



Intensification of a European Storm Cluster in a Warmer Climate: Evidence from Regional Storylines

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Abstract. In February 2022 a series of three extreme winter storms hit the coast of Northern Germany and Northwestern Europe. In this study, cyclones Ylenia, Zeynep and Antonia were attributed to anthropogenic climate change, assessed through event-based storylines across five climate states: pre-industrial, present-time, +2K, +3K and +4K. The storylines vary only in sea surface temperatures and greenhouse gas concentrations, isolating the thermodynamic components of anthropogenic climate change. Global storylines were dynamically downscaled for Europe, focusing on Northwestern Germany and the German Bight. Spectral nudging was used to keep the large-scale weather patterns close to observations. Spectral nudging was turned off in a second step, which allows an assessment of dynamical effects beyond the thermodynamic ones. Anthropogenic warming amplified both wind speeds and precipitation during the February 2022 extra-tropical cyclone cluster, strengthening gradually from present-time to +4K warming and remaining robust across dynamical configurations, indicating systematically intensifying impacts on the analysed domain under continued warming. Changes in precipitation are more evident in northern regions of the analysed domain, with a notable precipitation increase in the Norwegian west coast. The changes in wind speed and precipitation are shown to possibly be related to changes in the storm tracks position, indicating a strong relationship with the large-scale circulation, even though only slightly changes were observed in jet stream position. Without spectral nudging, future storylines exhibit greater ensemble spread and a northward-tilted storm track. Overall, the study found a gradual increase in areas with robust positive changes of wind speed and precipitation during the storm cluster in warmer climate states, with dynamical changes further amplifying the magnitude of already notable thermodynamic response, but evidencing the role of internal variability between storyline members in decreasing the spatial robustness.

1 Introduction

Extratropical storms are major drivers of high-impact weather in the mid-latitudes, producing both natural hazards and socio-economic impacts such as flooding (Wallace and Hobbs, 2006; Hawcroft et al., 2018). Although their activity over the North Atlantic shows strong interannual and multidecadal variability without clear trends (Feser et al., 2015, 2021; Krueger et al., 2019; Krieger et al., 2021), their future behaviour under anthropogenic warming remains a critical area of research (Ginesta et al., 2024). While projections of storm frequencies are inconsistent, many studies converge on stronger future wind speeds (Feser et al., 2015; Krieger and Weisse, 2026). Exact locations of such increases are strongly influenced by changes in the large-scale atmospheric circulation (Seneviratne et al., 2021). In particular, regions like Central and Western Europe may face



rising wind-related hazards in the future (Donat et al., 2010; Mölter et al., 2016). The response of extreme precipitation is harder to constrain because it depends not only on thermodynamic intensification but also on complex regional processes such as convection, cloud microphysics, turbulence, and soil-moisture feedbacks (Kendon et al., 2021; Tradowsky et al., 2023). Even so, anthropogenic emissions have already increased the likelihood of extreme rainfall in many regions (Philip et al., 2018; Otto et al., 2018). The passage of extra-tropical cyclones is responsible for much of the day-to-day variability of weather in the mid-latitudes, and during winter months the cyclone associated precipitation exceeds 80 % in the Northern Hemisphere (Hawcroft et al., 2012). At low-lying coasts and in combination, strong wind (often accompanied by storm surge conditions that block seaward drainage) and heavy precipitation can overwhelm coastal drainage systems, pushing them into critical states (Bormann et al., 2024; van den Hurk et al., 2015). Because of that, changes in both wind and rainfall are critical to assess. Regional climate models (RCMs) help to resolve these impacts by providing finer spatial detail than global models (Giorgi and Mearns, 1991). Applying spectral nudging further improves the simulation of RCM hindcasts by constraining their large-scale circulation towards that of the driving global model or forcing reanalysis (von Storch et al., 2000; Schubert-Frisius et al., 2017). Attributing individual extreme weather events to anthropogenic climate change remains a scientific challenge due to the inherent complexity of internal variability and the limited signal-to-noise ratio in localized extremes (Trenberth et al., 2015). Combining spectral nudging with event-based storylines allows to generate targeted simulations of specific storms still vivid in the collective memory (Feser and Shepherd, 2025) under different climate states and supports attribution of their thermodynamic and dynamical changes to anthropogenic climate change (van Garderen et al., 2021; Athanase et al., 2024; Feser et al., 2024; Feser and Shepherd, 2025). The spectrally nudged storyline approach has emerged as a robust complement to probabilistic methods by conditioning the analysis on the specific dynamical situation of the observed event and assessing how it is modified by thermodynamic aspects of climate change (Shepherd, 2016; van Garderen et al., 2021). This conditional framing enables a physically grounded attribution of anthropogenic climate change impacts on individual events, while maintaining consistency with the large-scale atmospheric flow. To our knowledge, no studies downscaling global storylines have been conducted attributing changes in wind speed and associated precipitation for a serial cluster of extratropical cyclones. The specific storm cluster of February 2022 was characterized by extremes in both wind speed and precipitation, which brought severe socio-economic impacts to Northwestern Europe. To better disentangle the thermodynamical changes to large-scale dynamics, we will make use of regional simulations with spectral nudging (large-scale constraint), without spectral nudging (no constraining) and a hybrid setup, starting with spectral nudging and then turning off spectral nudging during the passage of the storm cluster. To fulfil the objectives, we analyse mean sea level pressure (SLP), u and v wind components at 10 m (using derived wind speed and direction), total precipitation, and complementary, temperature and relative humidity at pressure levels. The February 2022 storm cluster comprising the storms Ylenia, Zeynep, and Antonia (Dudley, Eunice, and Franklin; international names) provides a compelling case study for this approach. Driven by an unusually strong jet stream and a robust polar vortex, the cluster produced destructive winds, extreme gusts associated with a sting jet in Zeynep (Williams et al., 2025), and heavy precipitation that caused widespread flooding and substantial socio-economic losses (Mühr et al., 2022; PERILS AG, 2023). Its rapid succession of intense storms illustrated how clustered events can amplify regional impacts (e.g., Bormann et al., 2024). Ylenia initiated the sequence with gusts of 120–160 km h⁻¹ and frontal rainfall that triggered flood alerts. Zeynep, the strongest



storm of the cluster, produced extreme surface gusts including a UK record of 196 km h^{-1} (Mühr et al., 2022; Volonté et al., 2024). Antonia closed the sequence with persistent westerly to north-westerly winds and localized 24-hour precipitation exceeding 30 mm on 19/20 February 2022 in the UK and in Germany up to 37.9 mm on February 20, 2022 (more than 100 mm accumulated over a period of 6 days) (Mühr et al., 2022).

65 This study uses event-based storylines with modified sea-surface temperatures and greenhouse-gas concentrations to represent different climate states and to attribute and quantify the anthropogenic contribution for this storm cluster. We will address the following research questions:

- How well do regional storylines with and without spectral nudging reproduce the February 2022 storm cluster over Europe and Northern Germany? Is there an added value in comparison to global storylines driving the regional simulations?
- 70 • Which role do thermodynamic and large-scale dynamical changes play in shaping the intensity and characteristics of the storm cluster?
- How are storm properties, especially wind speed and precipitation, projected to evolve under future climate storylines?

2 Data and Methods

75 2.1 Spectral Nudging

To preserve the dynamical consistency of the storyline simulations while allowing regional-scale thermodynamic responses to unfold, spectral nudging is applied for both global and regional storylines. Spectral nudging constrains large-scale atmospheric fields using a scale-selective nudging technique in spectral space (Waldron et al., 1996; von Storch et al., 2000). This ensures that the large-scale weather patterns, such as high- and low-pressure systems, remain consistent with observations, while 80 allowing finer-scale features to respond to local atmospheric processes (von Storch et al., 2000). As the nudging is confined to higher altitudes, the atmospheric state at lower levels is free to adjust to surface geographical properties (von Storch et al., 2000). The global storylines are constrained at large spatial scales by spectrally nudging only vorticity and divergence fields above 750 hPa towards the NCEP–NCAR reanalysis 1 (Kalnay et al., 1996; Kistler et al., 2001) using a plateau-shaped height profile (van Garderen et al., 2021; van Garderen and Mindlin, 2022; Feser et al., 2024). The regional storylines are nudged 85 towards the global storylines only for zonal and meridional horizontal wind components above 850 hPa with an exponential increase with height. Spectral nudging is applied every third time step and for all wavenumbers up to 20 in the zonal direction and 22 in the meridional direction.

2.2 Event-based Storylines Framework

We used a conditioned storyline approach to examine how the February 2022 storm cluster responds to different climate 90 states. We used one present-time storyline (P) and four with modified sea surface temperatures and greenhouse gas levels: pre-industrial (PI), plus 2K (+2K), plus 3K (+3K) and plus 4K (+4K). By keeping the large-scale dynamics constrained through



spectral nudging, the approach isolates the thermodynamic fingerprint of anthropogenic climate change and creates physically plausible pre-industrial and warmer worlds with improved signal-to-noise for high-impact events. To better disentangle thermodynamical changes from large-scale dynamical changes, we used three configurations: simulations with spectral nudging (strong large-scale constraint), simulations without spectral nudging (no large-scale constraint), and a hybrid setup in which spectral nudging is switched off shortly before the storm cluster reaches Europe.

2.3 Downscaling global storylines with a regional model

Global spectrally nudged storyline simulations based on the ECHAM6 (ECHAM; Giorgetta et al., 2013; Stevens et al., 2013) atmospheric model (as described in van Garderen et al. (2021); van Garderen and Mindlin (2022); Feser et al. (2024)) and forced with modified sea surface temperature and greenhouse gases (GHG) representing different climate states were used to force regional COSMO-CLM (CCLM, www.clm-community.eu; Rockel et al., 2008; Steppeler et al., 2003) simulations. The global storylines have a spectral resolution of T255 (≈ 60 km). The regional downscaling with CCLM was performed on a EURO-CORDEX domain (Jacob et al., 2014; Fig. 1) at 0.11° horizontal resolution (≈ 12 km) with hourly temporal resolution. For each storyline, five ensemble members were produced for 1 January - 1 March 2022 using three setups: spectrally nudged (SN), non-spectrally nudged (NSN) and a hybrid configuration (SN_NSN). In the hybrid runs, spectral nudging is applied initially but switched off on 15 February before the storm cluster reaches Northern Europe. SN simulations isolate thermodynamical changes, NSN simulations include both dynamical and thermodynamical changes, and the hybrid configuration tests the sensitivity of storm evolution to early-stage dynamical constraints while allowing later-stage freedom (Table 1).

Table 1. Definition of storylines and details on constraining and diagnostics.

Climate storyline	SST & GHG forcing	Model setup	Large-scale constraint	What it diagnoses
PI (Pre-industrial)	pre-industrial SST & GHG	SN	Strong (spectral nudging)	Thermodynamic changes only
		NSN	None	Combined thermodynamic + dynamical changes
		SN_NSN	Partial (off from 15 Feb)	Sensitivity to early dynamical conditioning
P (Present-time)	Observed SST & GHG	SN	Strong	Baseline reproduction of 2022 cluster
		NSN	None	Baseline with free dynamics
		SN_NSN	Partial	Transitional sensitivity test
+2K	+2K SST & elevated GHG	SN	Strong	Thermodynamic future response
		NSN	None	Full future dynamical + thermodynamic response
		SN_NSN	Partial	Sensitivity to dynamical freedom
+3K	+3K SST & elevated GHG	Same three setups	Same	Same diagnostic purposes
+4K	+4K SST & elevated GHG	Same three setups	Same	Same diagnostic purposes

2.3.1 Model domain and study area

The model domain, the study area and the German Bight and German coastal regions are shown in Figure 1. Our focus on this region is motivated by the WAKOS project (Water on the Coasts of East Frisia; <https://hereon.de/wakos>) and the substantial impacts regularly observed from North Atlantic extratropical storms, including widespread wind damage, coastal storm surges,

and compound flooding. As already pointed, the February 2022 storm cluster caused severe infrastructural and economic losses across northern Germany (Mühr et al., 2022; PERILS AG, 2023). One of WAKOS project aims is to disseminate how the extreme events severity may change as a result of climate change, and what precautionary measures can be taken to facilitate adaptation.

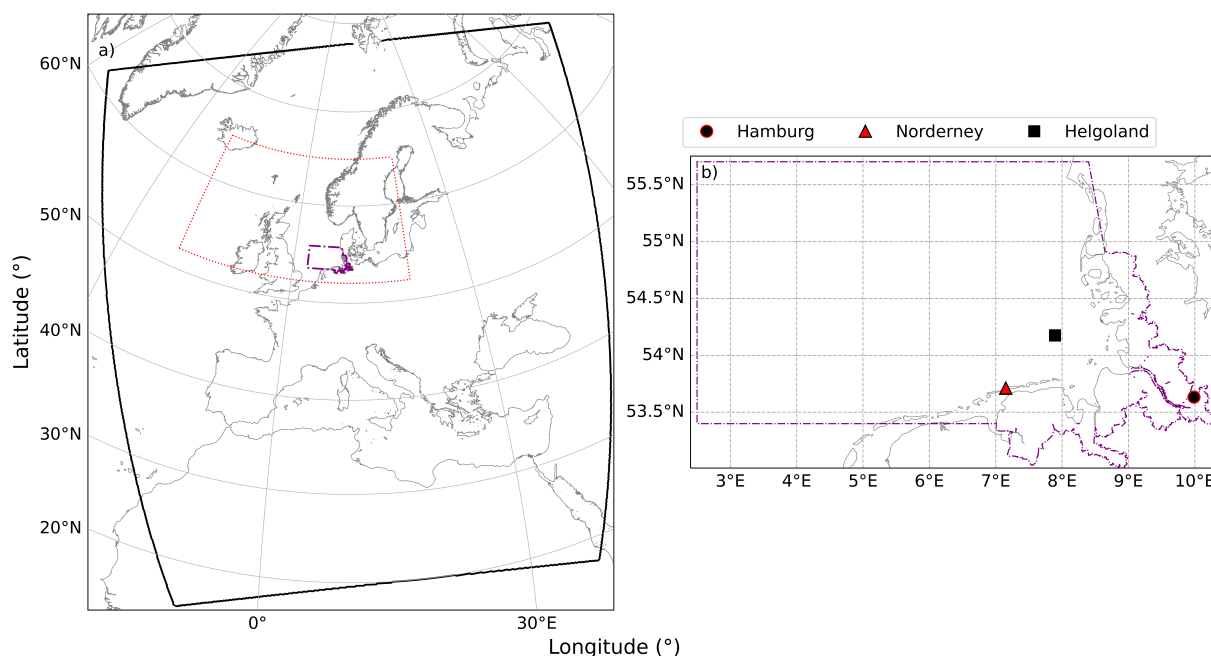


Figure 1. a) Model domain and b) study area, with in-situ data locations. The dash-dotted polygon delimits the German Bight and German coast and the dotted polygon is the domain used for storm tracking and spatial analysis.

2.4 Data Analysis

To evaluate the capacity model's ability to represent storms at a regional scale, we chose three stations in the German Bight and Northwestern Germany (Hamburg Fuhlsbüttel, Norderney and Helgoland; Fig. 1) to compare observations of wind speed, wind direction and precipitation (DWD Climate Data Center (CDC), 2024c, b, a) with present-time storyline simulations. We selected the closest gridpoint from the in situ locations and extracted the time series during the storm cluster period (Table 2). We use descriptive statistics such as correlation (r), mean bias and root mean squared error (RMSE), together with Taylor diagrams (Taylor, 2001) to compare spectrally, non-spectrally nudged and hybrid simulations against the in situ observations (zonal and meridional wind components and precipitation). The storm tracks were computed by following the minimum mean sea level pressure associated to the storms in the hourly SLP fields, using the storms' periods as temporal reference (Table 2) (e.g., Geng and Sugi, 2001; Hanley and Caballero, 2012). We used ERA5 (Hersbach et al., 2020) SLP fields to track the storms and compared those with available tracks computed using ERA5 and a different algorithm (Copernicus



Climate Change Service (C3S), 2025) to ensure the capacity of our simple method (Fig. A1). The jet stream core is defined by the latitude at the maximum zonal wind in the averaged 200 and 300 hPa fields for every time step and subsequently averaged over time. Anthropogenic climate change is defined in this study as the difference between warmer and PI storylines. Spatial differences between storylines were computed from ensemble-mean fields, using time-averaged mean wind speeds, averaged daily maximum wind speeds (maximum wind speeds) and accumulated precipitation over the storm-cluster period (here defined from 16 February 00:00 to 21 February 23:00). Robust signals were defined by a signal-to-noise ratio ($SNR = \frac{|\Delta \bar{x}|}{\sigma \Delta x}$) greater than one and agreement in at least 80 % of ensemble members. Percentage differences were calculated relative to the PI storyline. For the German Bight and coastal region, domain-averaged wind speeds and cumulative precipitation were computed from all grid points within the study area. Histograms of wind direction and wind speed for the three storms (Table 2) were also computed for the German Bight/coast.

Table 2. Individual periods of each storm.

Storm	Period
Ylenia	2022-02-16 04:00 - 2022-02-18 03:00
Zeynep	2022-02-18 14:00 - 2022-02-19 16:00
Antonia	2022-02-20 06:00 - 2022-02-21 12:00

3 Results

3.1 Evaluation of CCLM with in situ data

We first assess the P storyline's biases for wind speed (m s^{-1}), wind direction ($^{\circ}$), and total precipitation (mm) using in situ observations from the three selected stations in the German Bight and German coast (Fig. 1). We focus on these variables because our interest lies in storm impacts rather than storm formation. To assess the role of spectral nudging, we also analysed non-nudged and hybrid simulations, which show how storms evolve once the large-scale constraint are removed (SN_NSN). A comparison with in-situ observations shows the importance of the setup across the three CCLM storylines (SN, NSN, SN_NSN) (Fig. A2–A4). Wind speed is generally well reproduced, though the NSN and SN_NSN simulations underestimate the peak associated with storm Zeynep and show a slight delay in peak timing (Fig. 2). Statistical similarities decrease from SN to NSN and SN_NSN (Fig. 2). Wind direction is captured with greater skill compared to wind speed, with all configurations representing the dominant flow, although directional offsets occur during rapid shifts and during Zeynep (Fig. 3). Precipitation exhibits the largest biases, though differences between setups are small. All simulations reproduce the timing of the major precipitation event during Antonia, but intensities are overestimated (Fig. 4). This is consistent with the mismatch between grid-cell averages and point measurements (Prein et al., 2015). The discrepancies are expected given that RCMs represent grid cell averages, whereas in situ measurements reflect point observations (Pryor et al., 2012). Overall, the simulations capture the main storm related variability in wind speed and direction. For Zeynep, the SN setup shows an underestimated but detectable



wind speed peak, while NSN and SN_NSN show a weaker signal, with SN_NSN exhibiting only a slight increase compared to
155 the other storms. Zeynep can be reliably tracked only in the SN setup. The Taylor diagram (Fig. A5) further highlights the setup
differences: the SN setup lies closest to the observations, reflecting its tighter constraint to the large-scale reanalysis through
spectral nudging. This is expected, as nudging keeps the simulated large-scale circulation aligned with the driving data. In
contrast, NSN and SN_NSN deviate more strongly due to their lack of or reduced large-scale dynamical constraint. Compared
to observations, CCLM and the global ECHAM show comparable performance for wind, while it exhibits a lower precipitation
160 bias. The stations are located in marine, coastal, or urban environments, where increased resolution can amplify the sensitivity
to surface roughness and local physics (Kalnay, 2003). Diaconescu and Laprise (2013) showed that RCMs can, in some cases,
improve the large-scale features of the forcing fields, but the added value of dynamical downscaling is often associated with
the improved representation of small-scale processes and regional extremes, especially those related to precipitation. RCMs
are often better suited for impact studies because they provide finer spatial detail and more realistic temporal variability than
165 their driving global climate models, even if they do not deliver consistent added value across all conditions (Di Luca et al.,
2015). Since each model carries its own systematic biases, the degree of added value depends strongly on the specific variable
being evaluated (Giorgi and Mearns, 1991).

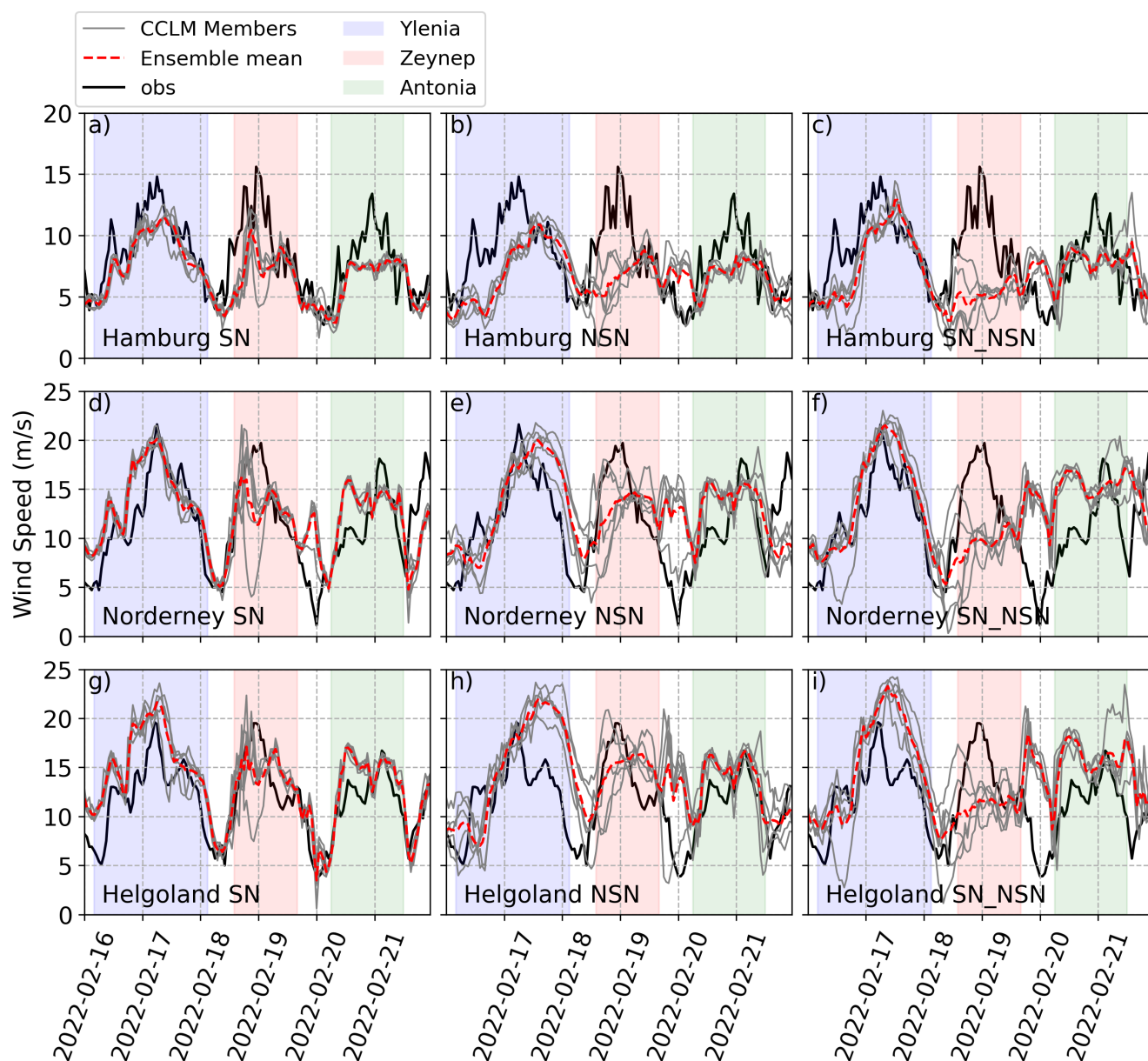


Figure 2. Wind speed (m s^{-1}) evaluation of CCLM SN, NSN and SN_NSN present-time against observed wind speed (obs). From top to bottom: Hamburg, Norderney and Helgoland. The shaded areas represent the three storms. SN=spectrally nudged; NSN=non-spectrally nudged; SN_NSN=hybrid.

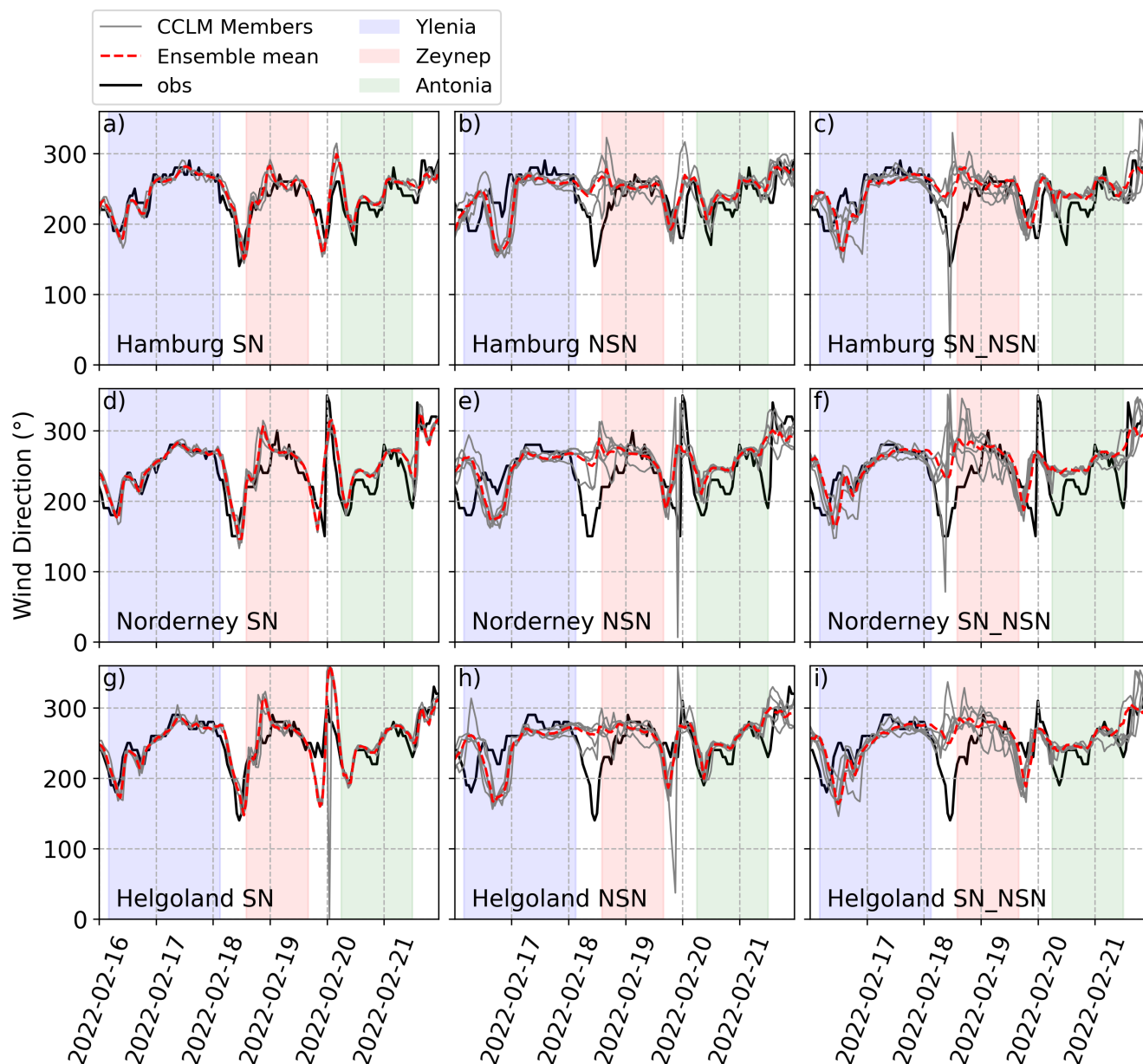


Figure 3. Wind direction (°) evaluation of CCLM SN, NSN and SN_NSN present-time against observed wind direction (obs). From top to bottom: Hamburg, Norderney and Helgoland. The shaded areas represent the three storms. SN=spectrally nudged; NSN=non-spectrally nudged; SN_NSN=hybrid.

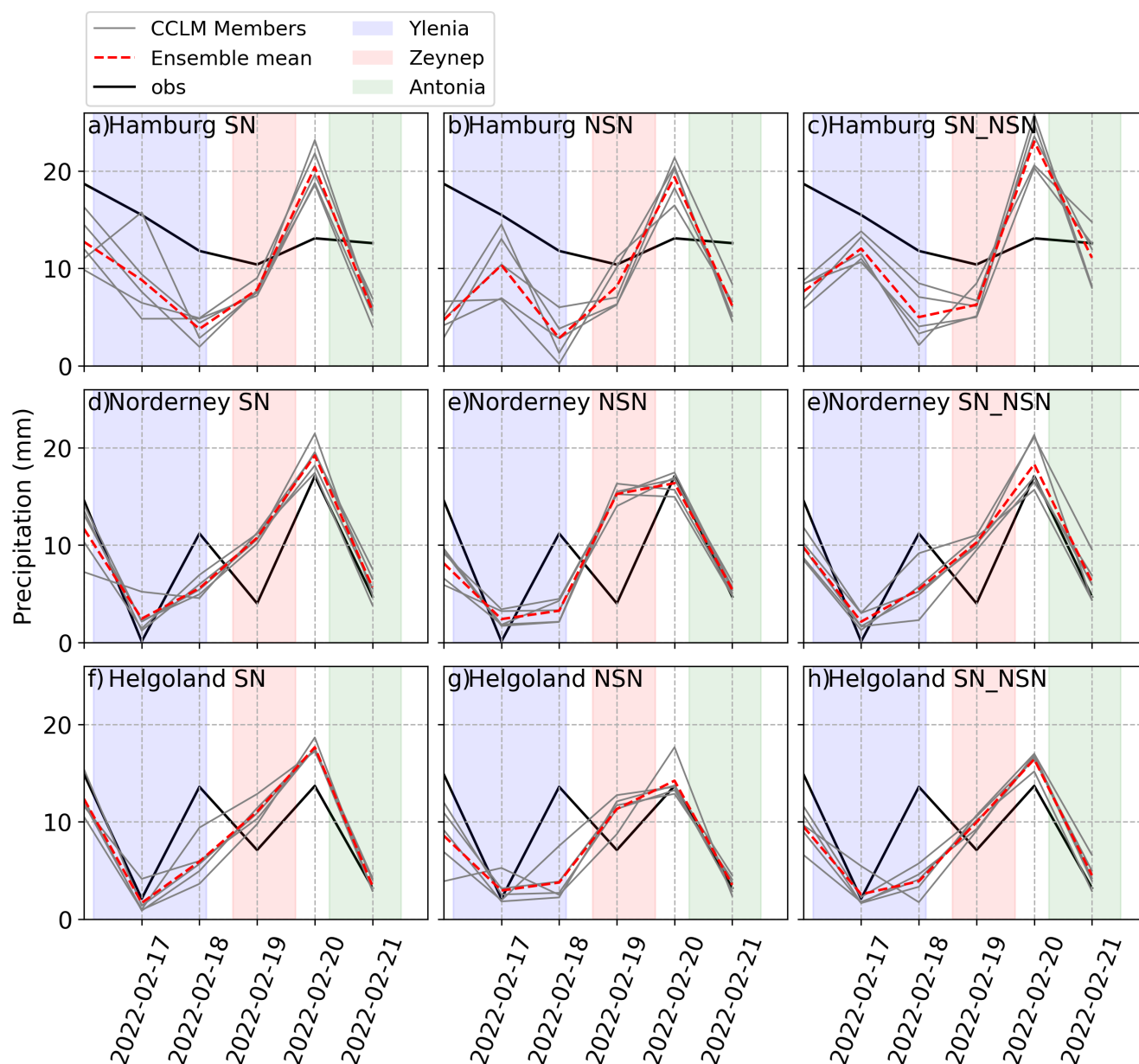


Figure 4. Accumulated precipitation (mm/day) of CCLM present-time simulations against observed precipitation (obs). From top to bottom: Hamburg, Norderney and Helgoland. The shaded areas represent the three storms. SN=spectrally nudged; NSN=non-spectrally nudged; SN_NSN=hybrid.



3.2 Storylines and anthropogenic climate change

3.2.1 Large-scale circulation differences across storylines

170 We now turn to the changes in present-time, +2K, +3K, and +4K storylines relative to the pre-industrial reference storyline to assess how thermodynamic and dynamic changes modify the same sequence of storms. These storylines allow us to place the observed event within a broader climate context and quantify how its characteristics may shift under different warming levels. Storm track changes (Fig. 5) show no uniform pattern across storms. Notable differences include: (i) a northward tilt of Ylenia's future tracks in NSN (Fig. 5c), also visible to a lesser extent in SN_NSN (Fig. 5e); (ii) equatorward shifts of Antonia's +3K
175 and +4K tracks in SN (Fig. 5b); and (iii) a pronounced equatorward shift of Antonia's PI track in SN_NSN (Fig. 5f). Zeynep was trackable only in SN, with a weak signal, likely due to its small scale, explosive convective nature linked to enhanced baroclinicity following Ylenia (Weijenborg and Spengler, 2020; Ermis et al., 2024). Non-constrained simulations also show slower storm propagation, with storms taking longer to cross the domain. Jet stream differences (Fig. A6) show a poleward shift in future storylines, most pronounced in the non constrained simulations. The increased jet stream waviness over Europe
180 may contribute to the track tilts observed in NSN and SN_NSN in future storylines, as storm tracks and the jet stream are closely connected (Athanasiadis et al., 2010) and the eddy-driven jet stream acts as a guide for extra-tropical cyclones (Köhler et al., 2025).

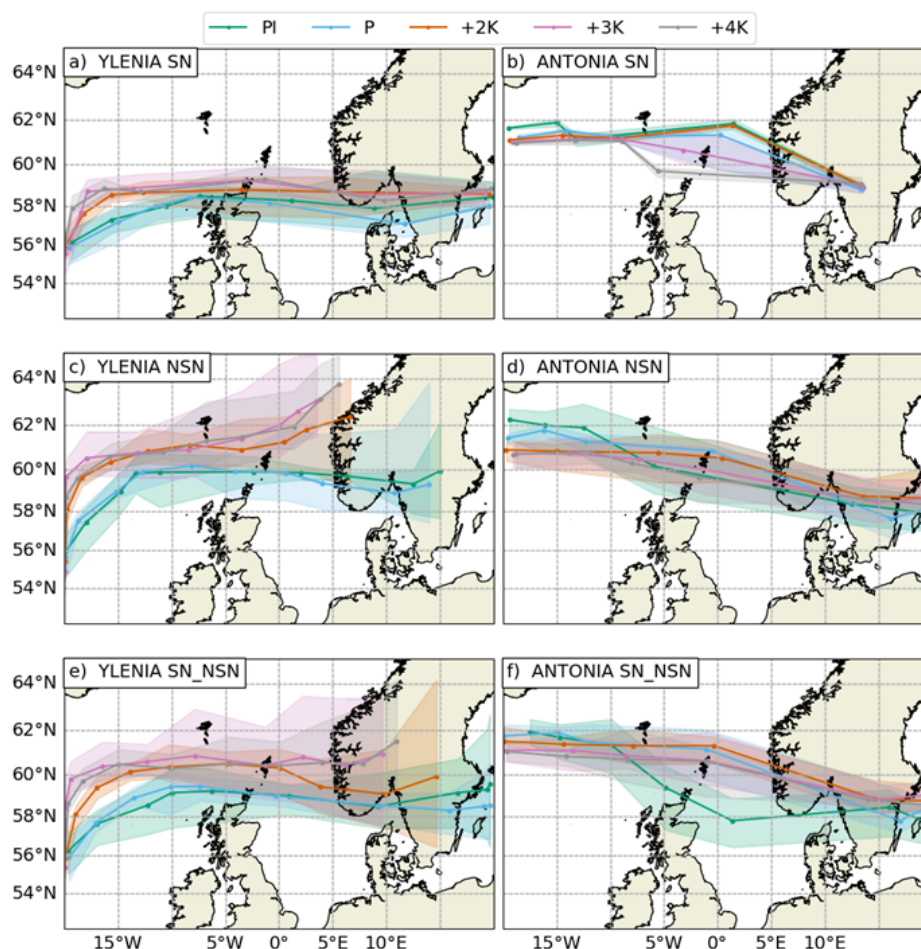


Figure 5. Storms tracks of Ylenia (left) and Antonia (right). Solid lines represent the ensemble average of each storyline and dots show the centre of the storms every 6 hours. Shadings are the minimum and maximum latitude values between individual ensemble members storm tracks. From top to bottom: SN, NSN, and SN_NSN simulations.

3.2.2 Changes in Winds and Precipitation

We now examine spatial changes in wind speed and precipitation associated with the storms by comparing P and future storylines (+2K, +3K, +4K) with the PI storyline, considering average changes over areas with robust increase. Both mean and maximum wind speeds increase across all simulations, as illustrated by the differences in the +4K case (Figs. 6,7). The robust increases are larger in the non-constrained simulations (NSN and SN_NSN) than in SN, although they occur over a smaller spatial extent. Robust increases in mean wind speed range from about 4 to 15 % and are concentrated over the central domain, including the North Sea in the SN configuration, while being less pronounced over land, except in the northern part of England.

Maximum wind speeds show a robust increase of at least 6 %. For accumulated precipitation over the storm period (Fig. 8), robust positive changes occur mainly in the central to northern domain, with the largest increases along the Norwegian coast.

More than 20 % of the increase in precipitation can be attributed to anthropogenic climate change, in the sense defined in this study (see Section 2.4). The areas exhibiting robust positive changes for all variables expand progressively with warming. For results across all storylines and tables summarizing the spatial patterns, see the Supplementary material (Fig. A7-A9, Tables A1-A3).

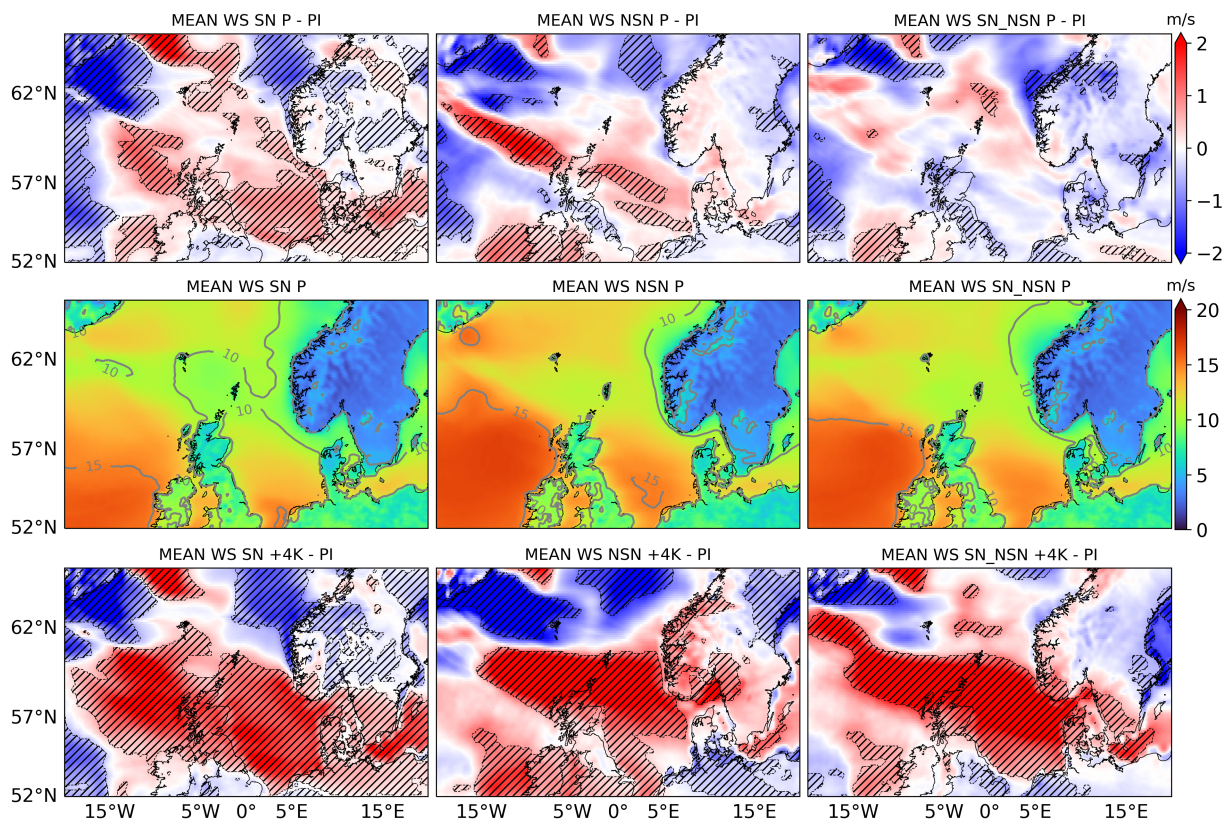


Figure 6. Changes in ensemble mean 10m wind speed for the storm cluster for present-time and +4K minus pre-industrial storylines. Hatching indicates regions where at least 80 % of ensemble members agree on the sign of the change and the signal to noise ratio is larger than 1. The second row represents the present-time storyline ensemble mean 10m wind speeds averaged over the storm cluster period (shading and contours).

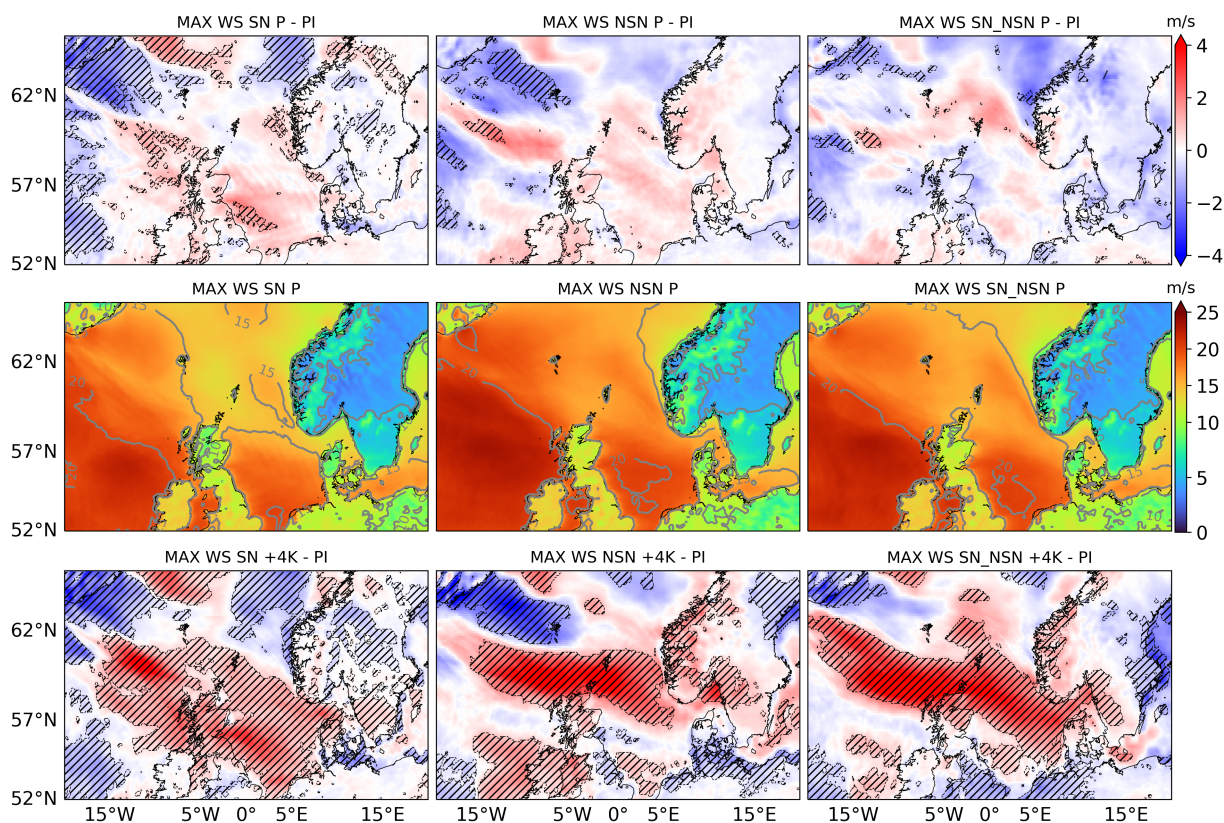


Figure 7. Changes in ensemble mean maximum 10m wind speed for the storm cluster for present-time and +4K minus pre-industrial storylines. Hatching indicates regions where at least 80 % of the ensemble members agree on the sign of the change and the signal to noise ratio is larger than 1. The second row represents the present-time storyline ensemble mean of maximum 10m wind speeds averaged over the storm cluster period (shading and contours).

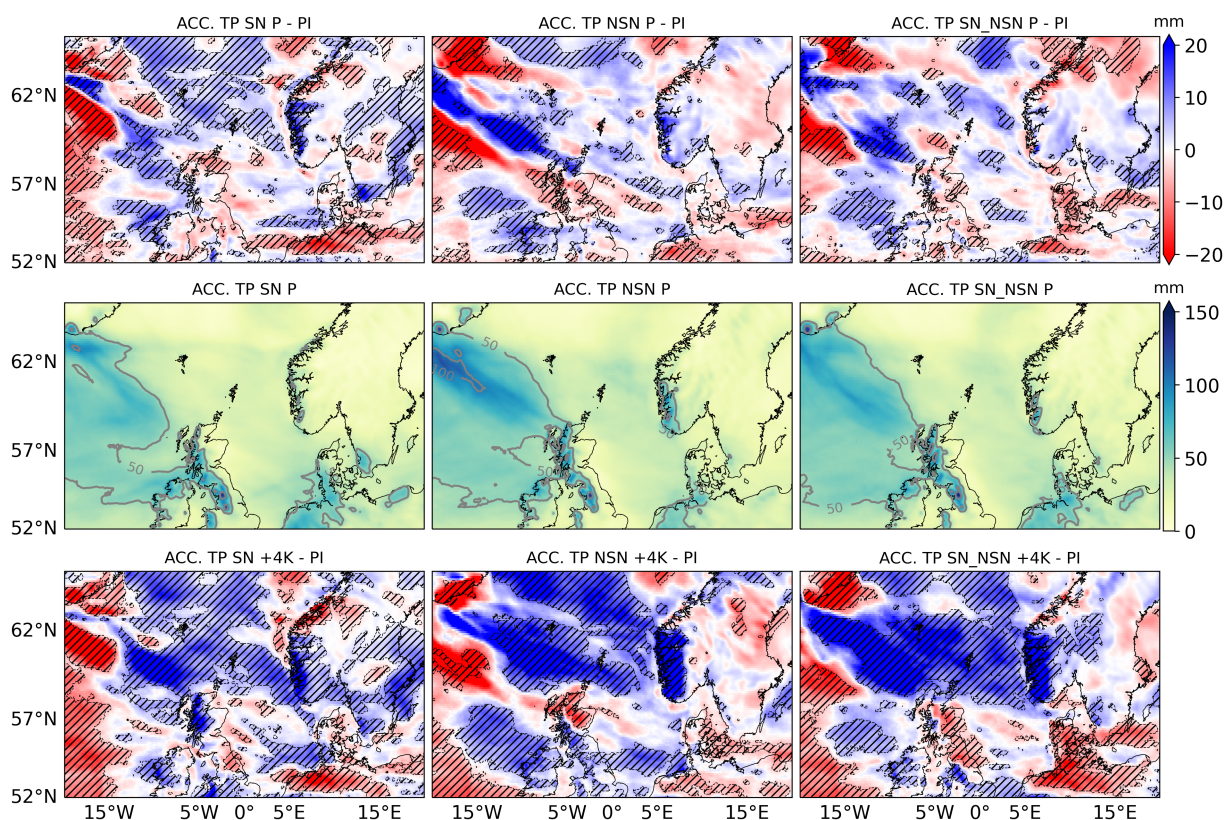


Figure 8. Changes in accumulated precipitation over the storm cluster period for present-time and +4K minus pre-industrial storylines. Hatching indicates regions where at least 80 % of the ensemble members agree on the sign of the change and the signal to noise ratio is larger than 1. Shading shows wetter areas as blue and drier areas as red. The second row represents the present-time storylines ensemble mean of total precipitation accumulated over the storm cluster period (shading and contours).

Over the German Bight and the German coast (Fig. 1), cumulative precipitation differs among setups, with greater variability in the non-constrained storylines and higher totals in the SN (Fig. 9). The SN setup, reflecting mainly thermodynamic changes, shows a clear increase in mean wind speeds, with maximum wind speeds decreasing during Antonia. When dynamical changes are included, NSN and SN_NSN show mixed responses across storylines: mean wind speeds increase during Zeynep but decrease or show similar levels during Ylenia and Antonia. These decreases correspond to the northward tilted storm tracks, reducing their influence over the German Bight/coast. When wind speeds do increase, dynamical changes amplify the thermodynamic signal, strengthening the anthropogenic climate change contribution.

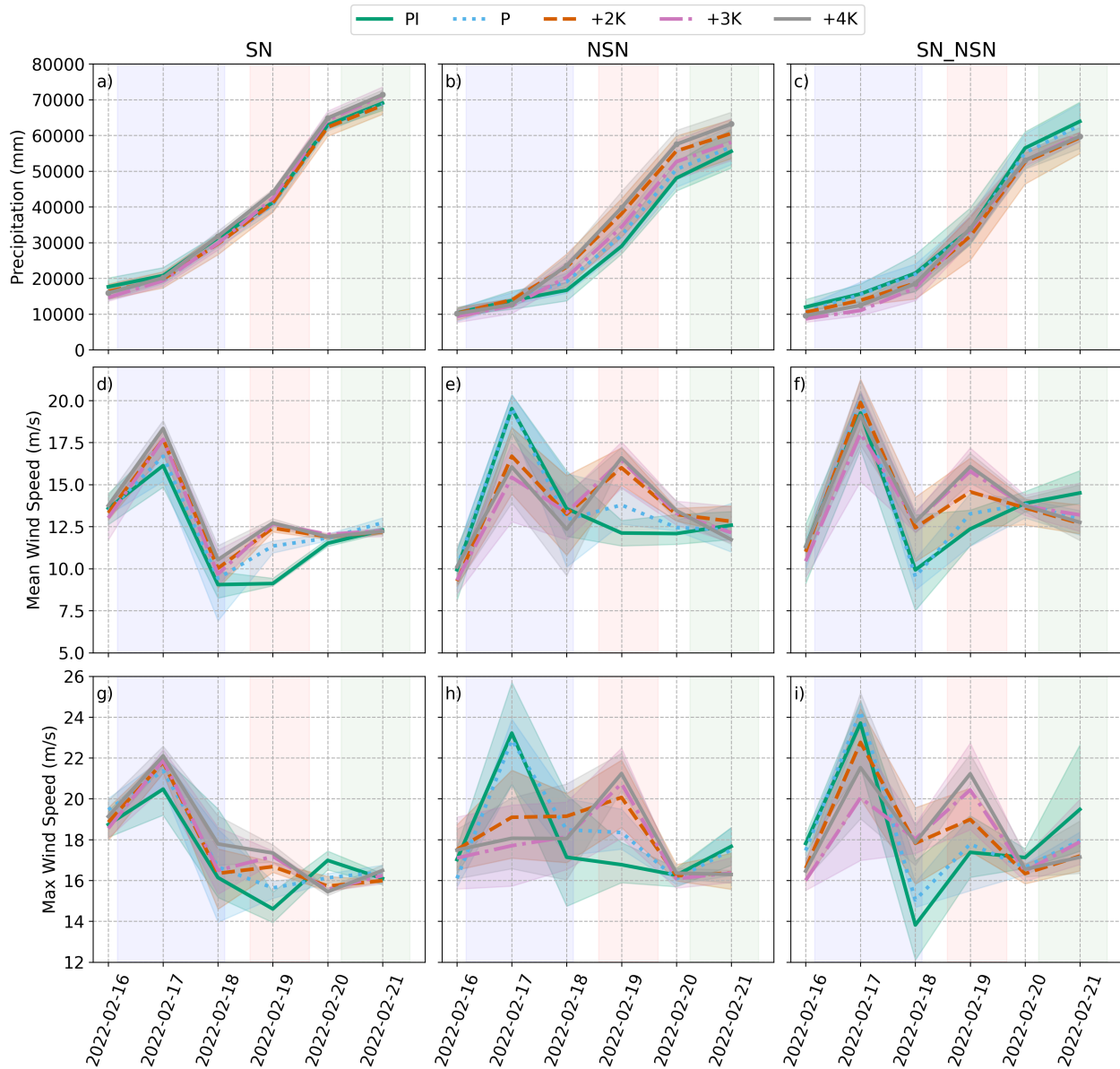


Figure 9. Cumulative precipitation and time series of mean wind speed and maximum wind speed domain-averaged over the German Bight and the German coast (see Fig.1). Solid thick lines denote ensemble-mean values, and shadings are the maximum and minimum values across ensemble members.

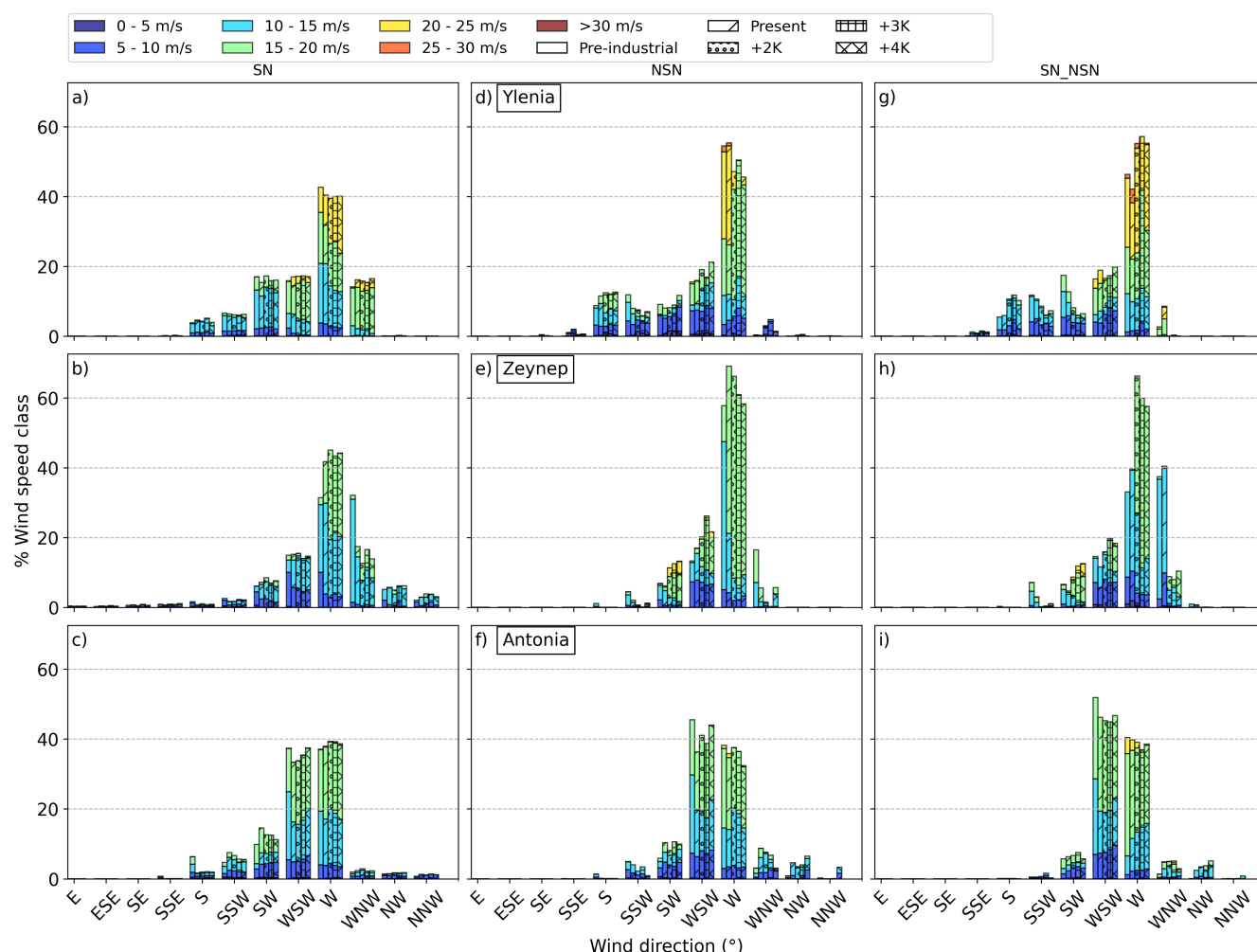


Figure 10. Histogram summarizing the wind direction and percentage of wind speed classes associated to the different storylines and setup simulations for the three storms in the German Bight and German coast area.

Changes in wind direction in the German study area are more pronounced in the unconstrained setups (Fig. 10). In SN, the main difference occurs during Zeynep, where the prevailing wind direction shifts from WNW in the PI storyline to W in the P and future storylines. An increase in the proportion of higher wind speed classes within the dominant wind direction can also be observed during Ylenia and Zeynep in the SN setup. In contrast, the storm-track tilts seen in the unconstrained setups are reflected in the absence of the highest wind speed classes in future storylines for Ylenia and Antonia.

As shown in Table 1, the SN configuration isolates the thermodynamic response to warming, exhibiting consistent increases in wind speed and precipitation across all warming levels in regions associated with the storm-track position. In contrast, NSN and SN_NSN demonstrate how dynamical changes and internal variability can modify or even counteract this thermodynamic signal. For example, northward-shifted tracks in SN would reduce wind impacts for storm Ylenia in the study domain,



whereas for Antonia a southward shift would enhance them. This behaviour is reflected in Fig. 6: for the SN storylines, a robust positive wind-speed increase extends from 62°N to south of 57°N, whereas for the NSN and SN_NSN storylines the robust signal is confined to around 57°N. This difference is largely driven by the improved representation of Zeynep in the SN storylines, whose storm track passes over the southern part of the domain. The spread across ensemble members and configurations therefore reflects the combined influence of thermodynamic forcing, circulation changes (dynamics), and internal variability. The ensemble-mean differences between configurations are interpreted as reflecting thermodynamic and dynamical forcing, whereas the remaining spread among ensemble members represents internal variability superimposed on these forced responses.

Large-scale dynamical changes also affect the results over the German Bight and adjacent coasts, with their influence strongly depending on the model configuration. When area-averaged, mean wind speeds increase relative to PI in the SN setup, whereas maximum wind speeds show a more configuration-dependent response. Interestingly, in the unconstrained setups, the winds associated with Zeynep show a notable increase in P and future storylines relative to PI, even though Zeynep was not trackable. For cumulative precipitation, the spread among ensemble members is larger in the unconstrained configurations. NSN exhibits a gradual increase across storylines, while SN_NSN shows P and future storylines remaining very similar to each other, all below PI.

Having defined the roles of the different configurations, we interpret storyline differences through the lens of three mechanisms:

Thermodynamical changes: Thermodynamical changes are present in all setups but are isolated in SN. They manifest as increased moisture availability (Fig. A10) and enhanced precipitation efficiency. These processes explain the progressive expansion of areas with robust positive wind-speed and precipitation changes in SN, as well as the consistent increases across warming levels. The better representation of Zeynep due to the spectral nudging is also responsible for the extended robust positive wind speed area compared to the NSN and SN_NSN setups.

Dynamical changes: Dynamical changes emerge in NSN and SN_NSN, including shifts in storm tracks, altered storm propagation speeds, and changes in jet-stream position. These shifts can weaken or strengthen local impacts. Distinctly, the decrease in wind speeds on unconstrained configurations in the German study area can be associated to the northward tilt of storm tracks, reducing the impacts with increased warming climate backgrounds, while the increase during Zeynep can be associated to the slower propagation of the first storm, Ylenia, extending the time of influence over the study area. The smaller percentage in robust positive areas on unconstrained configurations compared to SN is explained by the lack of accuracy in simulating Zeynep storm. The ensemble-mean response in NSN and SN_NSN is consistent with dynamical modifications, such as shifts in storm tracks, altered storm propagation speeds, and changes in jet-stream position. Because these signals satisfy the robustness criteria ($SNR > 1$ and $\geq 80\%$ ensemble agreement), they likely reflect a forced dynamical response. However, it is important to consider that individual realisations may still be influenced by internal variability, and not all differences between members can be interpreted as dynamical changes.

Internal variability: Internal variability is largest in NSN and SN_NSN. It explains the spread in cumulative precipitation and the storm-to-storm differences in track shifts. In this study, the robustness of climate-change signals is not solely determined



by the magnitude of warming (signal of ensemble-member differences), but also by how these signals compare to the internal variability inherent to each variable and model configuration (SNR). The magnitude of internal variability differs substantially across configurations: internal variability is largest in NSN and SN_NSN, where the unconstrained circulation permits greater divergence among ensemble members, and smallest in SN due to spectral nudging. Furthermore, it primarily manifests as ensemble spread in precipitation totals and storm trajectories. Robust climate-change signals therefore depend not only on the magnitude of the ensemble-mean response but also on its strength relative to this variability (SNR). Overall, the robust signals identified in this study represent ensemble-consistent forced responses, whereas the remaining member-to-member differences are attributable to internal variability.

4 Discussion

The high-resolution COSMO-CLM storylines, driven by global spectrally nudged storylines, allow for an attribution of extreme extratropical storm events to anthropogenic climate change. The storylines capture the main wind and precipitation peaks associated with the February 2022 storm cluster when comparing the P simulations with observations. The largest discrepancies are observed in the unconstrained setups, more evident during storm Zeynep, while spectral nudging improves the representation of the storms. The storylines approach enables a conditional assessment of how the observed storm cluster might have evolved under different climate states and helps to quantify the influence of anthropogenic climate change.

Anthropogenic climate change, defined in this study as the difference between warmer and pre-industrial storylines, leads, overall across all storylines and model setups, to at least a 4 % increase in mean wind speed and a 24 % increase in precipitation associated with the storm cluster, based on the average over areas exhibiting robust positive changes (ranging from about 1 % to about half of the total area) (Tables A1-A3). The spatial extent of these robust positive changes increases progressively with warming, with dynamical changes further amplifying the magnitude of already notable thermodynamic response in warmer climate states, but evidencing the role of internal variability between storyline members in decreasing the spatial robustness of observed changes.

Extratropical cyclone changes are mediated primarily by changes in circulation, while thermodynamics (e.g., moisture) acts as a secondary or modifying influence (Catto et al., 2019; Sinclair et al., 2020). We find that thermodynamics alone already produces substantial positive changes (SN setup), with dynamical contributions adding between at least 15 % and as much as 82 % to the thermodynamic response in unconstrained simulations. As noted by McDonald (2011), stronger latent heating (thermodynamics) can intensify cyclones even if fewer are required to maintain meridional energy transport. Local changes in temperature gradients, such as a reduced land–sea contrast between North America and the eastern North Atlantic, also influence cyclone behaviour (Hall et al., 1994), although their relative importance varies between regions and models (Lainé et al., 2009).

The spectrally nudged storylines are designed to constrain the dynamics but even for the unconstrained setups these are not completely free running simulations, as they evolve out of a spectrally nudged state (ECHAM global fields). We do not say that



thermodynamics is more important than dynamics but we show that thermodynamics do play a role in climate change related changes of extratropical cyclones, and not just the dynamics.

We refer to Øelund et al. (2026), who also applied storyline attribution to an extratropical storm in Europe and found counter-intuitive behaviour that likely reflects the sensitivity of wind maxima to small-scale dynamical adjustments rather than to thermodynamic forcing alone. Modifying atmospheric conditions to represent a warmer climate may unintentionally alter a storm's dynamics and even reduce its intensity (Matte et al., 2022). In this study, we intentionally alter the fundamental dynamics to better understand potential outcomes in a warming climate state where dynamical and thermodynamic changes act together.

Previous studies of Northern Hemisphere winter cyclones (Bengtsson et al., 2009; Zappa et al., 2013) reported fewer cyclones but stronger wind intensities over Europe. Given the exponential relationship between wind speed and damage (Dorland et al., 1999), even moderate intensification can substantially increase impacts. Our results show for future storylines a progressive increase of areas with stronger average and maximum wind speeds associated with the storm tracks, consistent with earlier findings (Rockel and Woth, 2007; Pryor et al., 2012; Feser et al., 2015; Krieger and Weisse, 2026).

A warmer atmosphere increases moisture availability, increasing latent heat release and precipitation associated with extratropical cyclones (Booth et al., 2013; O'Gorman, 2015). Therefore, anthropogenic climate change contributes to the intensification of precipitation associated with storm cluster fronts and also the convective fraction of storms (Tierney et al., 2018). Slightly shifts in storm tracks may displace the robust positive precipitation changes northward, while increased water vapour (Fig. A11) amplifies totals (Athanas et al., 2024; Grayson et al., 2026). A pronounced increase in precipitation along the Norwegian coast is evident in the NSN and SN_NSN simulations, likely reflecting increased relative humidity combined with the northward tilt of the storm tracks.

Overall, our results reveal a gradual but spatially heterogeneous intensification of storm-related impacts across the storylines. The storm cluster is substantially influenced by climate change in future storylines, as evidenced by robust increases in maximum wind speed of at least 6% on average, alongside robust positive changes in other storm-related characteristics (Tables A1-A3).

A key limitation is that the model cannot properly simulate small, intense and fast-moving storms such as Zeynep. The preceding storm Ylenia may have enhanced baroclinicity, enabling Zeynep's explosive development (Roebber, 1984; Ginesta et al., 2024), and Zeynep's small-scale, transient nature requires higher resolution for full representation (Gray et al., 2024). The driving ECHAM simulations may also contribute to this limitation due to the storm's strong local convective features and an already weaker signal in the global simulations (Fig. 10). In our hybrid setup, the non-constrained component diverges rapidly from the spectrally nudged simulations in all members and storylines, limiting its added value. While the storyline approach does not address changes in storm frequency, it provides physically plausible narratives of how extreme events may intensify under global warming. Combining storylines and probabilistic-based methodologies could further strengthen future assessments (van Garderen and León-FonFay, 2026).



5 Summary and Conclusions

This study applied an event-based storyline approach to assess the influence of anthropogenic climate change on the February 2022 storm cluster. COSMO-CLM simulations of wind speed and precipitation under different climate backgrounds reveal a spatially heterogeneous but robust intensification of storm properties and consequently impacts in warmer climates. Anthropogenic climate change leads to an area-wise increase in mean and maximum wind speed, and precipitation. For areas of robust increase, mean near-surface wind speed increases at least 1 m s^{-1} , maximum wind speed at least 1.3 m s^{-1} and precipitation at least 9 mm for the warmest storyline (+4K) compared to pre-industrial climate. Dynamical changes increase these values even further. Below, we summarize the answers to our guiding questions:

1. How accurately do CCLM simulations with and without spectral nudging reproduce the storm cluster, and what improvement do they offer over ECHAM? Spectrally nudged simulations show smaller biases relative to observations and better capture storm Zeynep than the non constrained simulations. Compared to observations, the higher resolution of CCLM adds value to the downscaled precipitation, while for wind components, global and regional simulations show similar performance.

2. What is the role of anthropogenic climate change, thermodynamics, and dynamics? The northward shift in future storm tracks when dynamics is unconstrained, mostly visible in Ylenia's tracks, reduces impacts over the German Bight and German coast. Thermodynamically driven positive changes in storm properties are already considerable in the spectrally nudged configuration. However, when dynamic contribution and internal variability are combined with the thermodynamic response, the detected changes in wind and precipitation exhibit lower spatial robustness.

3. How do storm properties change under future storylines? Wind speed and precipitation associated with the storm cluster increase progressively with warmer climate states. In the German Bight and German coast, no systematic results are visible, as consequence of the different model configurations and the contribution of thermodynamics, dynamics and internal variability. While cumulative precipitation curves are similar in magnitude in all storylines, wind speed increase is visible during the Zeynep storm period. Differences in wind direction are more noticeable in the unconstrained configurations, reflecting the higher spread in storm tracks.

Our event-based storylines provide physically plausible estimates of how extreme storm impacts may evolve in a warmer world and in future works can be used to clarify the mechanisms driving these changes. In this study, we analysed not only the thermodynamical fingerprints of climate change but also tried to implement the associated large-scale atmospheric dynamical changes. A limiting factor was the challenge in simulating Zeynep, observable in the spectrally nudged setup but not in the unconstrained ones. A solution would be increasing the spectral nudging parameters in the global ECHAM fields to force even more a close representation of the forcing fields. The simulated storylines can also be used to force coastal sea level variability and other impact models, supporting the development of adaptation strategies. Because storylines are anchored in recent, high impact events familiar to the public, they offer an accessible way to communicate climate related risks and strengthen community awareness.

Besides the social importance of storylines on presenting anthropogenic climate change in an easier way to citizens, future research can be applied to explain the mechanisms behind the coupled dynamic and thermodynamic changes caused by an-



thropogenic climate change in specific extreme events, while also quantifying the internal variability component. To improve results, the inclusion of more ensemble members would provide statistical robustness. Event-based storylines can also be used as case study to investigate how cloud-radiative heating affects real cyclones in the midlatitude storm track regions under climate change and how the cloud-radiative impact compares to the impacts of latent heating and moisture increase (Voigt et al., 2023).

Code and data availability. Hourly station data are available from the CDC/DWD portal: <https://cdc.dwd.de/portal/>. ERA5 hourly fields and storm tracks are available from the Copernicus Climate Data Center: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-timeseries?tab=overview>; <https://cds.climate.copernicus.eu/datasets/sis-european-wind-storm-reanalysis?tab=overview>. Python codes, ECHAM6 and COSMO-CLM simulations are available upon request.

Appendix A

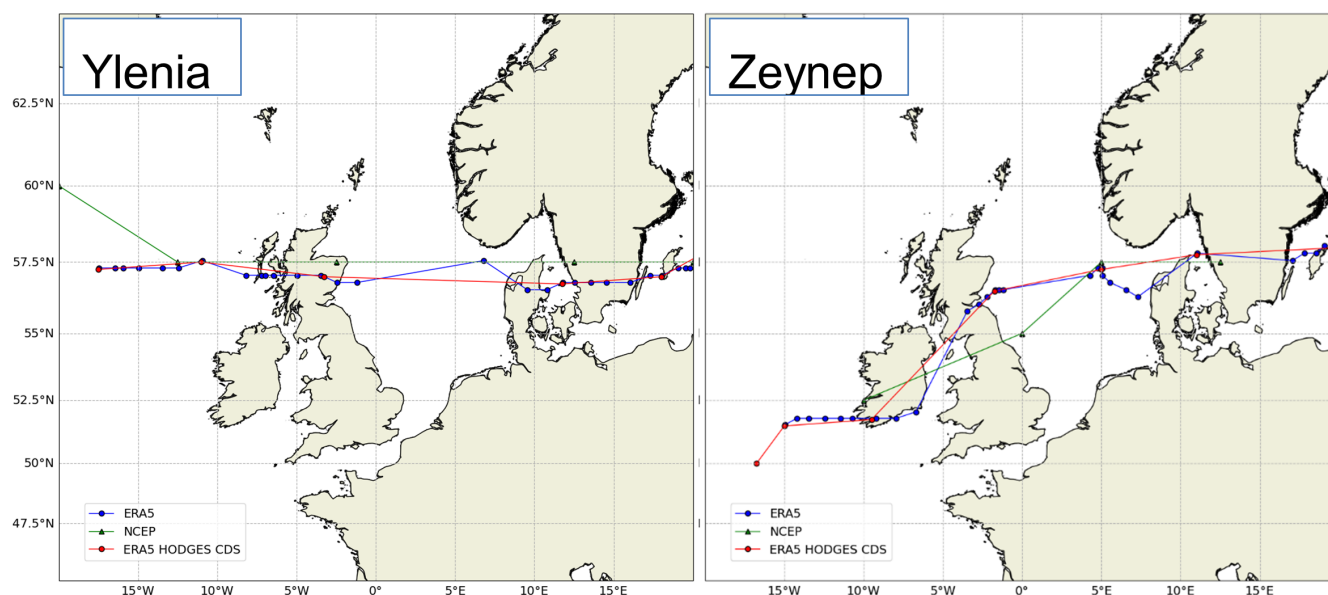


Figure A1. Comparison of tracking methods for the storms Ylenia and Zeynep using ERA5 and NCEP SLP fields. The ERA5 Hodges CDS tracks are available at the Copernicus Data Store and give tracks with centres every six hours. Our simple storm tracking method applied to ERA5 SLP fields generates tracks similar to the Hodges tracking method (Hodges, 1995, 1999).

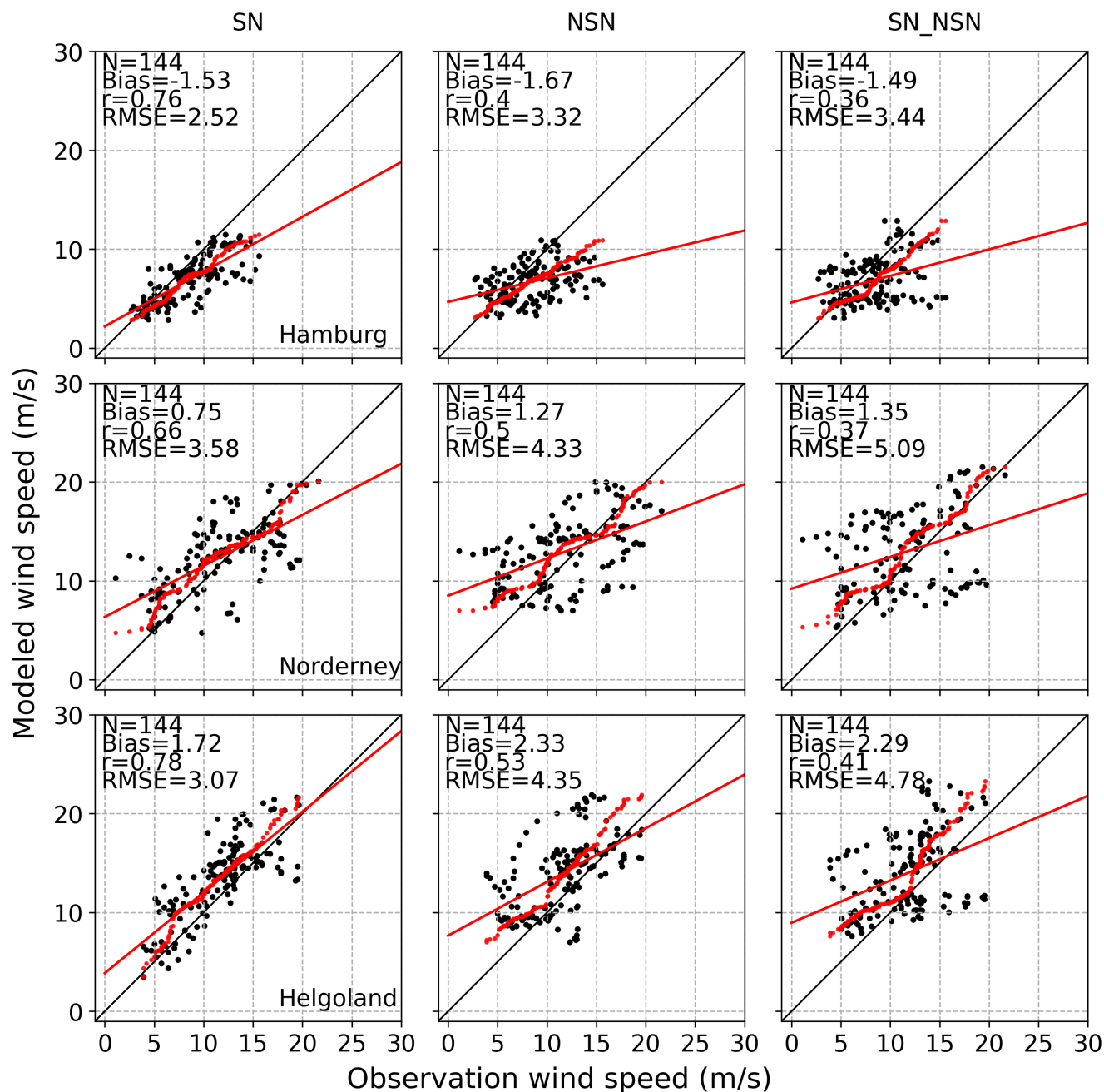


Figure A2. Scatter plot of in situ and present-time modelled wind speed (m s^{-1}), with evaluation statistics. The in situ locations are described in the first column, and the model setups are pointed in the first row titles. Red line is the linear regression, red dots the QQ plot and the black line the 1:1 ratio.

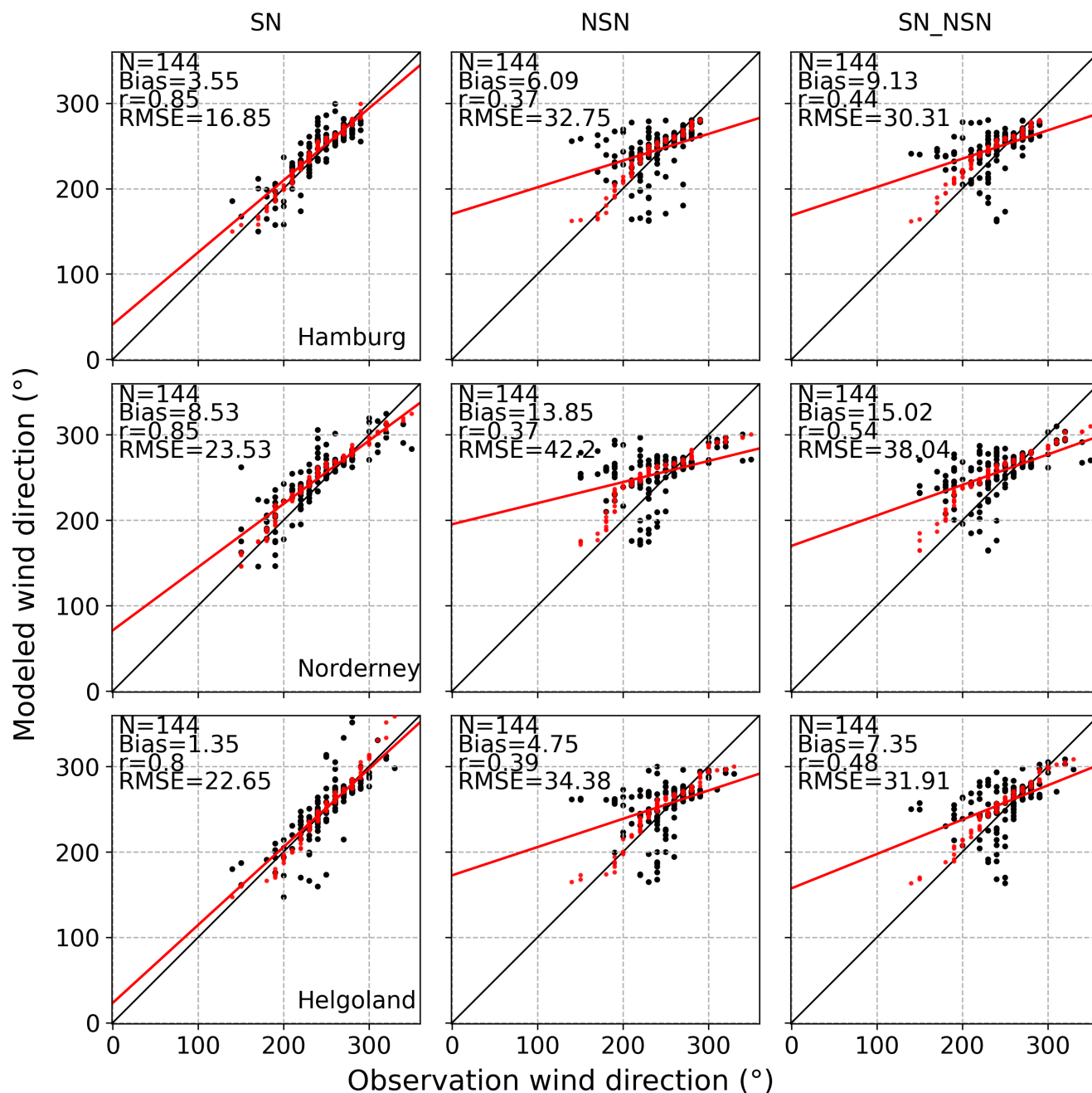


Figure A3. Scatter plot of in situ and present-time modelled wind direction (°), with evaluation statistics. The in situ locations are described in the first column, and the model setups are pointed in the first row titles. Red line is the linear regression, red dots the QQ plot and the black line the 1:1 ratio.

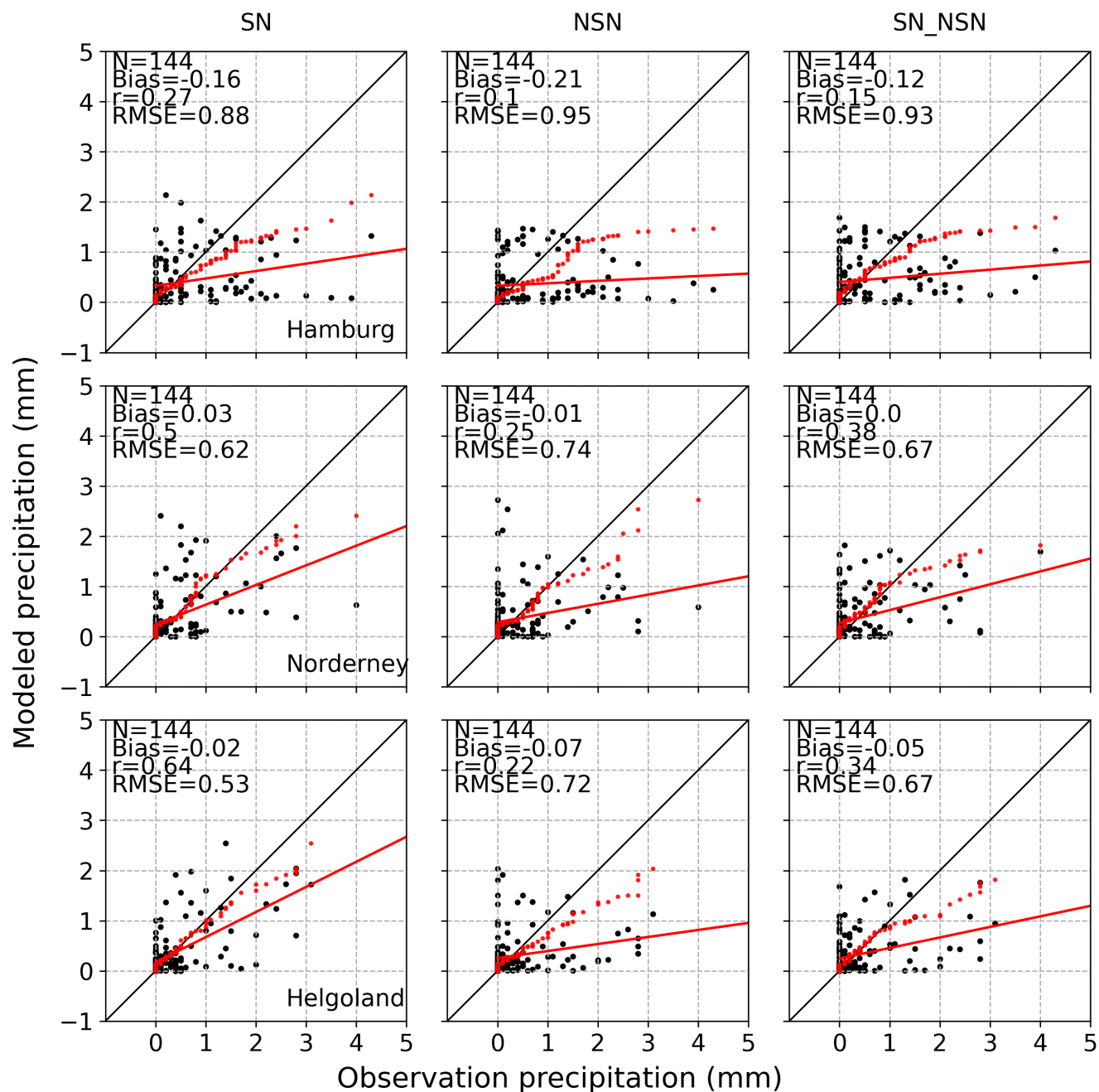


Figure A4. Scatter plot of in situ and present-time modelled precipitation (mm), with evaluation statistics. The in situ locations are described in the first column, and the model setups are pointed in the first row titles. Red line is the linear regression, red dots the QQ plot and the black line the 1:1 ratio.

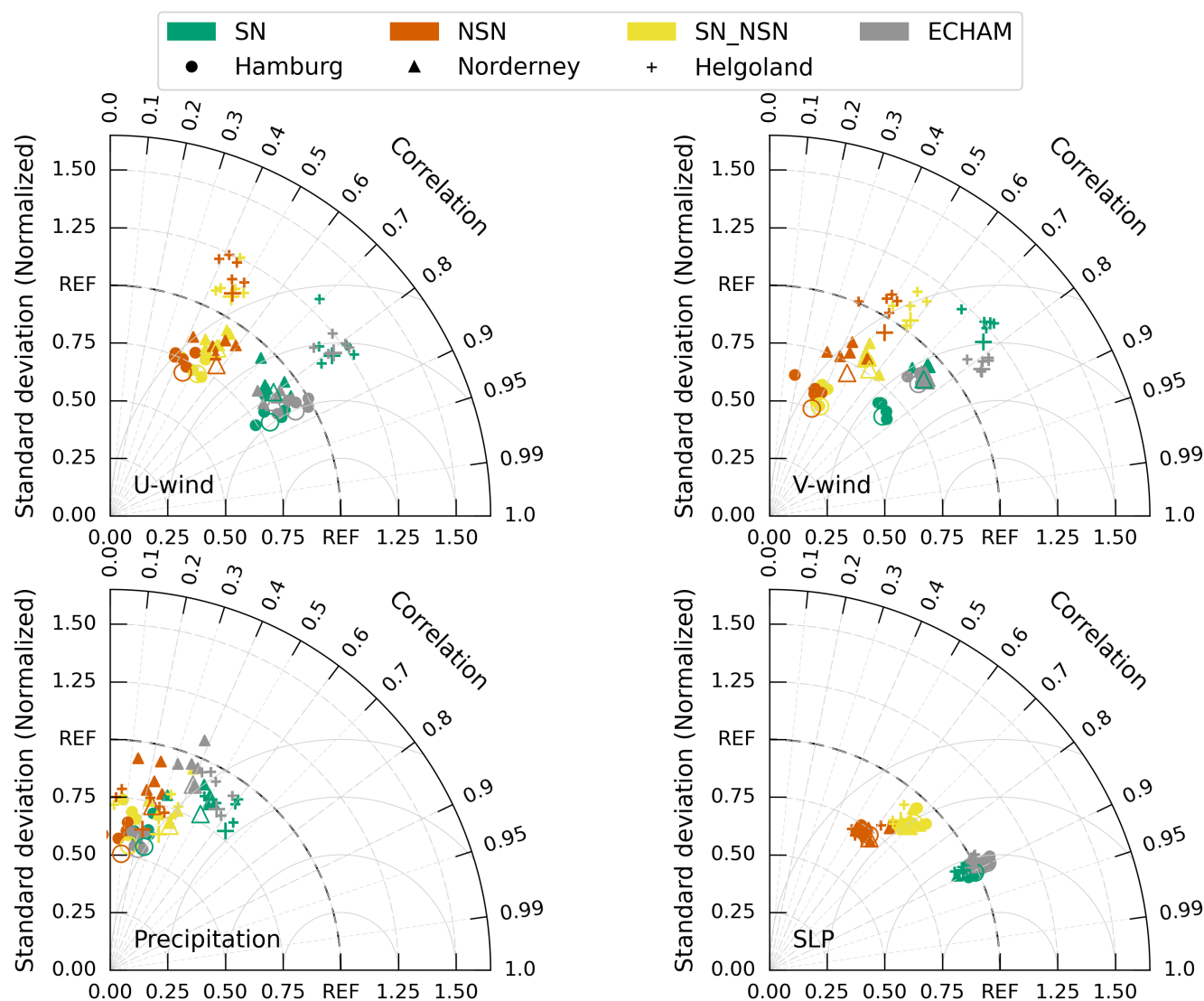


Figure A5. Taylor diagrams for u and v components of wind (m s^{-1}), precipitation (mm) and mean sea level pressure (hPa), evaluating the three model setups against observations on the three stations shown in Fig. 1. Also included are the ECHAM global storylines used to force the CCLM storylines. Larger open markers represent ensemble means.

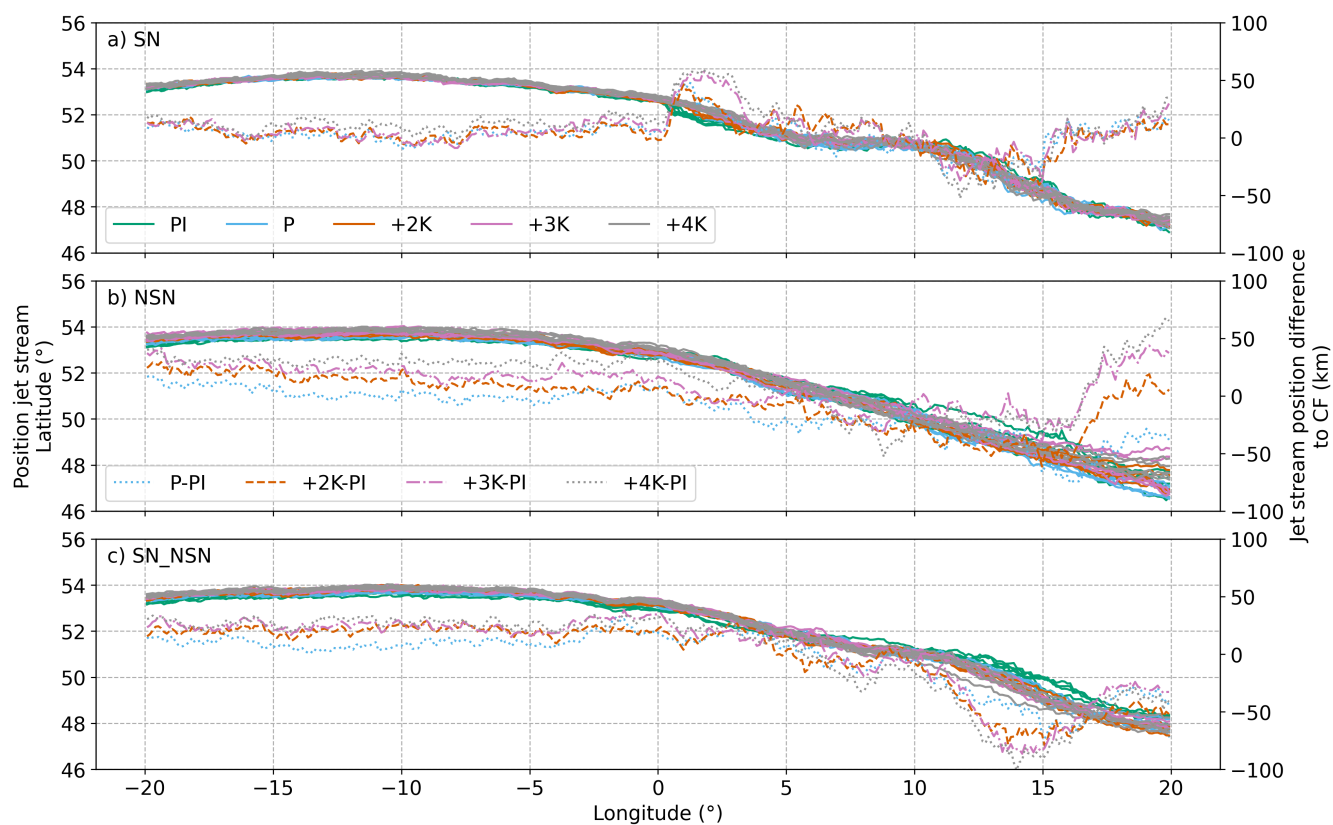


Figure A6. Jet stream position time-averaged over the storm cluster period for all the storylines (solid lines) and the differences related to the pre-industrial (dashed lines).

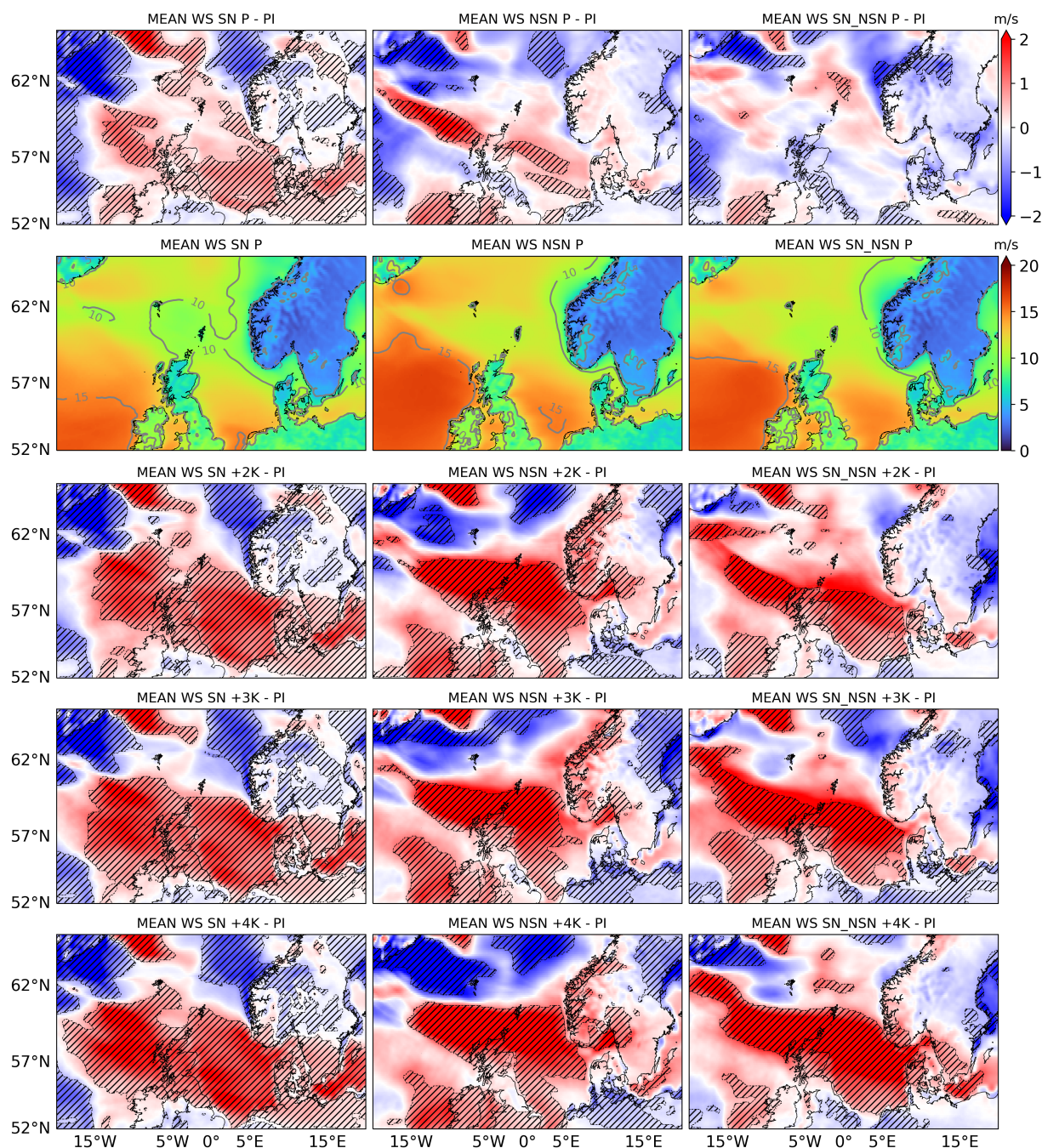


Figure A7. Simulated changes in storm cluster averaged 10 m wind speed time-averaged ensemble means between PI and the warmer storylines. Hatching indicates regions where at least 80% of ensemble members agree on the sign of the change and the signal to noise ratio is larger than 1. The second row represents the present-time ensemble mean of averaged 10 m wind speeds averaged over the storm cluster period (shading and contours).

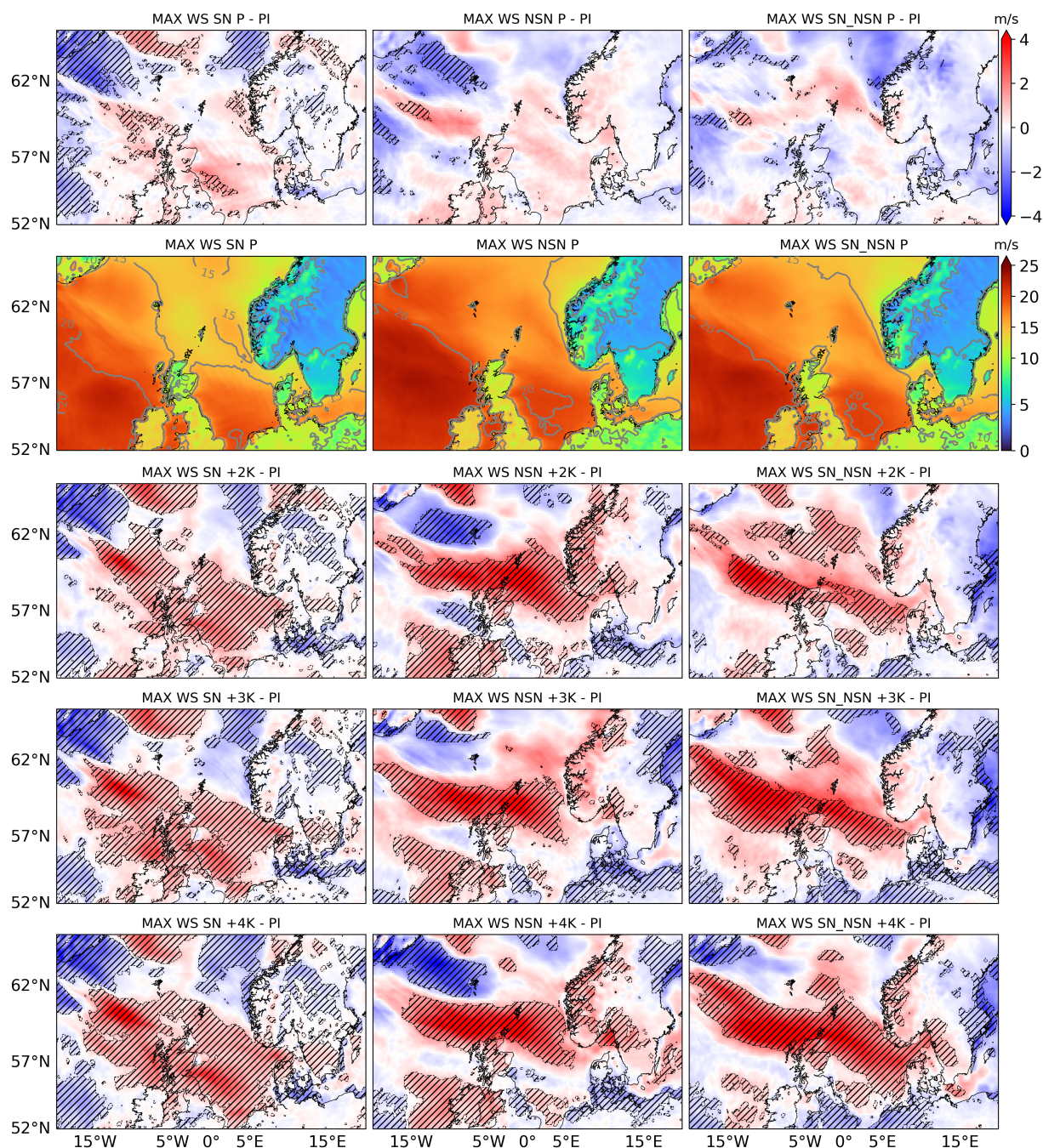


Figure A8. Simulated changes in storm cluster maximum averaged 10 m wind speed time-averaged ensemble means between PI and warmer storylines. Hatching indicates regions where at least 80 % of ensemble members agree on the sign of the change and the signal to noise ratio is larger than 1. The second row represents the present-time ensemble mean of 10 m maximum wind speeds averaged over the storm cluster period (shading and contours).

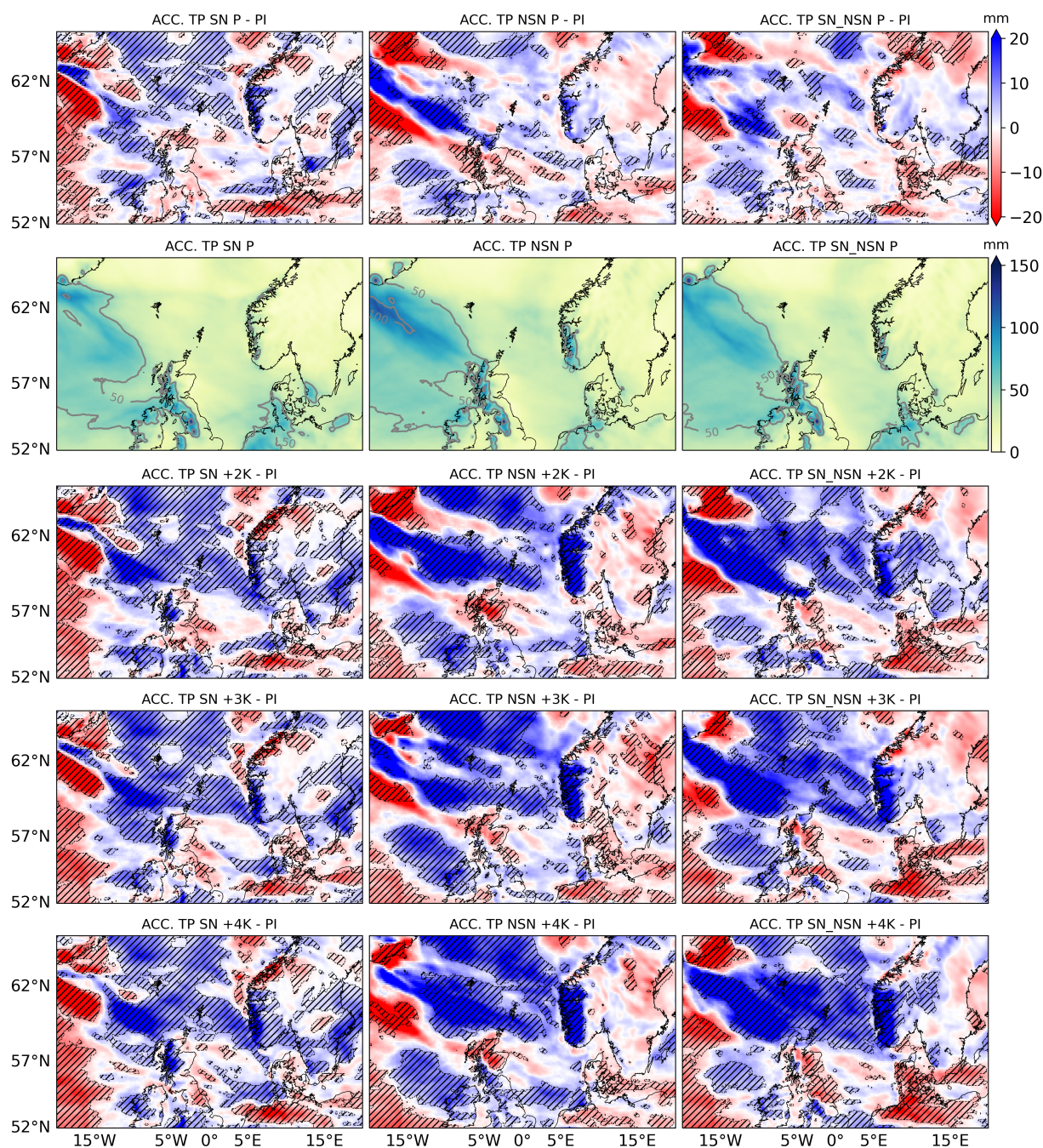


Figure A9. Simulated changes in accumulated precipitation over the storm cluster period between PI and warmer storylines. Hatching indicates regions where at least 80 % of ensemble members agree on the sign of the change and the signal to noise ratio is larger than 1. The colorbar shows wetter areas as blue and drier areas as red. The second row represents the present-time ensemble mean of total precipitation accumulated over the storm cluster period (shading and contours).

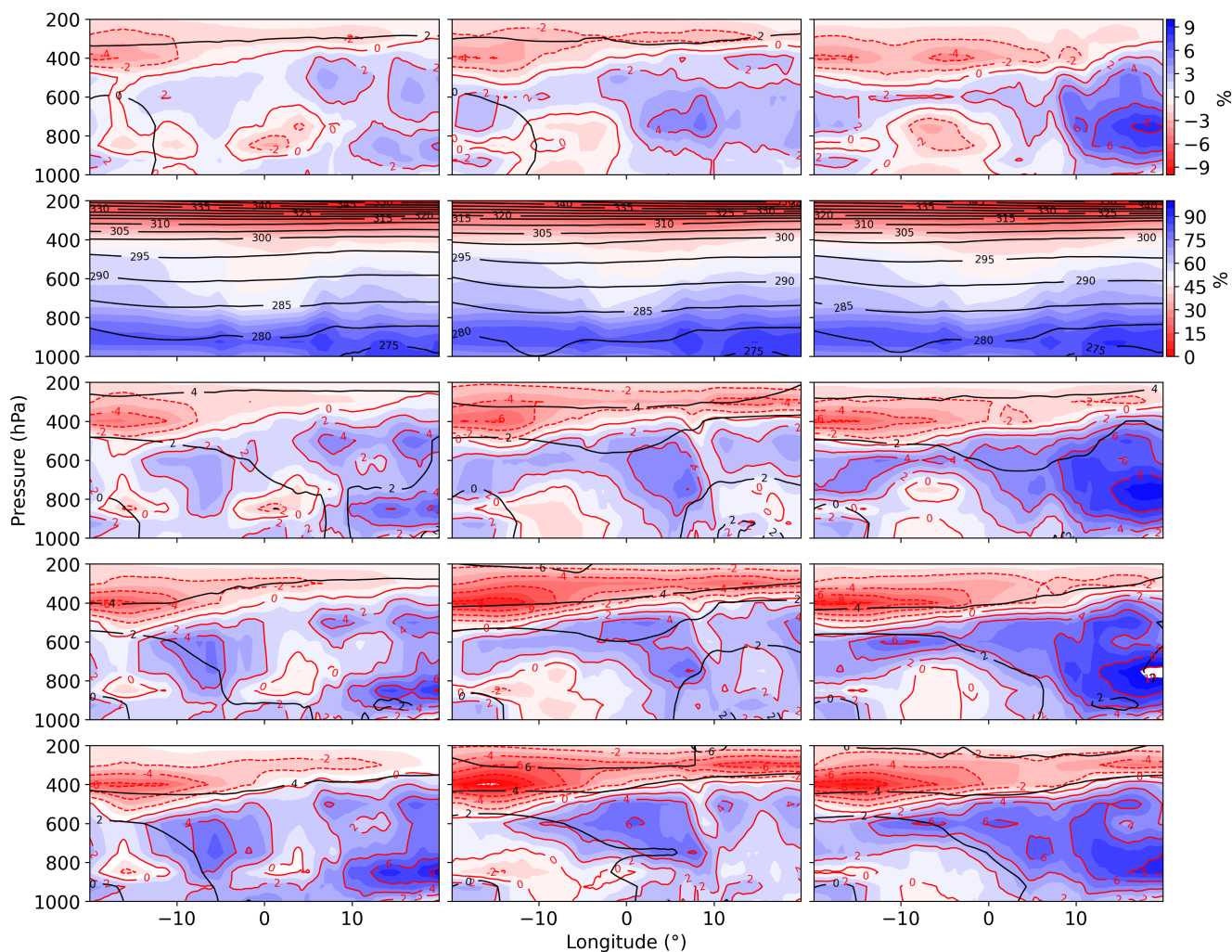


Figure A10. Relative humidity (%) (shaded) and potential temperature (K; black contours), averaged between 46° N to 56° N latitude and over the storm cluster period. The second row shows the present-time storyline and the other rows are the differences related to the pre-industrial storyline (present-time, +2K, +3K and +4K). The red contours are the differences related to PI in relative humidity (solid = positive; dashed = negative). From first column to third: SN, NSN and SN_NSN setups.

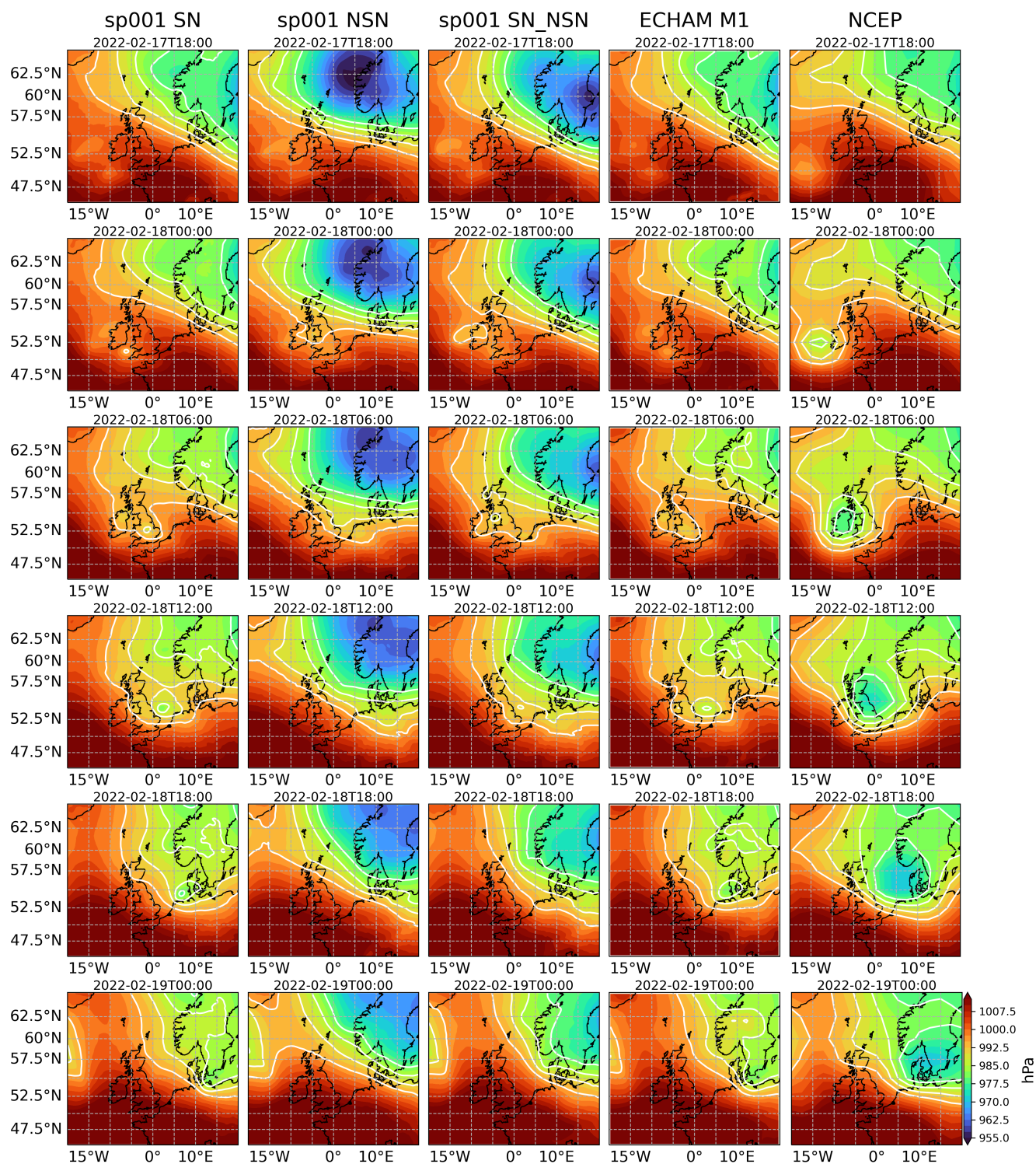


Figure A11. SLP (hPa) from CCLM ensemble member 1, spectrally and non-spectrally nudged, in comparison with the global ECHAM storylines and NCEP.



Table A1. Summary table of robust changes in mean wind speed: area of robust increase (%), robust increase mean and std (m s^{-1}) and robust increase (%)

SN			NSN			SN_NSN			
MEAN WS	Positive area	Δ increase		Positive area %	Δ positive mean $\pm$ std	Δ increase	Positive area	Δ increase	
	Δ positive mean $\pm$ std						Δ positive mean $\pm$ std		
(m s ⁻¹)	%	%	%		%	%	%	%	
P – PI	30.5	0.58 $\pm$ 0.35	5.8	12.6	0.85 $\pm$ 0.5	6.7	3.8	0.54 $\pm$ 0.23	4.3
+2K – PI	44.2	0.92 $\pm$ 0.49	9.5	33.5	1.38 $\pm$ 0.88	12.2	21.6	1.27 $\pm$ 0.75	9.9
+3K – PI	45.5	1.02 $\pm$ 0.51	9.9	28.1	1.46 $\pm$ 0.92	12.3	25.7	1.61 $\pm$ 0.87	12.2
+4K – PI	48.4	1.08 $\pm$ 0.56	10.7	33.2	1.51 $\pm$ 1.04	13.4	30.6	1.8 $\pm$ 0.96	15.5

Table A2. Summary table of robust changes in maximum wind speed: area of robust increase (%), robust increase mean and std (m s^{-1}) and robust increase (%)

	SN			NSN			SN_NSN		
	Positive area		Δ increase			Δ increase	Positive area		Δ increase
MAX WS (m s ⁻¹)	Δ positive mean $\pm$ std			Positive area %	Δ positive mean $\pm$ std		Δ positive mean $\pm$ std		
	%		%		%	%		%	
P – PI	6.1	0.87 $\pm$ 0.42	6.4	1.0	1.19 $\pm$ 0.51	6.6	0.7	1.0 $\pm$ 0.39	
+2K – PI	26.6	1.13 $\pm$ 0.6	7.9	27.1	1.77 $\pm$ 0.96	11.3	15.7	1.68 $\pm$ 0.93	
+3K – PI	29.6	1.3 $\pm$ 0.64	8.5	21.8	1.83 $\pm$ 0.97	10.5	17.0	2.36 $\pm$ 1.05	
+4K – PI	32.5	1.28 $\pm$ 0.7	8.7	27.2	1.78 $\pm$ 1.03	11.2	26.3	2.09 $\pm$ 1.07	

Table A3. Summary table of robust changes in precipitation: area of robust increase (%), robust increase mean and std (mm) and robust increase (%)

SN			NSN			SN_NSN			
ACC. TP	Positive area		Δ increase			Δ increase	Positive area		Δ increase
	Δ positive mean $\pm$ std			Positive area %	Δ positive mean $\pm$ std		Δ positive mean $\pm$ std		
(mm)	%		%			%	%		%
P – PI	21.4	6.57 $\pm$ 4.05	27.0	11.6	9.57 $\pm$ 7.22	26.5	10.9	8.56 $\pm$ 5.04	24.5
+2K – PI	30.7	8.76 $\pm$ 4.83	22.9	22.9	15.33 $\pm$ 10.47	42.8	25.4	13.65 $\pm$ 10.32	39.3
+3K – PI	30.6	9.16 $\pm$ 4.91	34.1	23.5	14.32 $\pm$ 9.23	42.0	22.9	15.32 $\pm$ 10.26	40.9
+4K – PI	31.3	9.14 $\pm$ 6.08	35.3	27.7	14.07 $\pm$ 9.85	41.4	27.9	14.46 $\pm$ 10.3	43.6

Author contributions. FA: Simulations, Formal Analysis, Investigation, Visualization, Writing – Original Draft, Review and Editing; FF: Conceptualization, Methodology, Supervision, Writing – Review and Editing; RW: Conceptualization, Supervision, Writing – Review and Editing, Funding Acquisition.

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360 *Disclaimer.*

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