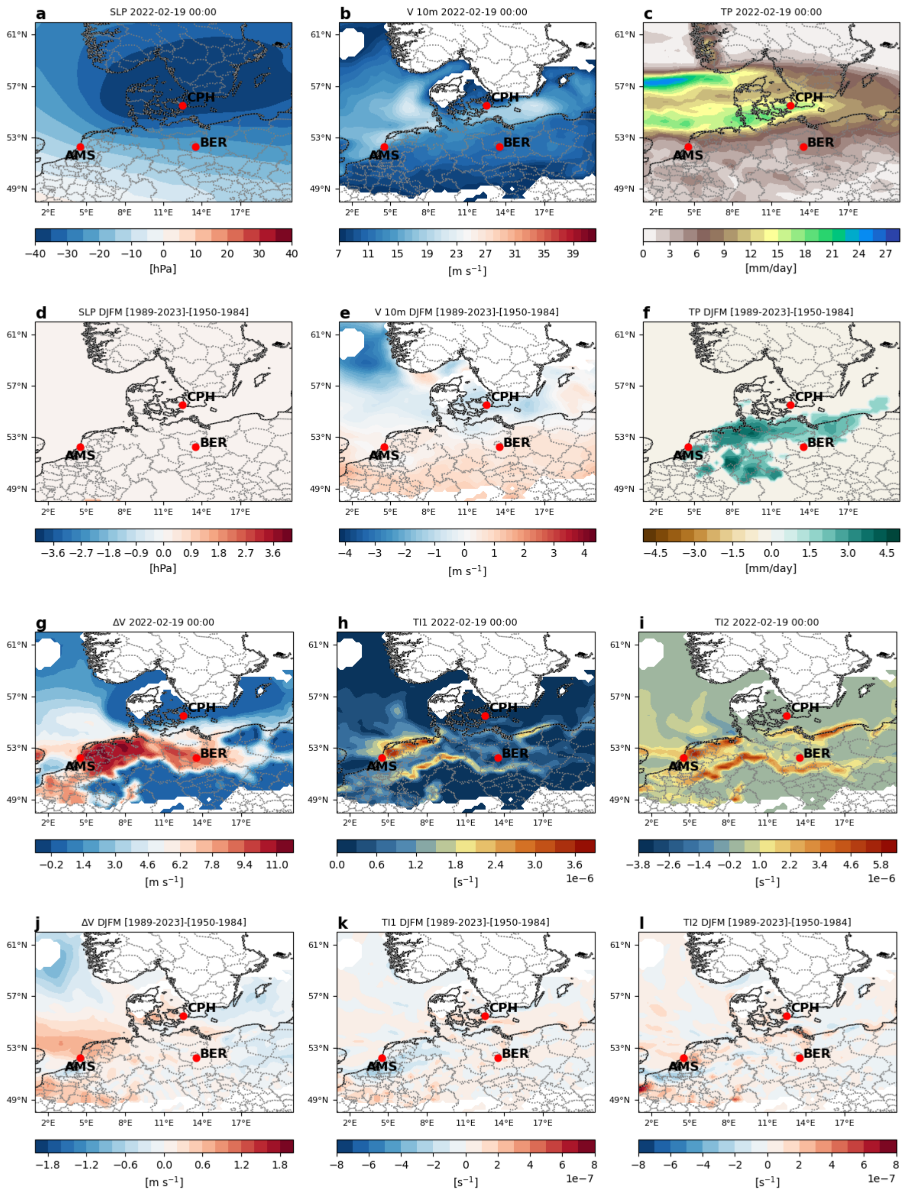

Figure 4: Analogue-based results for the Storm Eunice on 2022-02-19 00:00 (after the cyclone time). SLP **a** anomaly, V 10m **b** and TP **c**. Difference between factual [1989-2023] and counterfactual [1950-1984] period of the average SLP anomalies **d**, V 10m **e** and TP **f**. Bulk wind difference **g**, TI1 **h**, TI2 **i** and difference between factual [1989-2023] and counterfactual [1950-1984] period of the same variables ΔV **j**, TI1 **k** and TI2 **l**. In the second and fourth rows, shadings indicate significant changes. Red dots indicate major airports in the region: Amsterdam Airport (AMS), Copenhagen Airport (CPH) and Berlin Brandenburg Airport (BER).

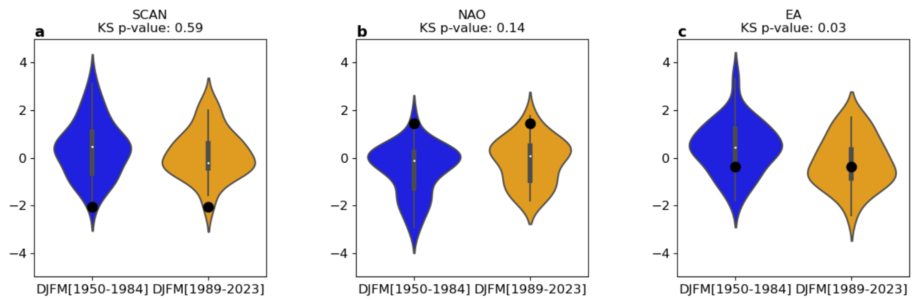

Figure 5: Violin plots showing the distribution of daily index values for SCAN **a**, NAO **b**, and EA **c** during the past (blue) and present (yellow) periods. Values for the peak day of the extreme event are marked by a black dot.

Comment #2

This comment relates to the modes of variability considered.
When accounting for low frequency variability you consider ENSO, the AMO and PDO indices. I was surprised you did not include the NAO as this is well known to greatly impact both the frequency and intensity of extratropical cyclones (granted for the North Atlantic/Europe primarily). Have you tested whether including the NAO in your assessment of natural variability changes your results? Some discussion relating to this is needed regardless.

We particularly thank the Reviewer for raising this point. In the revised version we will assess the low-frequency climate variability also including additional tele-connection indices as the suggested NAO, but also the East Atlantic (EA) and the Scandinavian (SCAN) pattern which are known to influence Euro-Mediterranean weather extremes. By performing statistical tests we note that for the case of Eunice (see Figure 5) only the EA pattern is significant, thus suggesting a very minor role of natural low-frequency variability in this event (one mode over six).

Minor comments

We will implement all corrections related to each minor/technical comment.