



# Extratropical Cyclone and Storm track Responses to Stratospheric Aerosol Injection in High-Resolution CESM Simulations

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**Abstract.** Extratropical cyclones (ETCs) drive weather variability and dominate extreme wind and precipitation events in storm track regions. This study investigates ETC responses to stratospheric aerosol injection (SAI) compared to a high-emission (RCP8.5) and a reference scenario, using high-resolution CESM simulations with 0.25°/0.1° horizontal resolution in the atmosphere/ocean. Storm track activity is quantified using 2–6-day bandpass-filtered mean sea level pressure (MSLP), and individual cyclones are tracked using CyTRACK. SAI produces regionally asymmetric responses: the North Pacific storm track shifts equatorward, linked to SST changes, while the North Atlantic storm track shifts poleward, linked to an SAI-induced positive North Atlantic Oscillation (NAO) phase. The RCP8.5 scenario shows the fewest cyclones in both hemispheres, whereas cyclone frequency partially recovers toward reference levels under SAI. A risk analysis linking extreme events to ETCs through combined distance and vorticity masking shows that extreme precipitation events (>50 mm/day) increase by 18% in both hemispheres under RCP8.5 but decrease by 11% in the Northern Hemisphere and 6% in the Southern Hemisphere under SAI. Near-surface wind extremes (>25 m/s) decrease by 11% under RCP8.5 and 5% under SAI in the Northern Hemisphere, but with different spatial patterns. In the Southern Hemisphere, extreme wind events decrease by 4% under RCP8.5 and 5% under SAI. These findings demonstrate that SAI does not simply reverse warming-induced changes but produces new circulation patterns, highlighting the need for regional assessments of geoengineering impacts on midlatitude weather extremes.

## 1 Introduction

While phasing out greenhouse gas emissions and removing greenhouse gases from the atmosphere remain the only measures that address the root cause of climate change, complementary measures such as Solar Radiation Modification (SRM) are increasingly discussed. SRM aims to artificially reflect a small fraction of incoming sunlight back into space to cool the planet (National Academies of Sciences, Engineering, and Medicine, 2021; Parson and Keith, 2024). One suggested method is sulphate Stratospheric Aerosol Injection (SAI), which seeks to mimic the effect of volcanic eruptions (Crutzen, 2006; Robock et al., 2009). Of all proposed SRM methods, SAI has likely received the most attention, because it is likely feasible and inexpensive, at least compared to both swift mitigation and to damages from climate change (Smith, 2024, 2020). Thanks to decades-long research on volcanic analogues and (tropospheric) sulphate pollution, there is a high confidence that sulphate aerosol could provide significant cooling, although uncertainties remain on the exact climate response. In implementing SAI, one would have several choices, most importantly timing, injection latitudes and injection intensity (MacMartin et al., 2022;



Ricke et al., 2023). It is possible to combine injections at four latitudes (30°N, 15°N, 15°S, 30°S) such as to stabilise not just the global mean surface temperature (GMST), but also the north-south and equator-pole gradients (Tilmes et al., 2018a).

However, SAI would not perfectly restore the climate, even if GMST were restored; there would remain some “residual climate change”. This makes sense, as SAI is designed primarily to restore near-surface temperatures, but - depending on the injection strategy - large deviations remain at higher atmospheric levels, which may have important consequences for the thermal stratification of the atmosphere and vertical wind shear via the thermal wind balance (Visioni et al., 2021; Tilmes et al., 2018b; Yu et al., 2025; Bednarz et al., 2023). SAI also tends to weaken the global hydrological cycle, reducing both precipitation and evaporation, with a general tendency for wet regions to become drier and dry regions to become wetter across both tropical and extratropical latitudes (Ricke et al., 2023).

Despite these discrepancies between SAI and CO<sub>2</sub> responses, it seems that a reasonably homogenous SAI used to halve GMST change would bring basic climate variables closer to their pre-industrial state in most regions (Irvine et al., 2019). SAI would also not prevent ocean acidification (De Miguel et al., 2026; Jin et al., 2022) and have some environmental side effects, including a moderate delay in the healing of the ozone hole (Tilmes et al., 2022), acid rain and air pollution (Visioni et al., 2020). Given that the amount of sulphate needed for significant cooling is likely an order of magnitude smaller than peak industrial sulphate pollution, the latter impacts would arguably be second-order, compared to SAI’s climate effects (Harding et al., 2024). Most salient, perhaps, are the political concerns around SRM, including the fear that (the hope for) successful SRM might delay mitigation (McLaren et al., 2016), as well as concerns regarding just governance, disagreement and conflict (including “counter-geoengineering”), as well as conflation with other political goals, e.g. international prestige (Parson and Keith, 2024; Lockley et al., 2022; Michaelowa, 2021; Parker et al., 2018).

In recent years, several high-profile commissions have called for combining a (temporary) moratorium on SRM implementation and large-scale experiments with promoting research (Commission, 2023; Horton, 2024).

A growing body of literature evaluates SAI’s physical impacts, for example, on climate tipping (Futerman et al., 2025; Zhao et al., 2025), extreme weather (Quagraine et al., 2025; Tew et al., 2023; Feder et al., 2026), downstream impacts such as health and agriculture, including in the Global South, e.g. (Egbebiyi et al., 2025; Hussain et al., 2026) and ecosystems (Roberts et al., 2026; Zarnetske et al., 2021), for which the effects can be highly scenario-dependent (Hueholt et al., 2024; De Miguel et al., 2026).

The bulk of this work relies on simulations run at CMIP6-standard horizontal resolution of around 1°, e.g. GeoMIP (Visioni et al., 2023) and ARISE (Richter et al., 2022) data sets. Only a few studies used far higher resolutions, e.g. (Feder et al., 2026; Irvine et al., 2019). In this paper, we will analyse the effects of SAI on extratropical cyclones.

Extratropical cyclones (ETCs) are synoptic-scale low-pressure systems forming in the midlatitudes and are driven by baroclinic instability. The pathways of extratropical cyclones are known as storm tracks. In the Northern Hemisphere, the North Pacific and North Atlantic Oceans are primary regions where many ETCs travel. These regions are characterised by strong land-sea temperature contrasts, especially during winter. In contrast, the Southern Hemisphere storm tracks form a more con-





tinuous circular pattern around Antarctica, arising from the lack of large landmasses to disturb the atmospheric flow.

In the midlatitudes, extratropical cyclones are responsible for damaging winds, coastal flooding, and extreme precipitation. They contribute an estimated 50% of total precipitation, which can increase to 80% during the storm track season, making them critical for regional water resources (Hawcroft et al., 2012). Under a future high-emission scenario, both total precipitation and ETC-related precipitation are expected to increase (Sinclair and Catto, 2023; Jucker et al., 2025). The total number of ETCs is expected to decline due to the weakening of the lower-tropospheric equator-to-pole temperature gradient, while cyclone intensity may increase due to increased moisture availability and more latent heat release (Walker et al., 2020; Priestley and Catto, 2022a). Storm tracks are projected to shift poleward in the Southern Hemisphere and North Pacific, with an extension of the North Atlantic storm track into Europe (Priestley and Catto, 2022a). In addition to anthropogenic forcing, internal modes such as ENSO and the PDO change storm track strength and position, mainly through their effect on large-scale SST patterns (Wang et al., 2023).

Previous research has shown that SAI can induce a positive phase of the North Atlantic Oscillation (NAO) (Banerjee et al., 2021; Jones et al., 2022; Tilmes et al., 2025). The positive phase of the NAO is linked to an enhanced pressure gradient between the Azores and Iceland, resulting in a stronger jet stream and a northward shift of the Atlantic storm track (Jones et al., 2022; Tilmes et al., 2025). In the Pacific, the Aleutian Low weakens under SAI (Tilmes et al., 2025).

Most prior studies examining SAI and storm tracks have used coarse-resolution models ( $1^\circ$ ) (Gertler et al., 2020; Reboita et al., 2024). At such resolutions, sharp SST gradients near western boundary currents are insufficiently resolved; higher ocean resolution, combined with sufficient atmospheric resolution to capture synoptic-scale variability, improves the location of storm track maxima and reduces intensity biases (Small et al., 2018; Chang et al., 2020; Priestley and Catto, 2022b). As shown by Wang et al. (2023), higher atmospheric resolution further substantially improves the representation of storm track structure and intensity in CESM specifically. Furthermore, storm track responses have often been characterised in the zonal mean, leaving basin-level asymmetries underexplored (Gertler et al., 2020).

This study investigates ETC responses to stratospheric aerosol injection compared to a high-emission (RCP8.5) and a reference scenario, using high-resolution CESM simulations. Storm track activity is quantified using both Eulerian diagnostics and Lagrangian cyclone tracking at the basin level. In addition, we introduce a risk analysis that links extreme wind and precipitation events to individual cyclones through a combined distance-vorticity mask. This approach allows us to quantify not only how storm track positions and cyclone frequencies change, but also how the spatial distribution and frequency of ETC-related extreme events are redistributed under SAI.

In summary, we investigate how storm track position and intensity change, how cyclone frequency is affected, and how ETC-associated extreme precipitation and wind events are redistributed under both scenarios.

The paper proceeds as follows. In section 2, the model data and main methodological choices are introduced. Section 3 presents the results: first, the individual cyclone tracks and Eulerian storm-track activity are shown and compared across scenarios, fol-



lowed by the risk analysis for ETC-related precipitation and wind extremes. Finally, section 4 discusses the main findings and their implications and section 5 summarises the conclusions.

## 2 Model and Methods

### 2.1 CESM simulations

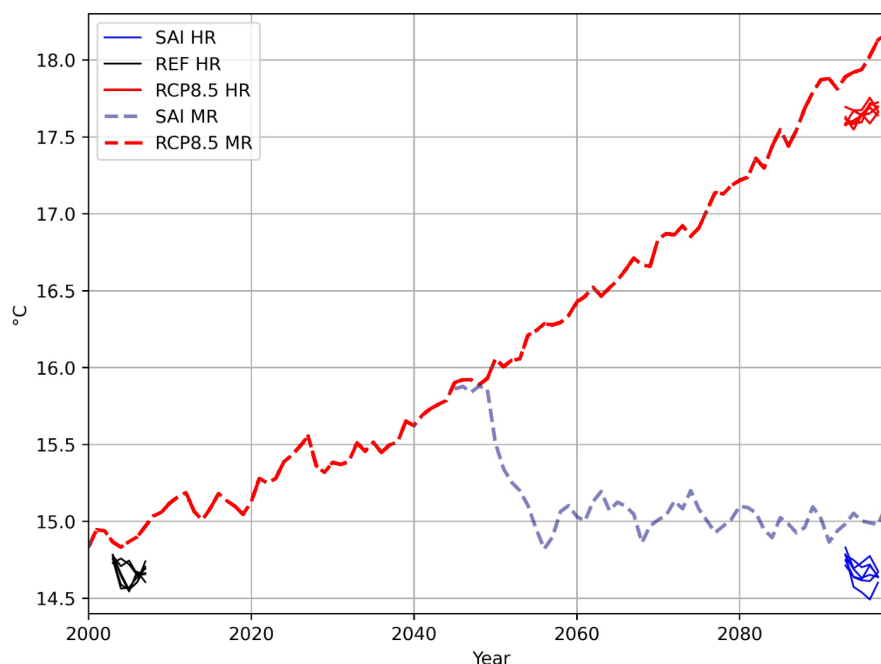
We use the Community Earth System Model (CESM) version 1.0.4 with  $0.1^\circ$  ocean and  $0.25^\circ$  atmospheric horizontal resolution, branched from a lower-resolution ( $1^\circ$ ) CESM configuration (Van Westen et al., 2020; De Jong et al., 2025). Previous work with the CESM high-resolution configuration has shown that this model realistically captures key aspects of the Northern Hemisphere winter storm track, including the spatial structure and associated wind and pressure fields (Wang et al., 2023). Atmospheric  $p\text{CO}_2$  increases at approximately 1% per year from 369 ppmv in 2000, following RCP8.5 ( $\text{CO}_2$  forcing only). The model spinup uses year-2000 conditions rather than pre-industrial conditions.

To save computation time, we use CAM, rather than WACCM, as the atmosphere component. As CAM does not simulate stratospheric aerosol, we model Stratospheric Aerosol Injection (SAI) by prescribing aerosol forcing fields derived from earlier CESM(WACCM6) simulations (Tilmes et al., 2018a). In these simulations,  $\text{SO}_2$  is injected at four latitudes ( $15^\circ\text{N}$ ,  $15^\circ\text{S}$ ,  $30^\circ\text{N}$ ,  $30^\circ\text{S}$ ) using a feedback-control algorithm that optimises three surface temperature targets: global mean surface temperature, the interhemispheric gradient, and the equator-to-pole gradient (Tilmes et al., 2018a). From these simulations, monthly climatological 2D aerosol distributions (latitude–pressure) are extracted and introduced into CAM5 within our high-resolution CESM configuration. The aerosol fields are scaled globally using a feedforward-feedback procedure to maintain global mean surface temperature at  $1.5^\circ\text{C}$  above pre-industrial levels (De Jong et al., 2025).

The RCP8.5 simulation runs from 2000 to 2100. The SAI simulation branches off in 2045, with injection beginning in 2050. High-resolution ensembles, each consisting of six members of five-year periods, are analysed for the reference period (December 2002–January 2008, corresponding to year-2000 conditions) and a later period (December 2092–January 2098) under both RCP8.5 and SAI.

### 2.2 Extratropical cyclone tracking and storm track analysis

Individual extratropical cyclones are tracked using CyTRACK (Pérez-Alarcón et al., 2024), a Lagrangian tracker applied to 6-hourly mean sea level pressure (MSLP), 3D geopotential height, and lowest model-level wind fields (corresponding to the 992 hPa equivalent hybrid sigma level, or  $\sim 80$  m above the surface). Tracks are retained only if they persist for at least 48 hours, travel at least 1000 km, and satisfy cyclone phase space (CPS) criteria for at least 24 hours, filtering out mesoscale disturbances and thermal lows (Coll-Hidalgo et al., 2024). Analysis is restricted to extended winter months: November–March (NDJFM) in the Northern Hemisphere and May–September (MJJAS) in the Southern Hemisphere. Due to the limited availability of 3D 6-hourly data, CyTRACK is applied to six ensemble members for the SAI scenario, but only one for the reference and RCP8.5 scenarios. A bootstrap resampling of the SAI ensemble members is used to quantify ensemble spread.



**Figure 1.** Global mean surface temperature (GMST) in the RCP8.5 and SAI simulations. High-resolution (HR;  $0.1^\circ$  ocean,  $0.25^\circ$  atmosphere) ensemble members are shown for the reference scenario (2002–2008) and for the period 2092–2098 in both RCP8.5 and SAI. The dashed lines show the GMST for the medium-resolution (MR;  $1.0^\circ$  ocean,  $0.5^\circ$  atmosphere).

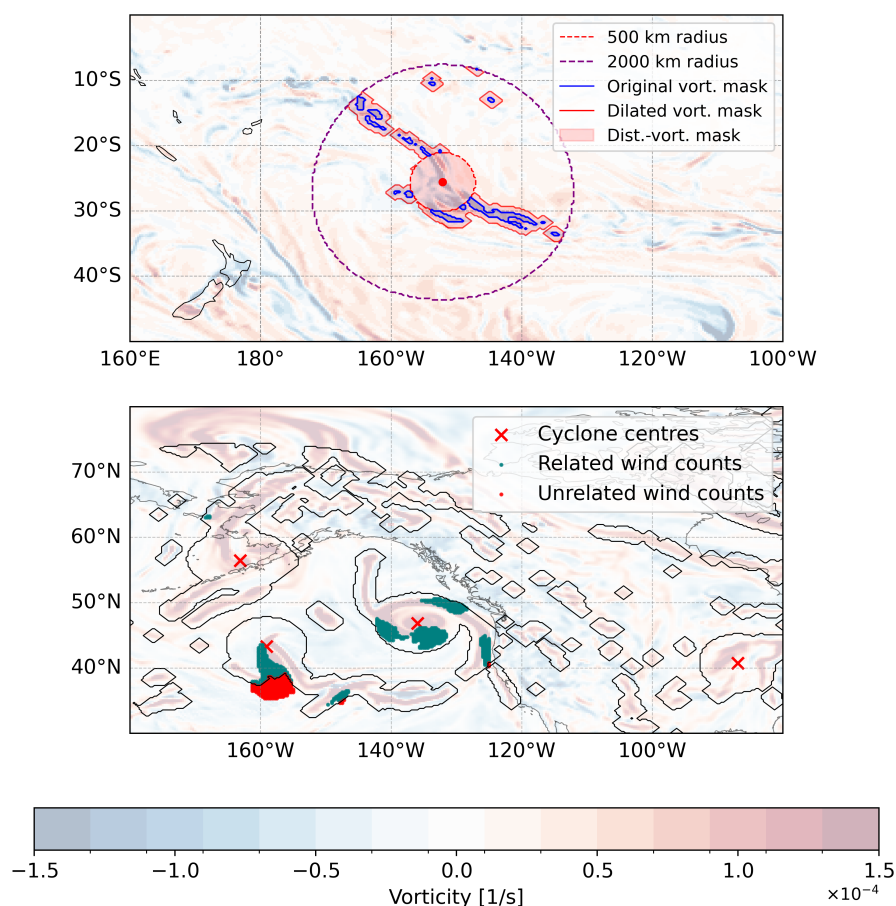
To complement the Lagrangian tracking with more robust statistics across the full 30-year simulation period, we also quantify storm track activity using a Eulerian approach. A 2–6-day Lanczos bandpass filter, following Harvey et al. (2020), is applied to daily MSLP. The standard deviation of the bandpass-filtered MSLP is used as a measure of storm track activity.

### 2.3 ETC-related extreme event attribution

- 130 To assess how SAI and RCP8.5 alter ETC-related extreme events, we need to determine which extreme wind and precipitation events are associated with extratropical cyclones. Attributing extremes to ETCs allows us to separate ETC-driven changes from those occurring in other meteorological contexts. Many previous studies have attributed precipitation and wind to extratropical cyclones using purely geometrical distance masks around the cyclone centre. A common choice is a fixed radius of order 1000–2000 km, within which all precipitation is counted as cyclone-related (Hawcroft et al., 2012). To attribute extreme wind
- 135 and precipitation events to individual ETCs, we instead employ a combined distance-vorticity mask in order to include the cyclone’s fronts but not unrelated extreme wind and precipitation events. For each cyclone centre at a given timestep, two spatial masks are constructed: (i) a 500 km circular mask centred on the cyclone, and (ii) a vorticity-based mask covering the 500–2000 km region around the centre. The vorticity mask is defined from the 850 hPa relative vorticity field as the region satisfying  $\zeta \geq 9 \cdot 10^{-5} \text{ s}^{-1}$  (NH) or  $\zeta \leq -9 \cdot 10^{-5} \text{ s}^{-1}$  (SH), and is expanded by four grid cells ( $\approx 100 \text{ km}$ ) to capture fragmented



140 vorticity structures. This threshold is comparable to the mean Coriolis parameter over 20°–80° latitude and was chosen based  
on visual inspection to ensure the mask captures the cyclone fronts while excluding unrelated small-scale vorticity features  
(Fig. 2). To reduce computational costs, wind fields ( $U, V$ ) are first averaged over  $5 \times 5$  grid cells, from which relative vorticity  
is computed. This field is then used to construct the vorticity mask. Cyclone presence is coarsened over the same  $5 \times 5$  cells  
( $\sim 100 \times 100$  km) using the maximum, so that a coarsened cell is marked as containing a cyclone if any native-grid cell within  
145 it does. Extreme event exceedances (wind and precipitation) are counted on the native grid; the resulting binary fields are  
then coarsened by averaging over  $5 \times 5$  cells, such that each coarsened cell indicates the fraction of native-grid cells where an  
exceedance occurs.



**Figure 2.** (a) Example of the construction of the vorticity mask on a single ETC centre. (b) Example of the vorticity mask on the Northern Hemisphere. Red crosses indicate cyclone centres; green dots mark wind extremes that fall inside at least one cyclone’s mask and are therefore counted as cyclone-related; red dots mark wind extremes that lie outside all masks and are counted as unrelated. Each wind extreme is counted only once, even if it falls within the masks of multiple cyclones.



## Event Counting

Wind responds nearly instantaneously to cyclone dynamics, so wind extremes are linked to cyclone positions at the same  
150 6-hourly timestep. Extreme events are flagged when near-surface wind (lowest model level) exceeds 25 m/s. To avoid over-  
counting, a reset threshold is applied: no new event is recorded at a grid point until the wind drops below the low threshold  
(10 m/s). Flagged extremes that fall within either mask are counted as ETC-related events.

Unlike wind, precipitation can lag behind the cyclone or occur in remote frontal structures. Precipitation rates are converted to  
6-hour totals and accumulated over a forward-looking 24-hour window: at each timestep  $t$ , the sum of timesteps  $t$ ,  $t + 1$ ,  $t + 2$ ,  
155 and  $t + 3$  is computed. An exceedance is flagged at  $t$  if this 24-hour total exceeds 50 mm, with a 24-hour exclusion window  
applied to prevent the same event from being counted multiple times. To account for temporal displacement between a cyclone  
and its associated precipitation, an exceedance at  $t$  is attributed to an ETC if the affected grid cell falls within the combined  
distance–vorticity mask (Fig. 2) at any of the five timesteps  $t - 1$  through  $t + 3$ . This range covers one timestep before the start  
of the precipitation window and the full duration of the accumulation period.

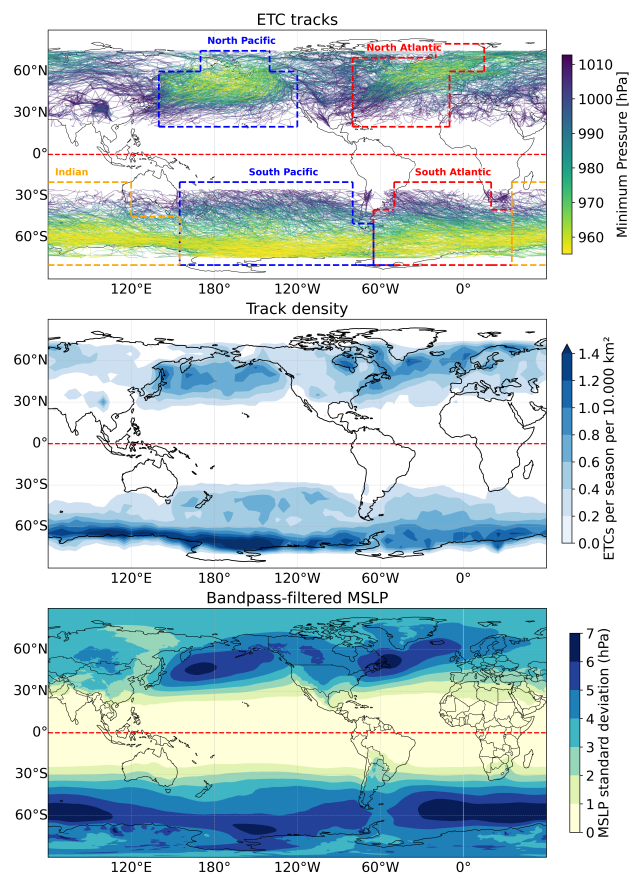
160 For example, if a 24-hour precipitation total is computed from Tuesday 06:00 to Wednesday 06:00 ( $t =$  Tuesday 06:00), it is  
attributed to an ETC if the grid cell lies within the ETC mask at any of: Tuesday 00:00 ( $t - 1$ ), Tuesday 06:00 ( $t$ ), Tuesday  
12:00 ( $t + 1$ ), Tuesday 18:00 ( $t + 2$ ), or Wednesday 00:00 ( $t + 3$ ).

We also record time series of each cyclone’s precipitation. At each timestep, we identify the upper tercile of precipitation  
values within the combined distance-vorticity mask around the cyclone centre and compute the corresponding area-weighted  
165 mean. Only the upper tercile is retained to exclude low precipitation from remote parts of the mask that are unlikely to be  
directly associated with the cyclone. For each cyclone, the maximum of these values along the track is retained. In parallel, we  
also compute the 99th percentile within the mask at each timestep and retain its along-track maximum for each cyclone.

## 3 Results

### 3.1 Storm track variability

170 Figure 3 presents the reference-scenario cyclone tracks, track density, and the standard deviation of the bandpass-filtered MSLP.  
The top panel shows individual ETC tracks coloured by minimum pressure, showing that the deepest cyclones are concentrated  
in the North Pacific and North Atlantic basins and a zonally symmetric circle in the Southern Hemisphere. The track density,  
obtained by counting tracks within  $5^\circ \times 5^\circ$ , closely matches the bandpass-filtered MSLP variability, confirming that the Eulerian  
and Lagrangian diagnostics capture the same storm track structures in these simulations; although this technique has been  
175 validated using other datasets, it is important to demonstrate its consistency in the present analysis. The equivalent figures for  
the RCP8.5 and SAI scenarios are shown in Figures A2 and A3.



**Figure 3.** (a) Individual ETC tracks coloured by minimum pressure, (b) track density normalised by season (NDJFM in NH, MJJAS in SH) and area, and (c) standard deviation of the 2–6-day bandpass-filtered MSLP. NDJFM months are shown for the NH and MJJAS for the SH, separated by the red dashed line.

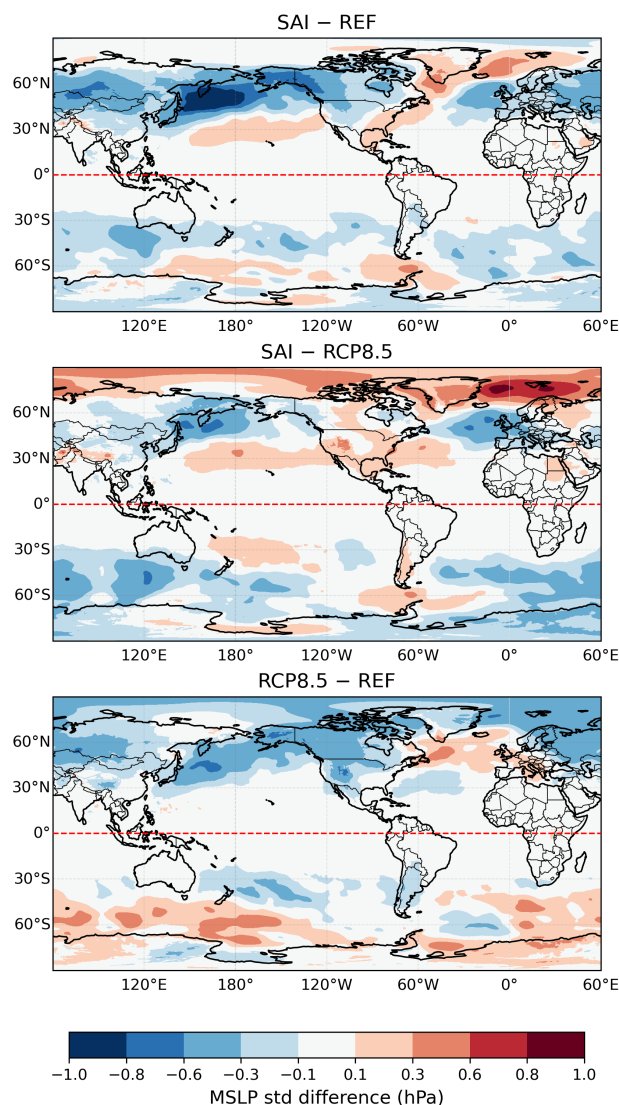
Because the bandpass-filtered MSLP is calculated using all ensemble members (full 30-year period), scenario differences in storm track activity are quantified using this metric (Figure 4). This allows us to relate changes in storm track intensity and position directly to the patterns of wind and precipitation extremes shown later.

180

Although both scenarios weaken overall storm track activity in the Northern Hemisphere, with area-averaged variability over 20°–80°N changing by –4.8% under both RCP8.5 and SAI in NDJFM, the spatial patterns differ considerably between the two scenarios. In the Southern Hemisphere, the two scenarios diverge: under RCP8.5, area-averaged variability over 20°–80°S increases slightly by +0.4% in MJJAS, while SAI reduces it by –2.4%. Under RCP8.5, the Southern Hemisphere storm track shifts poleward. This is evident in the pattern of changes: there is a decrease around 30°S, with an increase farther south, indicating a poleward shift. Under SAI, this poleward shift is partially offset, and overall storm track activity decreases.

185





**Figure 4.** Storm track variability differences between scenarios for NDJFM and MJJAS expressed as changes in the standard deviation of the 2–6-day bandpass-filtered MSLP. Area-averaged variability over 20°–80°N decreases by 4.8 % (RCP8.5) and 4.8 % (SAI) in NDJFM, and over 20°–80°S it increases by 0.4 % (RCP8.5) and decreases by 2.4 % (SAI) in MJJAS.

In the Northern Hemisphere, the basin-level responses reveal a clear asymmetry between the two ocean basins. In the North Atlantic, RCP8.5 decreases storm track activity in the Gulf Stream region while increasing it south of Greenland and toward Iceland. This pattern can be related to the North Atlantic cold blob visible in Figure A1, which is associated with a weakening of the AMOC (Van Westen et al., 2025) and the Labrador Current. The cold blob strengthens the southwest-to-northeast SST gradient southwest of Iceland, thereby increasing storm track activity in that region. Further northeast, however, the SST



gradient weakens, which reduces storm track activity northeast of Iceland. Under SAI, the North Atlantic storm track shifts poleward and extends northeastward into Europe, consistent with the positive NAO response documented under SAI (Banerjee et al., 2021; Jones et al., 2022; Tilmes et al., 2025).

195 In the North Pacific, RCP8.5 produces a uniform weakening of storm track activity, while SAI induces both a weakening and an equatorward shift. This shift corresponds to a reorganisation of the SST gradient: the gradient weakens around 40°N, where storm track activity decreases, and strengthens around 30°N, where activity increases. This SST anomaly pattern, which resembles a positive PDO phase (see Section 4), is likely driven by a weakening of the North Pacific subtropical gyre (Fig. A1). Given that all 0.25° simulations are branched from one 0.5° simulation (Fig. 1), it is impossible to tell whether the weakening  
200 of the subpolar gyre is due to a long-term climate response or natural variability.

In the Arctic, storm track variability decreases under RCP8.5, likely as a consequence of reduced sea ice extent weakening the meridional temperature gradient. This is partially restored under SAI, consistent with the recovery of Arctic sea ice.

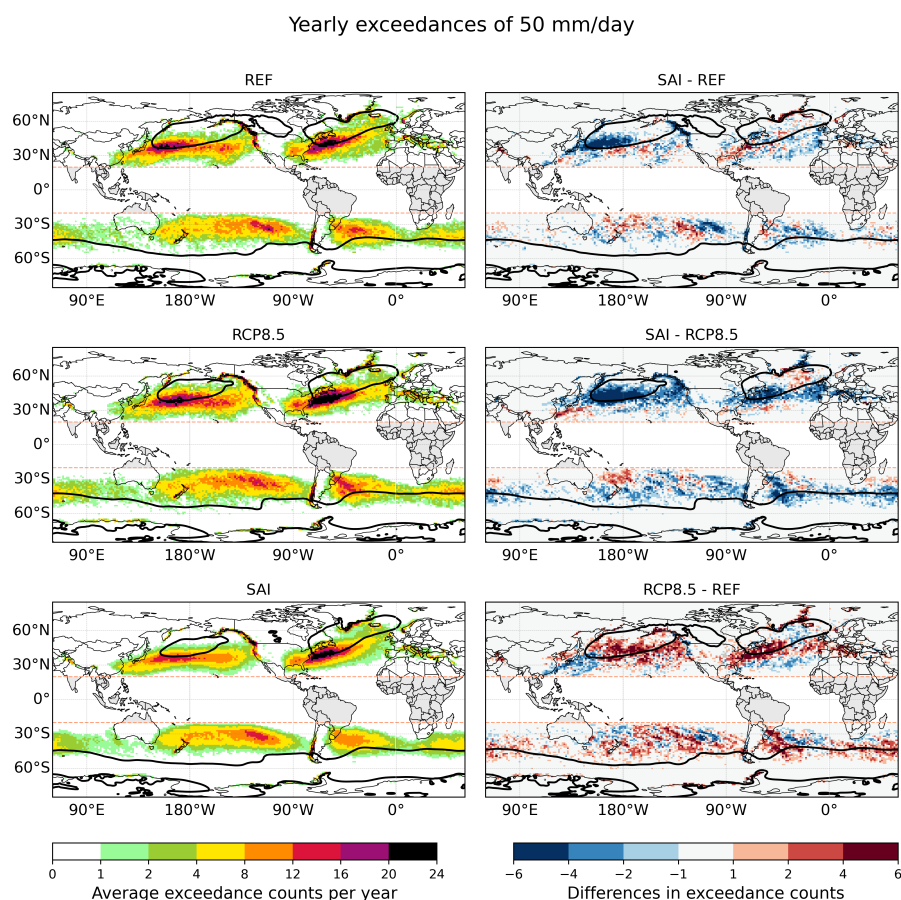
### 3.2 ETC Frequency

Table 1 presents the number of extratropical cyclone tracks identified by the tracker in the Northern and Southern Hemispheres.  
205 The REF and RCP8.5 scenarios are based on a single 5-year ensemble member, whereas the SAI scenario is evaluated across six ensemble members. The RCP8.5 scenario shows the lowest number of ETC tracks, particularly in the Southern Hemisphere. Under SAI, cyclone counts partially recover toward reference levels, indicating that SAI offsets some, but not all, of the warming-induced decline.

**Table 1.** Total number of ETCs tracked in NDJFM (NH) and MJJAS (SH) across the RCP8.5 and SAI scenarios for 2092–2098, and the REF scenario for 2002–2008. The values represent the number of ETCs tracked in one ensemble member; the standard deviation is computed across the six SAI ensemble members and reflects the ensemble spread in ETC counts.

| Scenario              | NH Total  | SH Total  |
|-----------------------|-----------|-----------|
| REF                   | 1358      | 1359      |
| RCP8.5                | 1255      | 1189      |
| SAI Ensemble member 1 | 1284      | 1318      |
| SAI Ensemble member 2 | 1292      | 1371      |
| SAI Ensemble member 3 | 1299      | 1318      |
| SAI Ensemble member 4 | 1300      | 1355      |
| SAI Ensemble member 5 | 1318      | 1363      |
| SAI Ensemble member 6 | 1310      | 1329      |
| SAI Ensemble mean     | 1300 ± 11 | 1342 ± 21 |

### 3.3 Extreme precipitation



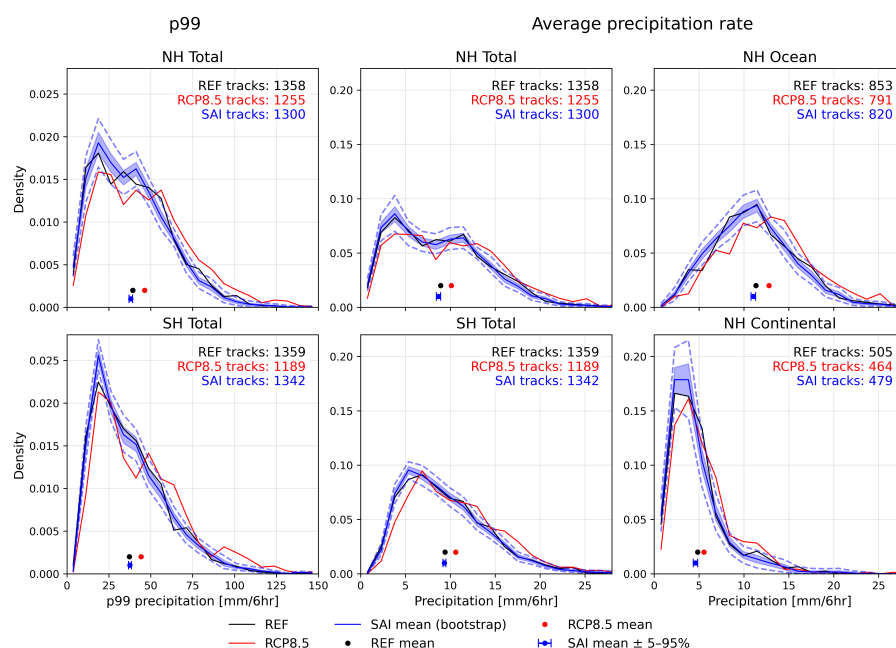
**Figure 5.** ETC-associated extreme precipitation exceedances ( $>50$  mm/day; left) and scenario differences (right). Black contours denote storm tracks (bandpass-filtered MSLP std  $> 4.8$  hPa). The black contours in the second column are the storm track from the scenario it is compared to (REF in the first and third panel, RCP8.5 in the second panel). Total ETC-associated exceedances relative to REF increase by 18 % under RCP8.5 in both hemispheres and decrease by 11 % (NH) and 6 % (SH) under SAI.

210 Figure 5 presents ETC-related counts of precipitation events exceeding 50 mm/day. Extreme precipitation counts concentrate  
 on the equatorward flank of the storm tracks, consistent with warm-front sectors. This pattern is more pronounced in the  
 Southern Hemisphere, where the storm track extends further poleward in the absence of large landmasses. In the Northern  
 Hemisphere, SAI and RCP8.5 produce distinct regional responses. Under SAI, extreme precipitation counts decrease over the  
 215 MSLP.

In contrast, RCP8.5 shifts extreme precipitation in the North Pacific slightly poleward and eastward, indicating that extreme



precipitation occurs farther downstream. In the North Atlantic, both SAI and RCP8.5 show an increase over the Gulf Stream, although this is much more pronounced and extends further east under RCP8.5. The Northern Hemisphere shifts under SAI are broadly consistent with the storm track changes observed in Figure 4. In contrast, the Southern Hemisphere shifts do not align as clearly, likely because the extreme precipitation events fall largely outside the defined storm track. Under RCP8.5, the precipitation shifts do not correspond to the storm track changes, suggesting that increased moisture availability plays a more important role than the weakening of storm track activity in both the North Pacific and the Gulf Stream regions. In the Southern Hemisphere, an equatorward shift in extreme precipitation events is evident to some extent.



**Figure 6.** (Left) Maximum 99th precipitation percentile within the distance–vorticity mask of the cyclone centre, (Right) Distribution of maximum area-averaged 6-hourly precipitation rate per ETC track in the NH (NDJFM), further divided into ocean and continental ETCs, and SH (MJJAS). Tracks are classified by basin according to the location of their minimum pressure (Fig. 3). The precipitation rate is area-averaged within the distance–vorticity mask. Blue line/shading: SAI bootstrap mean with 25th–75th and 5th–95th percentile ranges. Precipitation rates increase by  $\sim 13\%$  in both hemispheres under RCP8.5 and decrease by  $3\%$  (NH) and  $1\%$  (SH) under SAI, relative to REF.



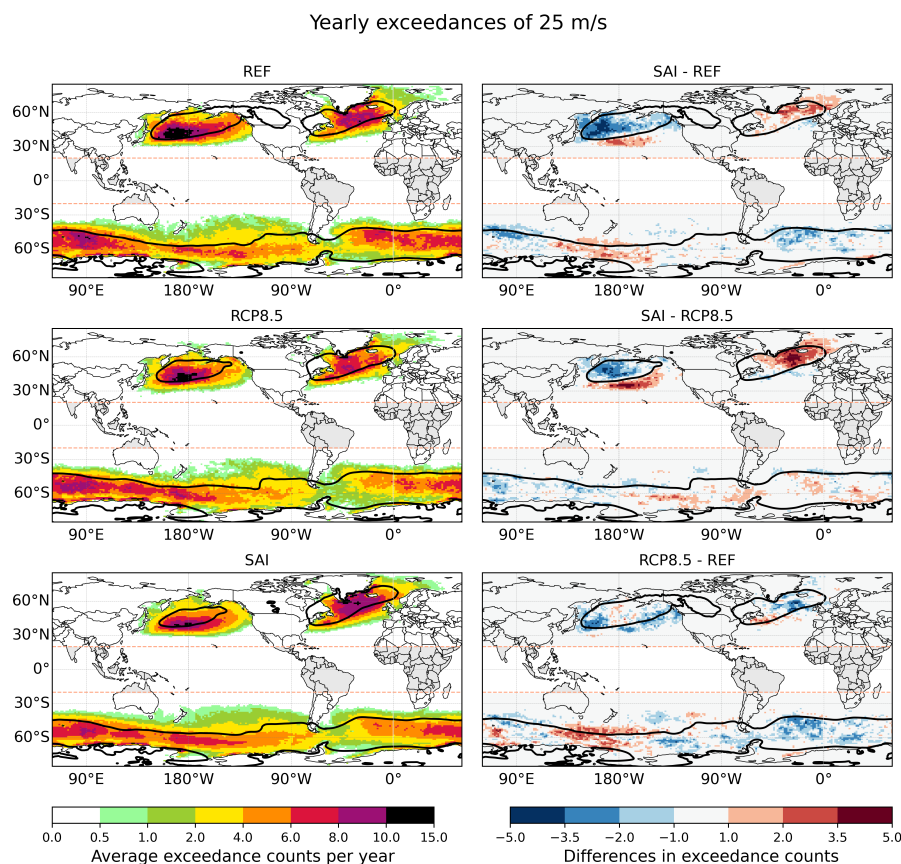
Figure 6 shows the track-maximum 99th-percentile precipitation in the left column, while the other two columns show the  
225 track-maximum area-weighted mean precipitation rate of the upper tercile within the distance-vorticity mask (see Section 2.3  
for both definitions). The maximum is used rather than the mean, as the distributions are more skewed towards lower values  
while having a similar overall shape; using the maximum, therefore, better highlights the most intense precipitation associated  
with each cyclone.

In both hemispheres, RCP8.5 produces the highest percentile values, while SAI brings these values much closer to the refer-  
230 ence. The increase in average precipitation rate under RCP8.5 indicates that individual cyclones become much wetter under  
warming. Under SAI, this increase is slightly overcompensated. Interestingly, the Northern Hemisphere distribution shows  
some bimodality, which reflects two distinct ETC populations: the relatively dry and weak continental ETCs and the wet and  
deep oceanic ETCs (Fig. 3).

Both precipitation intensity metrics indicate that SAI effectively compensates for the warming-induced increase in 6-hourly  
235 extreme and average precipitation within individual cyclones, even though the frequency of ETC-associated exceedances falls  
below REF.

### 3.4 Extreme winds

Figure 7 presents ETC-related counts of wind events exceeding 25 m/s. In the Northern Hemisphere, the spatial shifts in  
exceedance counts closely reflect the storm track changes seen in the bandpass-filtered MSLP variance (Fig. 4) and in the  
240 precipitation extremes (Fig. 5). Under RCP8.5, extreme wind counts in the North Atlantic shift equatorward, while in the North  
Pacific, they mainly decrease along the existing storm track without a pronounced displacement. Under SAI, extreme winds  
shift poleward and extend further northeast in the North Atlantic, and shift equatorward in the North Pacific, accompanied by  
a uniform decrease within the defined storm track.



**Figure 7.** ETC-associated extreme wind exceedances ( $>25$  m/s; left) and scenario differences (right). Black contours as in Fig. 5. Total exceedance counts relative to REF decrease by 11 % (NH) and 4 % (SH) under RCP8.5 and by 5 % in both hemispheres under SAI.

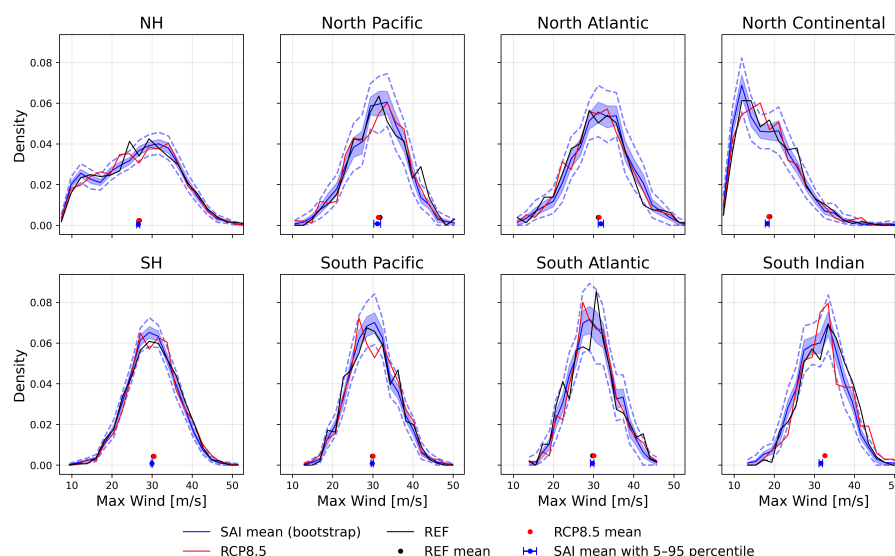
These patterns show that SAI does not restore the occurrence of wind extremes to reference-like conditions; instead, the spatial changes in exceedance counts are more pronounced under SAI than under RCP8.5. Even though total exceedance counts are closer to REF under SAI, the pronounced spatial redistribution means that individual regions do not experience a simple recovery. Regional assessments are therefore essential for understanding local risk.

Southern Hemisphere exceedance patterns are very similar for RCP8.5 and SAI. This suggests that SAI has minimal impact on extreme winds in this hemisphere and therefore does not reverse the warming-induced changes.

To complement the risk analysis, maximum wind speeds along individual cyclone tracks are examined as a measure of peak cyclone intensity.

Maximum wind distributions show generally small differences across scenarios. SAI produces slightly weaker cyclones over continental and North Pacific basins, and slightly stronger maximum winds in the North Atlantic. In the Southern Hemisphere, the largest SAI-related decrease occurs in the Indian Ocean, with maximum winds  $\sim 1$  m/s lower than REF.





**Figure 8.** PDF of maximum wind speed per ETC in the NH (NDJFM) and SH (MJJAS). Blue line/shading: SAI bootstrap mean with percentile ranges. Tracks are classified by basin according to the location of their minimum pressure (Fig. 3).

These small changes in maximum winds contrast with the larger changes in extreme wind events, highlighting that SAI mainly redistributes where extremes occur rather than changing ETC intensity.

## 4 Discussion

The results presented here are broadly consistent with previous research on SAI impacts on extratropical cyclones. The poleward storm track shift in the RCP8.5 scenario agrees with Priestley and Catto (2022a), as does the general reduction in cyclone numbers under a warming scenario. The partial offset of this poleward shift under SAI, particularly in the Southern Hemisphere, supports findings from Reboita et al. (2024) and Gertler et al. (2020).

This study provides several advances over previous work. First, by combining cyclone tracking, bandpass-filtered MSLP, and a risk analysis of extreme events, this study provides more evidence for storm track changes. A further advance is the use of high-resolution CESM simulations ( $0.25^\circ$  atmosphere,  $0.1^\circ$  ocean), which better resolve storm track structures and SST gradients compared to the coarser models used in most SAI–ETC studies (Wang et al., 2023; Chang et al., 2020). Additionally, by analysing storm track responses at the basin level rather than only in the zonal mean, we identify a clear asymmetry between the North Pacific (equatorward shift) and the North Atlantic (poleward shift) under SAI. However, the North Pacific shift should be interpreted with caution, as the associated SST anomaly may partly reflect internal variability rather than a forced SAI trend; this is discussed further in this section.

The basin-level asymmetry can be understood through the mechanisms induced by SAI. In the Atlantic, SAI-induced tropical



lower-stratospheric heating strengthens the stratospheric polar vortex, which propagates downward to produce a positive NAO-like response that shifts the Atlantic storm track poleward (Jones et al., 2022; Banerjee et al., 2021). In the Pacific, SAI-induced SST changes (Fig. A1) modify the lower-tropospheric baroclinicity and, together with a weakened Aleutian Low (Tilmes et al., 2025), drive an equatorward displacement and weakening of the storm track, consistent with the reduced wind extremes. The strong sensitivity of storm track position and intensity to the background SST changes is consistent with Wang et al. (2023). Together, these mechanisms explain why SAI produces opposite storm track shifts in the two basins despite a globally uniform temperature target. Additionally, the warming-induced increase in ETC-associated extremes reflects enhanced atmospheric moisture availability, while the reduction under SAI is consistent with the expected weakening of the global hydrological cycle (Ricke et al., 2023).

Several limitations should be considered when interpreting these results. Due to data availability, the RCP8.5 and reference scenarios include only a single 5-year ensemble member for the cyclone tracker, whereas the SAI scenario includes six members. Nonetheless, consistent changes are evident in the 30-year bandpass-filtered MSLP, and the ensemble spread for SAI in terms of storm track counts is relatively small. The bootstrapping approach for SAI uncertainties partially addresses this by quantifying the ensemble spread.

A separate source of uncertainty arises from the ensemble design: since all six SAI members are branched from the same medium-resolution simulation, low-frequency modes of variability are not independently sampled across members. Any such mode that was in a particular phase at the branching point will be shared across the ensemble.

The CyTRACK algorithm also has some limitations. The phase space criteria may exclude tropical-to-extratropical transition events, the 1000 km minimum distance threshold prevents identification of merging cyclones, and the 48-hour minimum life-time threshold removes short-lived but potentially intense systems.

The SST change (w.r.t. Reference) under SAI in the North Pacific resembles a positive PDO phase, see Fig. A1c. Even under RCP8.5, the SST change somewhat resembles a positive PDO pattern combined with overall warming. PDO-like SST changes shift the band of strongest SST gradients and therefore the region of highest baroclinicity, which may help explain the poleward shift of the storm tracks in the North Pacific. We note that the set-up of our simulations, with all high-resolution ensemble members starting in a single year (2092) from a single medium-resolution simulation, does not allow us to disentangle long-term SST trends from (multi-)decadal variability. In particular, it may be that both the RCP8.5 and SAI simulations were coincidentally started at a time of positive PDO, producing an apparent trend.

## 5 Conclusions

This study investigated the response of extratropical cyclones to stratospheric aerosol injection using high-resolution ( $0.25^\circ/0.1^\circ$ ) CESM simulations, comparing an SAI scenario with a high-emission (RCP8.5) and a reference scenario.

In terms of storm track locations and intensity, SAI produces regionally asymmetric responses: an equatorward displacement and weakening in the North Pacific, and a poleward shift in the North Atlantic. These shifts are identified across independent

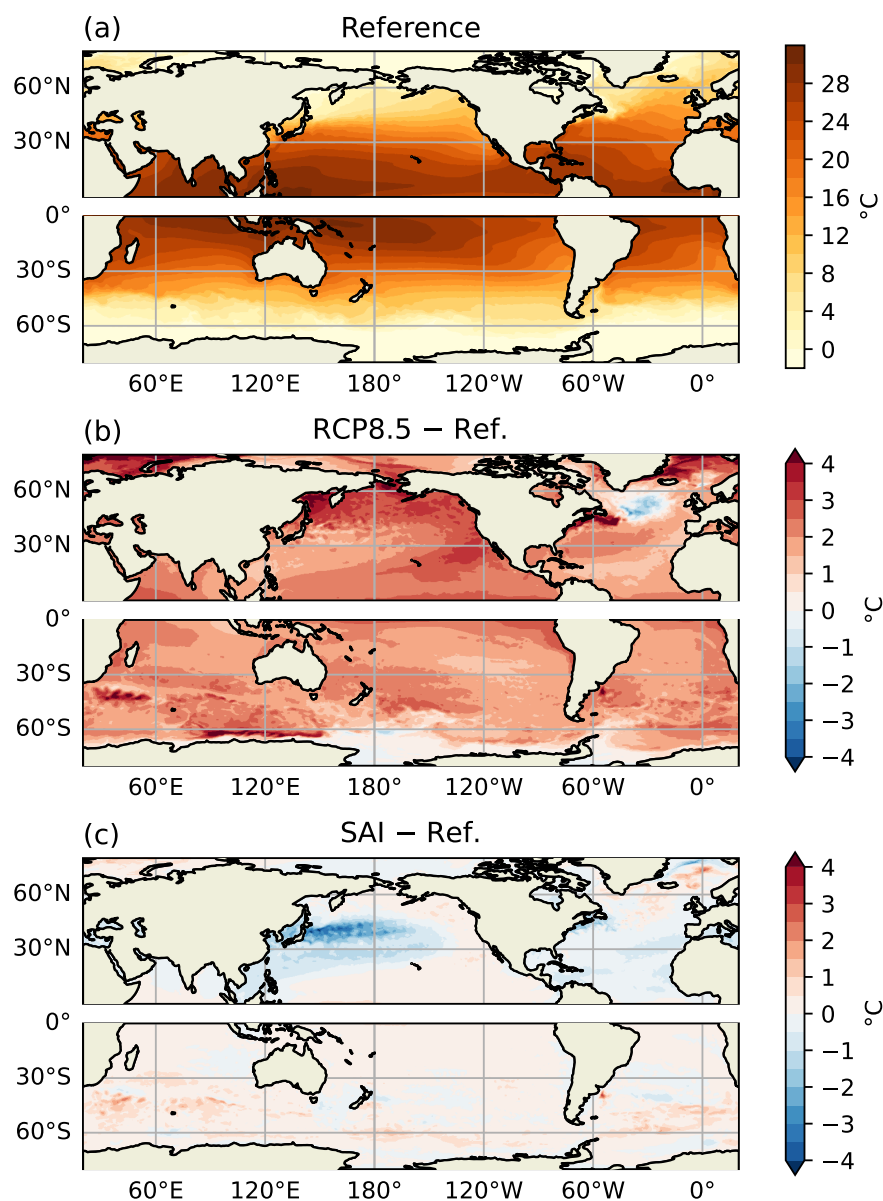


diagnostics: cyclone tracking, bandpass-filtered MSLP variability, and extreme-event analysis. They are driven by a strato-  
spheric polar vortex strengthening that produces a positive NAO in the Atlantic, and SST-driven baroclinicity changes in the  
Pacific. Cyclone counts under SAI recover toward, but do not fully reach, reference levels in both hemispheres, indicating that  
SAI offsets some but not all of the warming-induced decrease. Regarding changes in ETC-associated precipitation and wind  
310 extremes, RCP8.5 increases ETC-associated precipitation exceedance counts in both hemispheres and shifts the 99th-percentile  
and upper-tercile mean per-cyclone precipitation distributions toward much higher values, indicating substantially wetter cy-  
clones. Under SAI, the 99th-percentile and upper-tercile average precipitation rate per cyclone are restored to values close  
to the reference, but ETC-associated exceedance counts fall below reference levels in both hemispheres. For wind, RCP8.5  
and SAI both reduce ETC-associated exceedance counts, with SAI producing a stronger spatial redistribution of extremes.  
315 However, maximum wind-speed distributions show only modest, basin-dependent changes under both scenarios.

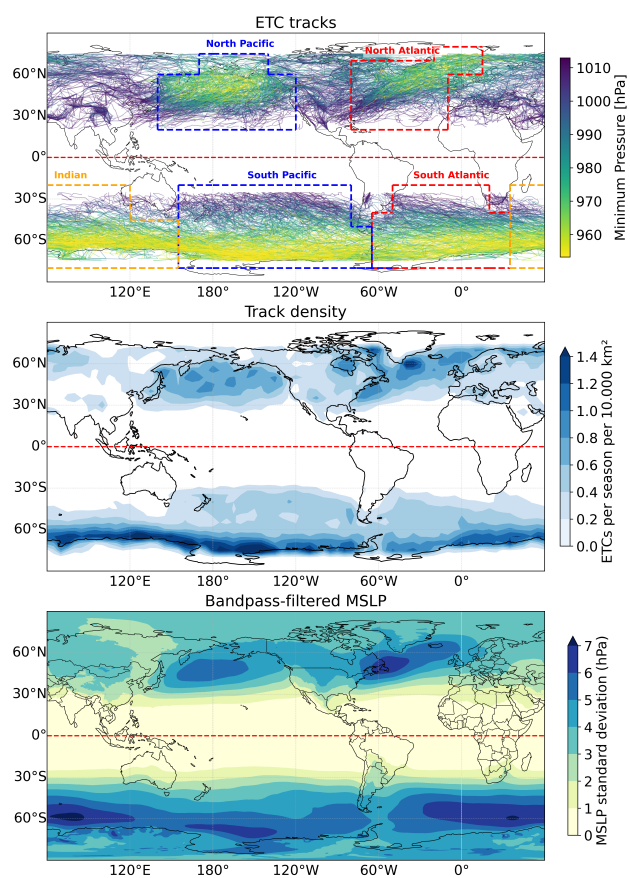
These results demonstrate that SAI does not simply reverse warming-induced changes in extratropical cyclones. Instead, it  
produces new circulation patterns with regionally varying and, in several metrics, overcompensating responses. The asymmetry  
between ocean basins and hemispheres highlights the importance of regional assessments.



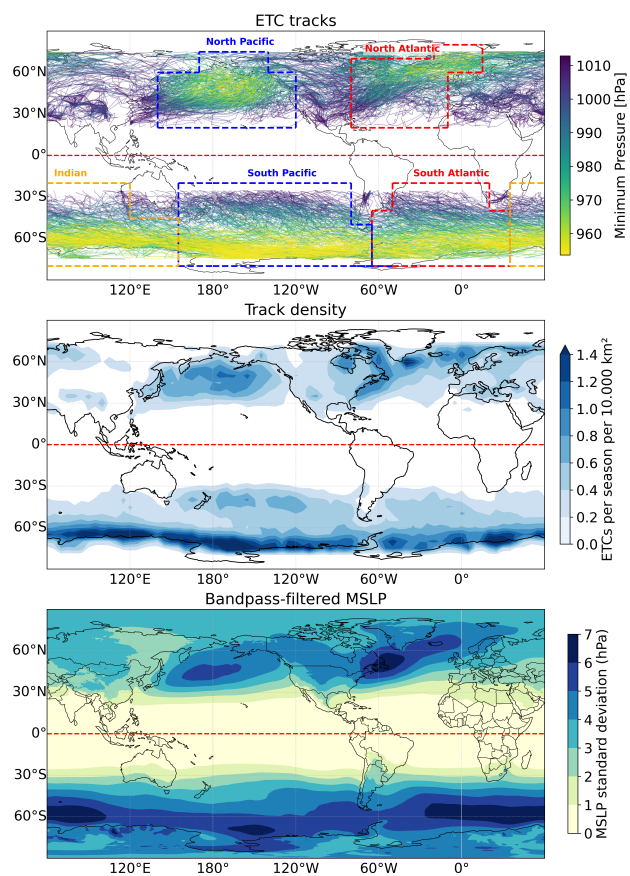
## Appendix A: Additional Figures



**Figure A1.** Seasonal mean SST for (a) the reference scenario (NDJFM in the Northern Hemisphere, MJJAS in the Southern Hemisphere), (b) RCP8.5 minus REF, and (c) SAI minus REF.



**Figure A2.** Same as Figure 3, but for the RCP8.5 scenario.



**Figure A3.** Same as Figure 3, but for the SAI scenario.





320 *Author contributions.* MdN worked on the original draft and editing, validation, formal analysis, methodology, visualization. JdJ worked on methodology, formal analysis and visualization. MB worked on conceptualization, supervision, methodology, original draft, draft review, project administration, funding acquisition. CW worked on conceptualization, supervision, draft review, methodology, project administration and funding acquisition.

*Competing interests.* The contact author has declared that none of the authors has any competing interests.

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### **Code and data availability**

330 The codes and intermediate data files will be made publicly accessible via GitHub and Zenodo on publication of the manuscript.



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