



# Competing roles of anthropogenic aerosols and greenhouse gases in June–August baroclinicity and storm-track trends

Ofer Cohen<sup>1</sup>, Neil Hart<sup>2</sup>, Satoru Okajima<sup>3</sup>, Philip Stier<sup>1</sup>, and Tim Woollings<sup>1</sup>

<sup>1</sup>Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford, United Kingdom.

<sup>2</sup>School of Geography and the Environment, University of Oxford, Oxford, United Kingdom.

<sup>3</sup>Institute of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan.

**Correspondence:** Ofer Cohen (ofer.cohen@reuben.ox.ac.uk)

## Abstract.

Northern Hemisphere summer (June–August) storm tracks have been extensively studied over recent decades, with evidence for weakening trends in parts of the Northern Hemisphere and strengthening trends in the Southern Hemisphere. However, the physical drivers of these trends, and their strong regional variability, are still debated. Here, we investigate recent changes in mid-latitude baroclinicity by analysing trends in Eady Growth Rate and baroclinic mean available potential energy (MAPE) in ERA5 reanalysis data and CMIP6 single-forcing large-ensemble experiments over both the industrial and satellite eras. We further decompose baroclinic MAPE and Eady Growth Rate into their physical components and compare the baroclinicity trends with trends in storm-track intensity. We find that changes in the meridional temperature gradient provide the dominant contribution to recent baroclinicity trends. Significant regional asymmetries are identified between the North Pacific and North Atlantic baroclinicity trends, with the strongest recent weakening occurring over the North Pacific storm-track region. Greenhouse-gas forcing produces a robust positive Southern Hemisphere baroclinicity trend and a mixed weakening response in the Northern Hemisphere, while aerosol perturbations generate substantial regional responses in both hemispheres and partially offset the greenhouse-gas-driven baroclinicity signal. In particular, changes in aerosol emissions during the satellite era are associated with enhanced negative baroclinicity trends over the North Pacific and contribute to the emergence of the greenhouse-gas-driven storm-track response. These results highlight the competing roles of greenhouse gases and aerosols in shaping recent mid-latitude circulation changes, and demonstrate that both forcings must be considered when interpreting historical storm-track trends and projecting their future behaviour.

## 1 Introduction

Storms in the mid-latitudes tend to occur in specific regions termed the storm-tracks (Hoskins and Valdes, 1990; Shaw et al., 2016; Woollings, 2016). These regions include the North Pacific and North Atlantic, as well as the southern hemisphere mid-latitudes (at around  $30 - 60^\circ N$  and  $30 - 60^\circ S$  respectively, Hoskins and Valdes, 1990; Shaw et al., 2016; Shaw, 2019; Kang et al., 2024a). These storm tracks are a result of the existing energy imbalance between the tropics and the polar regions, and they play a crucial role in the transfer of momentum and energy between the two (Lorenz, 1955; Held and Soden, 2006; Harvey et al., 2014; Shaw et al., 2016; Woollings, 2016). Accordingly, a large amount of the variability in weather patterns, and in the



25 frequency and intensity of extreme weather events in the mid-latitudes is attributed to changes in storm tracks, underlining the societal importance of better explaining their behaviour and expected changes (Francis and Vavrus, 2012; Cohen et al., 2014; Shaw et al., 2016).

This crucial importance has spurred a large body of research into storm tracks and their response to anthropogenic forcings (mainly focusing on the impact of anthropogenic warming on their intensity and position, O’Gorman and Schneider, 2008; 30 O’Gorman, 2010; Coumou et al., 2015; Chang et al., 2016). Specifically, previous investigations of storm-track changes focused on:

1. a mechanistic understanding of the governing processes causing changes in storm track behaviour in idealized simulations (O’Gorman and Schneider, 2008; Mbengue and Schneider, 2017a, 2018).
2. a study of recent reanalysis and observational records to identify trends in storm track behaviour (Coumou et al., 2015; 35 Chang et al., 2016; Hersbach et al., 2020; Chemke and Yuval, 2023, 2026).
3. a study of state-of-the-art global circulation models (GCMs), using historical simulations to compare with reanalysis trends and simulations of future climate scenarios to predict future behaviour under different anthropogenic forcings. This allows for the identification of the biases in the models and the differences between them when it comes to representing storm-track behaviour (Harvey et al., 2014; Shaw et al., 2018; Andrews et al., 2020a; Chemke and Yuval, 40 2023, 2026).

These investigations yielded leading hypotheses for the major storm-track responses to anthropogenic warming and their underlying physical causes. In particular, studies have suggested a general weakening of storm-track activity across seasons (Hall et al., 1994), potentially associated with enhanced latent heat transport and a reduced dry static energy flux. Separately, a poleward shift of the storm tracks has been linked to changes in the meridional temperature gradient (Harvey et al., 2014), 45 expansion of the Hadley circulation (Lu et al., 2007), and changes in the vertical temperature structure of the troposphere (Lorenz and DeWeaver, 2007; Rivière, 2011).

In the last decade, the Northern Hemisphere summer (June-August) storm tracks have been extensively studied and debated, suggesting a Northern Hemisphere weakening and a Southern Hemisphere strengthening of June-August storm tracks over the satellite era, and in climate model projections (Coumou et al., 2015). Additionally, differences between the North Atlantic and 50 North Pacific storm tracks were also described, suggesting that different anthropogenic drivers in these regions play a significant role in the observed patterns (Kang et al., 2023; Chemke, 2024; Kang et al., 2024b). For example, regional differences in aerosol emission trends over the last few decades have been suggested as a potential contributing factor for the differences between the behaviours of the North Pacific and North Atlantic storm track trends, but remained relatively understudied (Dong and Sutton, 2021; Dong et al., 2022; Kang et al., 2024b).

55 Simultaneously, baroclinicity is widely recognised as a key energy source for extratropical storms through the conversion of available potential energy into eddy kinetic energy (Lorenz, 1955; Lindzen and Farrell, 1980). However, long-term trends in baroclinicity and their relationship to storm-track changes have received comparatively less attention in previous studies





(Lehmann et al., 2014; Gertler and O’Gorman, 2019). Despite recent advances, it remains unclear how and why baroclinicity has changed in response to anthropogenic forcings, and how this has shaped recent storm track trends, particularly during Northern Hemisphere summer (June–August).

Anthropogenic greenhouse gas and aerosol emissions are expected to influence June–August baroclinicity through different physical mechanisms. Greenhouse-gas warming is generally expected to weaken mid-latitude meridional temperature gradients due to enhanced warming at high latitudes (Mbengue and Schneider, 2013; Coumou et al., 2015; Mbengue and Schneider, 2017a), further intensified by a warming trend in sea surface temperatures (SSTs) in the North Pacific and North Atlantic dominated by a negative trend in the mixed layer depth in these regions (Chen and Wang, 2015; Alexander et al., 2018; Jo et al., 2022). Anthropogenic aerosol emissions, by contrast, are much more regionally variable, and are thus expected to exert a regionally variable radiative forcing response through both aerosol-radiation and aerosol-cloud interactions, leading to spatially varying changes in temperature gradients and atmospheric circulation (Zelinka et al., 2020; Smith et al., 2020). The significant changes in aerosol emissions during the late twentieth century, with declining emissions over Europe and North America and continued increases over parts of Asia, provide an additional source of temporal and spatial variability that may contribute to recent changes in June–August baroclinicity and storm tracks. However, the question of the relative importance of greenhouse gases and aerosols in driving these circulation changes remains underexplored.

Therefore, the primary objectives of this study are to (i) quantify the recent trends in June–August baroclinicity in both hemispheres, (ii) identify the dominant physical contributors to these trends, (iii) assess the relative contributions of different anthropogenic forcings (with a specific focus on greenhouse gases and anthropogenic aerosols) using single-forcing experiments, and (iv) examine how the resulting baroclinicity changes relate to observed and simulated storm-track trends. To achieve these objectives, we analyse baroclinic mean available potential energy (MAPE) and maximum Eady Growth Rate (Lindzen and Farrell, 1980; Hoskins and Valdes, 1990), while decomposing them according their leading physical contributors (Mbengue and Schneider, 2017a; Mbengue et al., 2019). We further use CMIP6 single-forcing experiments to investigate the baroclinicity response to specific anthropogenic forcings across the industrial and satellite eras and relate these changes to trends in storm activity using Eddy Kinetic Energy (EKE) and sea level pressure variance (SLP variance) (Gillett et al., 2016; Smith et al., 2022).

## 2 Data and methods

### 2.1 Data

To investigate recent changes in baroclinicity patterns, we used ERA5 reanalysis data (Hersbach et al., 2020) as a baseline to identify historical baroclinicity trends. To study the physical drivers at the root of the observed trends, we incorporate four large ensemble single forcing experiments using CMIP6 models. Additionally, to distinguish between the competing physical processes, we use the different CMIP6 single forcing experiments and assess the anthropogenic causes for the historical baroclinicity and storm-tracks trends we report.



### 90 2.1.1 ERA5 reanalysis

To analyse the vertical structure of the atmosphere and its impact on the baroclinicity trends, we use the ERA5 global reanalysis (Hersbach et al., 2020) data from 1979 to 2024 (satellite era). ERA5 data has a horizontal resolution of  $0.25^\circ \times 0.25^\circ$ , and 37 vertical levels in pressure coordinates spanning from 1000hPa to 1hPa, allowing the study of the entire troposphere (Hoffmann and Spang, 2022). ERA5 data has been widely used as a reference in previous investigations of storm track trends and is thus  
 95 considered a reliable source for the historical changes since the onset of the satellite era (Chang et al., 2016; Chemke and Coumou, 2024; Chemke and Yuval, 2026).

### 2.1.2 CMIP6 single forcing experiments

To distinguish between the physical drivers contributing to the observed baroclinicity and storm-track trends, we use four CMIP6 single-forcing large ensemble datasets from the Detection and Attribution Model Intercomparison Project (DAMIP,  
 100 Gillett et al., 2016). Specifically, we analyze simulations from the HadGEM3-GC31-LL (Ridley et al., 2018; Andrews et al., 2020b), CanESM5 (Swart et al., 2019), CNRM-CM6-1 (Voldoire et al., 2019), and IPSL-CM6A-LR (Boucher et al., 2020) models. Some of these experiments are part of the Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP; Smith et al., 2022). These specific models were chosen because each model provides at least  $\sim 10$  ensemble members for the single-forcing experiments considered here, allowing an estimate of the range of internal variability. Sampling internal variability  
 105 is crucial for robust assessment of forced baroclinicity signals. We primarily analyse four experiments: aerosol-only forcing (hist-aer), greenhouse-gas-only forcing (hist-GHG), natural-only forcing (hist-nat; excluding anthropogenic influences), and the historical simulation, which includes all forcings (both natural and anthropogenic). To assess the role of stratospheric ozone, we additionally use the ozone-only forcing experiment (hist-totalO3), available for the HadGEM3-GC31-LL model.

In the hist-aer experiments, the simulated response includes both aerosol-radiation interactions, associated with aerosol  
 110 scattering and absorption, and aerosol-cloud interactions. The relative contribution of these processes varies among CMIP6 models owing to differences in aerosol schemes, cloud microphysics, and aerosol parameterisations (Smith et al., 2020; Zelinka et al., 2020). To characterise the aerosol perturbations experienced by each model, we analyse trends in aerosol optical depth (AOD) and aerosol absorption optical depth (AAOD). To also study the relative contribution of absorbing and scattering aerosols in the different models, we also calculate the column-mean single scattering albedo (SSA), defined as

$$115 \quad SSA = 1 - \frac{AAOD}{AOD} \quad (1)$$

which quantifies the relative influence of scattering to the total (scattering + absorption) aerosol extinction. While these diagnostics do not separately quantify aerosol-radiation interactions and aerosol-cloud interactions, they provide insight into differences in the total aerosol burden, the absorbing aerosol component and the relative importance of scattering and absorbing aerosols across the participating models. AOD is also widely used as a proxy for cloud condensation nuclei (CCN), despite  
 120 documented limitations (Stier, 2016). Here we use AOD as a simple proxy to quantify the aerosol perturbation in terms of extinction and CCN, while AAOD provides additional insights into aerosol perturbations to atmospheric absorption and thereby



diabatic heating. Additional research is needed to decouple the specific contribution of the aerosol-cloud and aerosol-radiation impacts on the baroclinicity and storm-track trends.

All experiments are analysed over the entire industrial period (1850–2014), with a specific focus on the satellite era (1979–2014). Monthly mean model output is used for the calculation of all diagnostics, and seasonal means are computed as weighted averages of monthly values. The data was accessed through the CEDA archive via the UK’s JASMIN cluster.

## 2.2 Calculating Baroclinicity

To investigate the recent observed storm tracks trends, and better understand their underlying physics, we calculate the seasonally averaged baroclinicity using both the Eady Growth Rate (Lindzen and Farrell, 1980; Hoskins and Valdes, 1990) and the baroclinic MAPE metrics (Lorenz, 1955; Mbengue and Schneider, 2017a, b; Mbengue et al., 2019). Additionally, we also calculate the decomposition of Eady Growth Rate and baroclinic MAPE according to their leading physical contributors to better study the underlying physical forces at play (Mbengue et al., 2019).

### 2.2.1 Eady Growth Rate

For a first approximation of the baroclinicity in the troposphere, we calculate the Eady Growth Rate, following the method presented in Hoskins and Valdes (1990) and Lindzen and Farrell (1980). We define the maximum Eady growth rate as:

$$\sigma \approx 0.31 \cdot \frac{|f|}{N} \cdot \left| \frac{\partial \mathbf{u}}{\partial z} \right|, \quad (2)$$

where  $f$  is the Coriolis parameter,  $N$  is the Brunt-Väisälä frequency, and  $\mathbf{u}$  is the zonal wind vector. According to convention, we calculated Eady Growth Rate between 850 – 500hPa, keeping our analysis consistent with previous studies (Lindzen and Farrell, 1980; Hoskins and Valdes, 1990).

To investigate the causes of Eady growth rate trends, we decompose  $\sigma$  into the two dominant factors:

$$\sigma = 0.31 \cdot |f| \cdot Q \cdot S, \quad (3)$$

where,  $Q \equiv |\partial_z \mathbf{u}|$ , and  $S \equiv N^{-1}$ . This form allows us to attribute the trend in  $\sigma$  to changes in vertical zonal wind shear through  $Q$ , and changes in static stability through  $S$ . A first-order Taylor expansion gives

$$\delta \sigma \approx 0.31 \cdot |f| \cdot (S \delta Q + Q \delta S), \quad (4)$$

neglecting nonlinear interaction terms.

Because  $|\partial_z \mathbf{u}|$  is closely linked to the thermal-wind relationship, an alternative physical interpretation can be obtained by studying the connection between the zonal wind shear and the meridional temperature gradient. In practice, however, we use the direct decomposition in terms of  $|\partial_z \mathbf{u}|$ , and  $N^{-1}$  because it is robust for both ERA5 and CMIP6 data and does not rely on additional assumptions. Monthly  $\sigma$  values were calculated using monthly mean fields, and seasonal mean  $\sigma$  values were calculated using the seasonal mean weighted winds, calculated from the monthly mean wind data. In reanalysis data, Eady Growth Rate was calculated using the 37 standard atmospheric levels, while in the CMIP6 data Eady Growth Rate was calculated on the native model levels.



### 2.2.2 Baroclinic MAPE

To improve our understanding of the baroclinicity trends and their causes, we calculate the baroclinic mean available potential  
 155 energy (baroclinic MAPE) and decompose it according to its leading physical contributors. Contrary to Eady Growth Rate,  
 baroclinic MAPE is proportional to the squared meridional temperature gradient and the inverse static stability and depth of  
 the troposphere. Following Mbengue et al. (2019) and Mbengue and Schneider (2017a) we define baroclinic MAPE as:

$$MAPE = \frac{p_0 L_z^2}{24 \Gamma_d} \cdot \left(1 - \frac{p_t}{p_s}\right) \langle \partial_y T \rangle^2 \langle -\kappa (p \partial_p \theta)^{-1} \rangle \quad (5)$$

where  $p_0$  is the reference pressure defined as  $1000hPa$ ,  $L_z = 2000km$  is a constant baroclinic zone width,  $\Gamma_d$  is the dry  
 160 adiabatic lapse rate,  $p_s$  is the surface pressure,  $p_t$  is the tropopause pressure calculated using the WMO criteria (Reichler et al.,  
 2003),  $T$  is the vertical temperature profile,  $\theta$  is the potential temperature and  $\kappa$  is the adiabatic exponent. The angled brackets  
 indicate a vertical mean over the approximate depth of the troposphere  $\langle \cdot \rangle = \int_{p_t}^{p_s} (\cdot) dp / (p_s - p_t)$ . To ensure the stability of  
 the analysis, we defined the troposphere for the vertical mean calculations in the meridional temperature gradient and the  
 inverse stability as the atmospheric layer between  $800hPa$  and  $200hPa$  (contrary to the focus on the lower troposphere in  
 165 Eady Growth Rate). To assess the robustness of the results, we also calculated the vertical means in the calculation for the  
 entire calculated tropospheric depth (between  $p_s$  and  $p_t$ ) and for the lower troposphere (between  $850$  and  $500hPa$ ), yielding  
 similar but less stable results (mainly due to the influence of processes within the boundary layer creating large static stability  
 anomalies, not shown). To calculate the tropopause pressure ( $p_t$ ) the vertical geopotential height, temperature and pressure  
 fields were interpolated into a  $500m$  resolution to improve its precision. All other means were calculated on the model's native  
 170 vertical levels.

Following Mbengue et al. (2019), we decompose MAPE into the pressure depth of the troposphere ( $1 - \frac{p_t}{p_s}$ ), the squared mean  
 meridional temperature gradient ( $\langle \partial_y T \rangle^2$ ), and the inverse of the static stability of the troposphere ( $\langle -\kappa (p \partial_p \theta)^{-1} \rangle$ ). Using this  
 decomposition, we can investigate the physical processes causing the baroclinicity and storm-tracks trends in recent decades.  
 Using the decomposition framework, we can approximate the portion of the baroclinic MAPE trends that is attributed to trends  
 175 in each of its decomposed parts by adding the contributed trends from each parameter. If we follow Mbengue et al. (2019),  
 and define  $G \equiv \langle \partial_y T \rangle^2$ ,  $S \equiv \langle -\kappa (p \partial_p \theta)^{-1} \rangle$  and  $H \equiv 1 - \frac{p_t}{p_s}$ , the approximate (neglecting non-linear interactions) baroclinic  
 MAPE trend becomes:

$$\delta MAPE \approx GS\delta H + GH\delta S + SH\delta G \quad (6)$$

according to a first order Taylor expansion, with  $\delta$  defined as the linear trend. This allows for the assessment of the contribution  
 180 of each factor to the calculated baroclinicity trends.

To investigate the seasonal mean baroclinicity state, we calculated baroclinic MAPE and its decomposition for the seasonal  
 mean (DJF, MAM, JJA, and SON means) temperature and pressure (calculated from the monthly mean original data). In this  
 analysis, we focus specifically on the seasonal trends that occur during Northern Hemisphere summer and Southern Hemisphere  
 winter months (June–August), and neglect the monthly variability within the seasonal mean.



## 185 2.3 Calculating storm-track intensity

To compare the baroclinicity trends to shifts in storm-track behaviour, we also calculated the storm track intensity for the single forcing model experiments. Using the daily output from the model experiments, we calculated a proxy for eddy kinetic energy (EKE) and the variance of sea level pressure (SLP variance).

### 2.3.1 Eddy Kinetic Energy

190 Daily transient eddy kinetic energy (EKE) was calculated from daily wind fields on pressure levels for the CMIP6 single forcing simulations. To isolate transient variability associated with storm-track activity, an 8-day running mean was used to define the slowly evolving flow. Daily wind anomalies were then defined as deviations from this 8-day running mean:

$$u'(t) = u(t) - \bar{u}_{8day}; v'(t) = v(t) - \bar{v}_{8day} \quad (7)$$

when  $\bar{u}_{8day}$  and  $\bar{v}_{8day}$  represent the 8-day running mean field. A proxy for the horizontal Eddy kinetic energy was then  
 195 calculated as

$$EKE_{vertical} = \frac{1}{2} \cdot (u'^2 + v'^2) \quad (8)$$

yielding a measure of transient atmospheric kinetic energy associated with synoptic variability. Seasonal means of EKE were computed from the daily EKE fields. Vertically integrated EKE was calculated over the 800–200 hPa layer according to

$$EKE = \frac{1}{g} \cdot \int_{800hPa}^{200hPa} EKE_{vertical} dp \quad (9)$$

200 where  $g$  is gravitational acceleration, and  $p$  is pressure. This vertically integrated quantity provides a bulk measure of tropospheric storm activity and was used as a storm-track kinetic energy metric in our analysis.

### 2.3.2 Sea level pressure variance

Seasonal storm-track variability was also diagnosed using the variance of high-pass-filtered daily mean sea-level pressure (SLP). Daily SLP fields were filtered to isolate synoptic-scale variability associated with transient midlatitude cyclones by  
 205 removing variability on timescales longer than approximately one week. This was achieved by subtracting an 8-day running mean from the daily SLP field:

$$SLP'(t) = SLP(t) - \overline{SLP}_{8day}(t) \quad (10)$$

where  $\overline{SLP}_{8day}$  denotes the centered 8-day running mean SLP. The resulting high-pass-filtered anomalies represent transient synoptic pressure disturbances associated with storm activity. Seasonal storm-track intensity was then quantified as the variance  
 210 of these filtered anomalies within each season:

$$\sigma_{SLP}^2 = Var(SLP'(t)) \quad (11)$$



Large values of  $\sigma_{SLP}^2$  indicate enhanced synoptic-scale pressure variability in the region, and therefore increased storm-track activity. Seasonal variances were calculated directly from the daily anomalies for each grid point and season.

## 2.4 Calculating temporal trends

215 To identify the impact of anthropogenic forcings on the storm tracks and mid-latitude baroclinicity, we calculated the temporal trends for the baroclinicity and storm-track measurements over the satellite era (1979–2024) in ERA5 and the industrial (1850–2014) and satellite (1979–2014) eras in the single-forcing model experiments. To calculate the temporal baroclinicity trends for each season, the seasonal mean baroclinicity fields were first calculated using the mean temperature, wind, pressure, and geopotential fields. Then, the mean, and the anomaly from it, were calculated, and the anomaly was used to calculate the linear  
 220 trend and its significance at each location. The significance of the trend was calculated by assuming a null hypothesis of there being no meaningful trend ( $trend = 0$ ), and using the Student's t-test to show that the trend is significantly different from 0, above the 95% confidence level. For the CMIP6 single forcing large ensemble model data, we calculated the trend for each one of the individual members within each experiment, and assumed the trend is significant if more than 80% of the members agreed on its sign.

## 225 3 Results

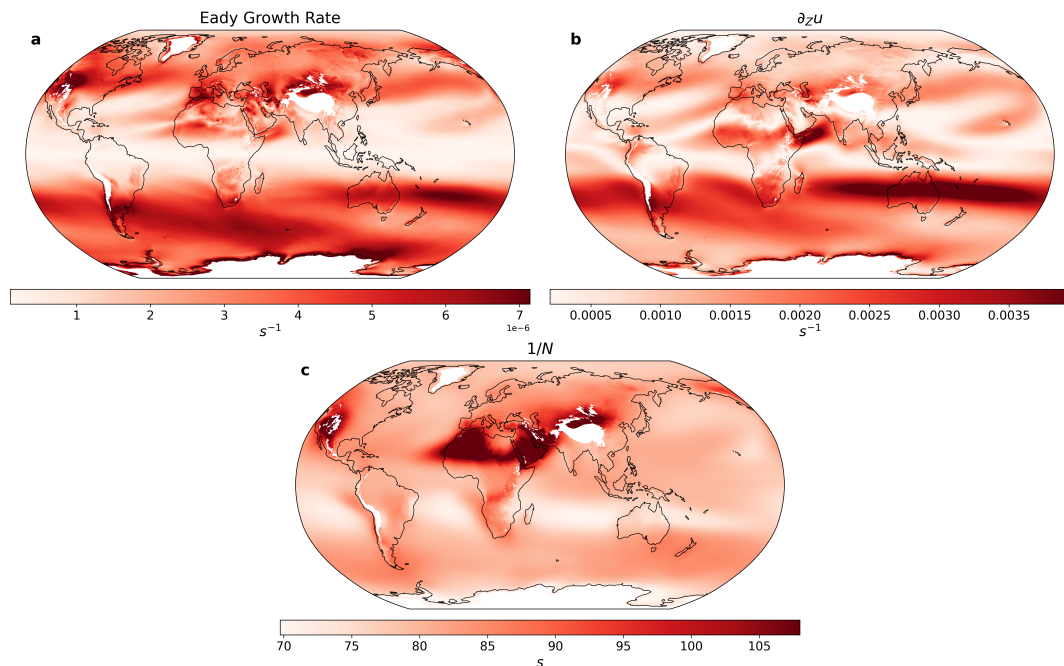
We begin by investigating the observed baroclinicity trends in June–August ERA5 since 1979 to create a baseline for the historical trends. This is followed by an investigation of the baroclinicity and storm track intensity trends in the different single-forcing model experiments, to better isolate the drivers and physical processes affecting the observed historical trends.

### 3.1 Satellite era trends using ERA5 reanalysis

230 Focusing on Northern Hemisphere summer (June–August), we analyse the trends in Eady Growth Rate and baroclinic MAPE and their decomposition over the satellite era in ERA5 (1979–2024, Figures 1 and 2). Looking at the seasonal mean baroclinicity maps, we see that the Eady Growth Rate and baroclinic MAPE exhibit high amplitudes in the extratropical southern and northern hemispheres (Figure 1a and 2a). Notably, the mean baroclinicity maps using Eady Growth Rate and baroclinic MAPE depict a high degree of similarity, and a spatial correlation of  $R = 0.72$  (Table 1). Additionally, following the claim presented  
 235 in Mbengue and Schneider (2013) that Eady Growth Rate behaves similarly to the square root of baroclinic MAPE, we find that the spatial correlation with this square root of MAPE is  $R = 0.84$  (Table 1).

In both Eady Growth Rate and baroclinic MAPE, we also find high baroclinicity values over land areas in the Northern Hemisphere, which may be the result of warm land surface conditions in the summer months that cause more thermal instability in the lower troposphere, as well as land and mountainous regions that force large meridional temperature gradients, increasing  
 240 the baroclinicity measured by both Eady Growth Rate and baroclinic MAPE (Figures 1 and 2).

Assessing the summer mean maps for the decomposition of baroclinic MAPE and Eady Growth Rate, we notice that the mean squared meridional temperature gradients and the zonal wind shear very closely resemble the mean summer baroclinic



**Figure 1.** June-August mean maps for Eady Growth rate (a),  $\partial_z u$  (b),  $N^{-1}$  (c). Means were calculated using ERA5 reanalysis data for the period of 1979–2024. Regions with surface pressure below 800hPa were excluded from analysis.

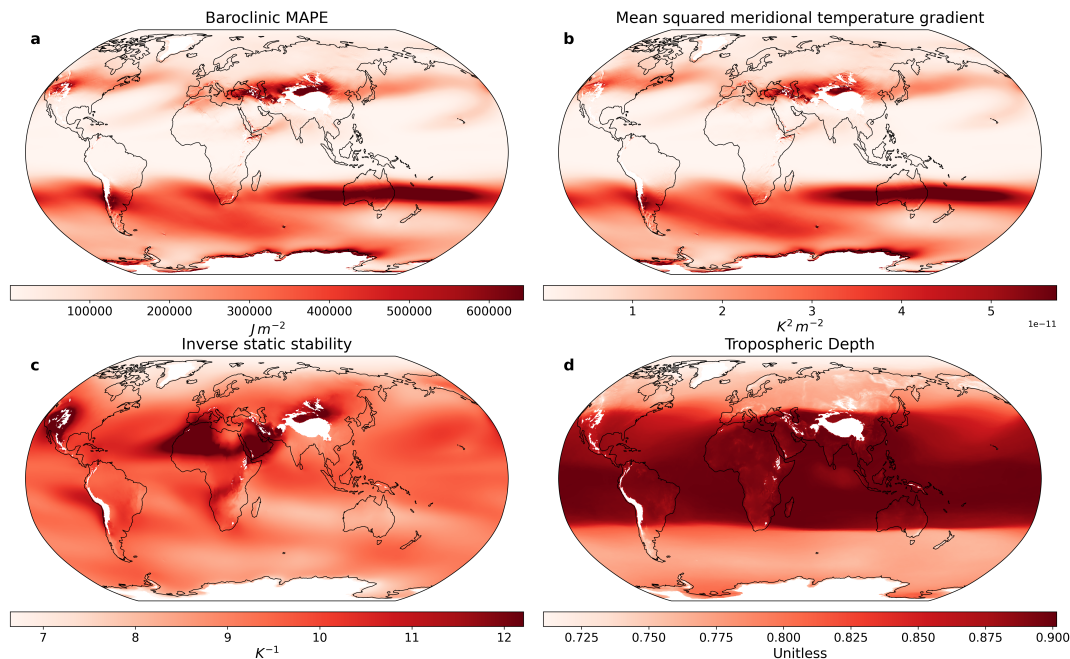
MAPE and Eady Growth Rate maps and have significant spatial correlations with them (see Table 1), indicating their large primary influence on baroclinicity (Figure 2b).

245 The inverse of the static stability and the tropospheric depth show high mean values in the tropics, presenting the influence of the high surface temperatures on the near-surface stability (as is evident by the unstable conditions seen over desert areas such as the Sahara, Figures 2c and 1b), as well as the extent and edges of the Hadley circulation separating the tropics and the mid latitudes (Figure 2d). In the summer mean map of tropospheric depth, we clearly see the slight seasonal shift of the Hadley circulation to the north during Northern Hemisphere summer, as is expected with the shift in the maximum radiation  
 250 and temperature bands towards the hemisphere experiencing summer conditions (Figure 2d).

Figures 3 and 4 depict the trend maps of Eady Growth Rate and baroclinic MAPE and their decomposition over the 1979-2024 period from ERA5 reanalysis data. The trends in the original components used to calculate baroclinic MAPE (the meridional temperature gradient, inverse of the static stability and tropospheric depth) can be seen in Figure A1. Analysing these trends, we find an overall good agreement between the trend patterns of Eady Growth Rate and baroclinic MAPE (Figures 3a and 4a), with a spatial correlation of  $R = 0.56$  between them (Table 1).  
 255

Analysing the trend patterns, we find a significant negative trend in Northern Hemisphere Eady Growth Rate and baroclinic MAPE (seen in the zonal mean trends in Figure A1a and b), as well as positive significant trends in parts of the Southern Hemisphere mid-latitudes (Figures A1a, 3 and 4a). These mid-latitude trends are clearer and more significant in the Southern





**Figure 2.** June-August mean maps for baroclinic MAPE (a), squared meridional temperature gradient (b), inverse static stability (c), and tropospheric depth (d). Means were calculated using ERA5 reanalysis data for the period of 1979–2024. Regions with surface pressure below 800hPa were excluded from analysis.

Hemisphere, primarily at latitudes of about  $30^{\circ}\text{S}$ , from the South-Eastern Pacific to the Southern Atlantic, on the edge of the Hadley cell (Figures 3 and 4). Another positive trend band is also evident further south, at about  $60^{\circ}\text{S}$ , and a general poleward shift is seen over most of the South Pacific (Figures 3a and 4a).

The Northern Hemisphere zonal mean trends also tend to be more significant for Eady Growth Rate, compared with baroclinic MAPE, primarily at high latitudes (Figure A1a and b). In the North Atlantic, a region studied extensively for its influence on European weather systems, we find contrasting regional trends over the satellite era. In both Eady Growth Rate and baroclinic MAPE, there is an evident positive observed baroclinicity trend in the north-eastern Atlantic and over western Europe and a negative trend over the north-western part and eastern North America (Figure 3a and 4a). Additionally, a negative trend is seen in Eady Growth Rate and baroclinic MAPE over Iceland and the Mediterranean, while a positive trend is seen over north-western Europe. This baroclinicity trend pattern is similar in nature to the Summer North Atlantic Oscillation (SNAO) pattern and its suggested influence on summer North Atlantic storm-track and baroclinicity conditions in the region (Folland et al., 2009; Dong et al., 2013). Meanwhile, in the North Pacific, a general negative baroclinicity trend is observed in baroclinic MAPE and Eady Growth Rate, in agreement with the proposed mechanisms from previous studies (Figure 3a and 4a, Coumou et al., 2015; Mbengue and Schneider, 2017a; Chemke and Yuval, 2023). This contrast between the North Atlantic and North Pacific basins suggests that different processes or forcings contribute to the observed regional baroclinicity trends.



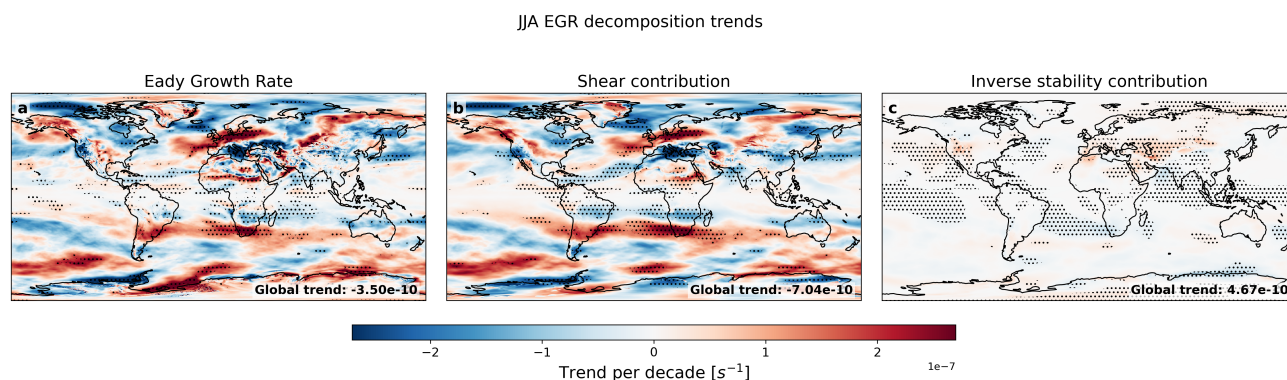
|                          | Eady Growth Rate | $\partial_z u$ | $N^{-1}$ | baroclinic MAPE | $\sqrt{\text{MAPE}}$ | squared temp. gradient | inverse static stability | tropospheric depth |
|--------------------------|------------------|----------------|----------|-----------------|----------------------|------------------------|--------------------------|--------------------|
| Eady Growth Rate         | -                | 0.68           | 0.07     | 0.72            | 0.84                 | 0.68                   | -0.19                    | -0.51              |
| $\partial_z u$           | 0.67             | -              | -0.15    | 0.64            | 0.74                 | 0.56                   | -0.15                    | 0.04               |
| $N^{-1}$                 | -0.12            | -0.15          | -        | -0.07           | -0.04                | -0.15                  | 0.77                     | 0.10               |
| baroclinic MAPE          | 0.56             | 0.61           | -0.10    | -               | 0.92                 | 0.97                   | -0.17                    | -0.21              |
| $\sqrt{\text{MAPE}}$     | 0.64             | 0.74           | -0.13    | 0.87            | -                    | 0.87                   | -0.19                    | -0.32              |
| squared temp. gradient   | 0.57             | 0.59           | -0.15    | 0.94            | 0.82                 | -                      | -0.26                    | -0.27              |
| inverse static stability | -0.17            | -0.16          | 0.49     | -0.16           | -0.13                | -0.23                  | -                        | 0.49               |
| tropospheric depth       | 0.05             | 0.03           | -0.01    | 0.17            | 0.11                 | 0.07                   | -0.03                    | -                  |

**Table 1.** Area weighted spatial correlations between June–August mean (above diagonal) and trend (below diagonal) maps of Eady Growth Rate,  $\partial_z u$ ,  $N^{-1}$ , baroclinic MAPE, the square root of baroclinic MAPE, mean squared meridional temperature gradient, inverse static stability and tropospheric depth.

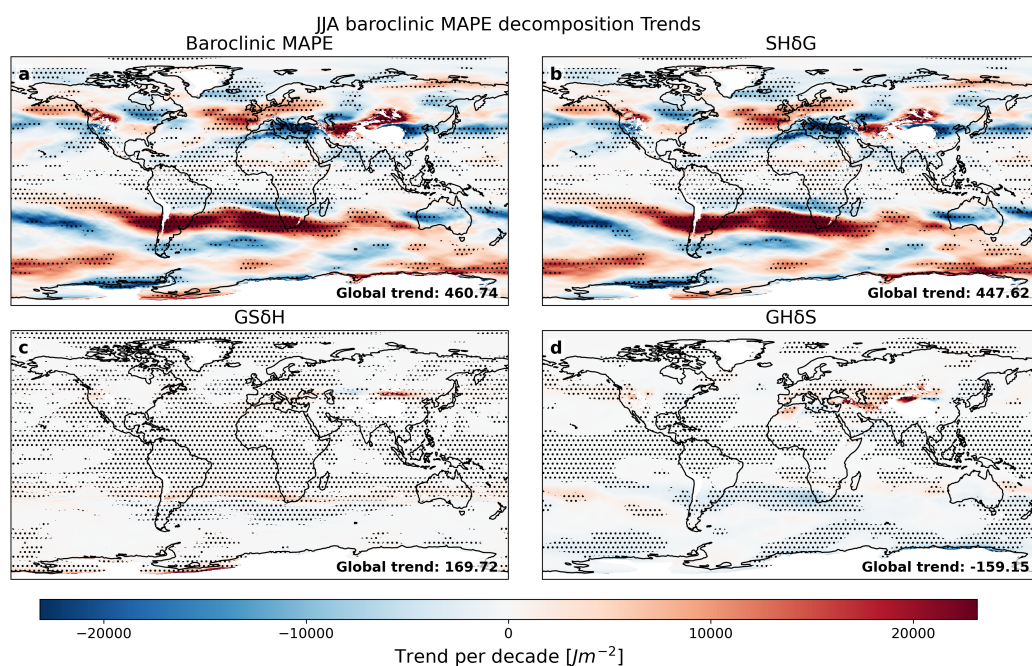
Strong negative baroclinicity trends over the Mediterranean, as well as positive trends over land areas in South Asia and the Himalayas (and other mountainous regions around the world) further reinforce that regional rather than hemispheric warming patterns shift local meridional temperature gradients, leading to major influence on the regional baroclinicity conditions and trends, specifically in mountainous and very topographically heterogeneous regions (Figure 3a and 4a). This pattern of a decrease in the baroclinicity over the Mediterranean, an increase over central Asia and a decrease over the Tibetan Plateau is also consistent with the summer Eurasian jet trends identified by Dong et al. (2022).

For both the Eady Growth Rate and baroclinic MAPE metrics we find that their trends most closely resemble the component due to zonal wind shear / mean squared meridional temperature gradient (Figures 3b, 4b and A1c). Accordingly, the spatial correlation between the trends in the zonal wind shear and those in Eady Growth Rate and the trends in squared meridional temperature gradient and those in baroclinic MAPE are significant, with  $R = 0.67$  and  $R = 0.94$  respectively (Table 1). This is in agreement with the connection between the wind shear and the meridional temperature gradients, and with previous studies suggesting that the decrease in the meridional temperature gradient, caused by anthropogenic forcings, is a major driver of the observed trends in June–August mid-latitude storm-tracks in the Northern Hemisphere (Coumou et al., 2015; Mbengue and Schneider, 2017a; Chemke and Yuval, 2023; Dong et al., 2022; Kang et al., 2023).

While these trends have often been linked to polar amplification, there is considerable regional structure in the trends, which is likely not explained solely by Arctic amplification. Observing the spatial trends in inverse static stability and the decompositions of baroclinic MAPE ( $GH\delta S$ ) and Eady Growth Rate according to it, we find that the tropical static stability experiences a negative trend during northern-hemisphere summer since 1979, excluding the warm desert regions where continued warming



**Figure 3.** June-August trend map for Eady Growth Rate and its decomposition. Trends were calculated using ERA5 reanalysis data from 1979 to 2024. Stippling indicates a significant trend above the 95% confidence bounds using the Student's t-test method. Regions where the surface pressure is lower than 800hPa were excluded. For reference, the global mean trends are shown in the bottom right of each panel.



**Figure 4.** June-August trend map for baroclinic MAPE and its decomposition. Trends were calculated using ERA5 reanalysis data from 1979 to 2024. Stippling indicates a significant trend above the 95% confidence bounds using the Student's t-test method. Regions where the surface pressure is lower than 800hPa were excluded. For reference, the global mean trends are shown in the bottom right of each panel.



is expected to create more unstable conditions in the lower troposphere (Figure A1d). This change, however, seems to have only a minimal effect on the Eady Growth Rate and baroclinic MAPE trends in the storm track regions, as seen in Figures 3c and 4c.

295 The trends seen in tropospheric depth show a general increase in the depth of the troposphere and the height of the tropopause since 1979, as expected with anthropogenic global warming causing the deepening of the tropospheric air columns and the expansion of the Hadley cell (Figure A1e). We also find latitudinal bands of high positive trends in the tropospheric depth on the edges of the Hadley cell, depicting its expanding nature caused by anthropogenic warming (Figure A1e, Reichler et al., 2003; Adam et al., 2014; Mbengue and Schneider, 2018; Kang et al., 2025). These tropospheric depth trends seem to have a  
 300 minor impact on the trends in baroclinic MAPE, compared to the influence held by the meridional temperature gradient (Figure 4c).

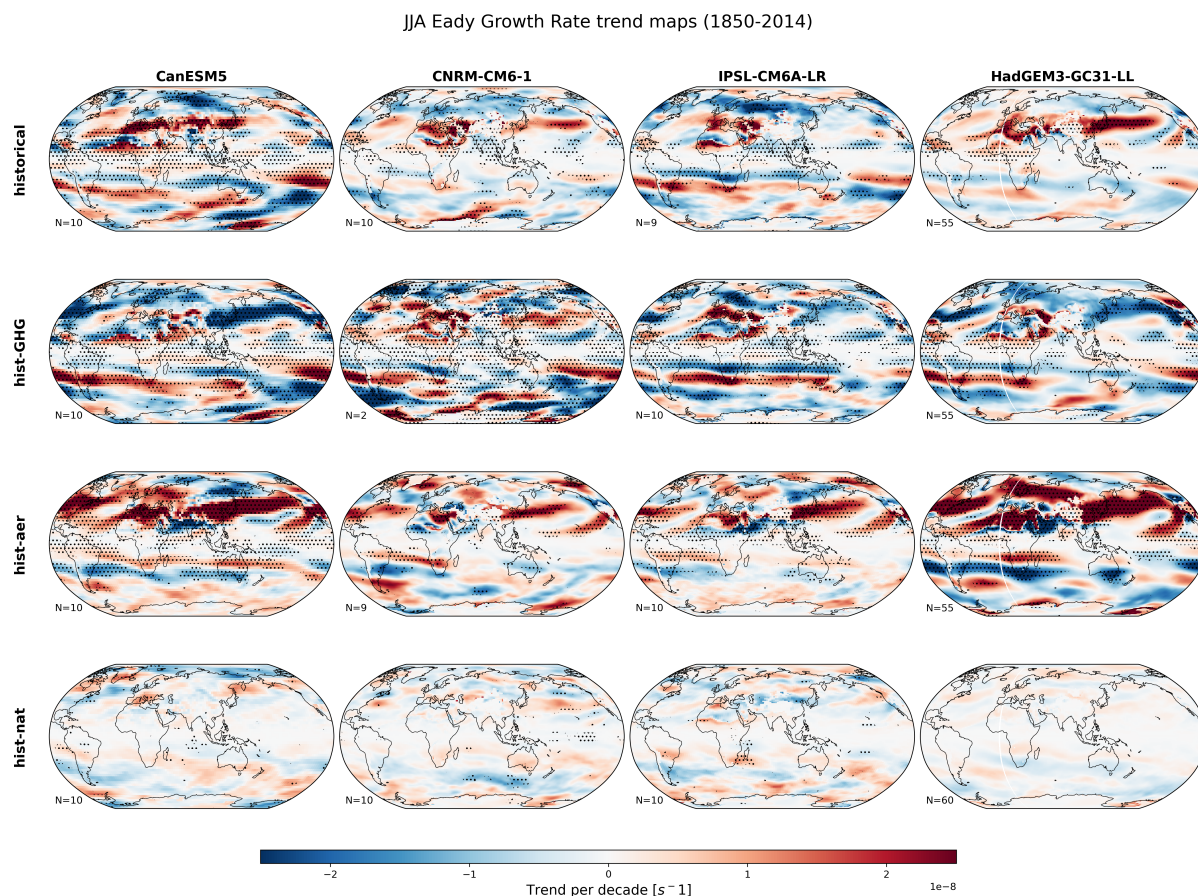
### 3.2 Single-forcing experiments

To investigate the mechanisms underlying the observed June–August baroclinicity and storm track trends, we analyse simulations from four CMIP6 single-forcing ensembles, for the historical, hist-GHG, hist-aer and hist-nat experiments. Seasonal  
 305 trends in baroclinic MAPE and Eady Growth Rate were calculated for both the industrial (1850–2014) and satellite-era (1979–2014) periods. Following the ERA5 reanalysis trends presented in the previous subsection, we focus on June–August (JJA) trends in the Northern and Southern Hemisphere mid-latitudes ( $30^{\circ} - 60^{\circ}$  in each hemisphere), encompassing the storm-track regions. In addition, because ERA5 exhibited contrasting baroclinicity behaviour between the North Atlantic and North Pacific sectors, regional mean trends in Eady Growth Rate and baroclinic MAPE are additionally evaluated over the North Atlantic  
 310 ( $30^{\circ} - 60^{\circ}\text{N}$ ,  $280^{\circ} - 350^{\circ}\text{E}$ ) and North Pacific ( $30^{\circ} - 60^{\circ}\text{N}$ ,  $120^{\circ} - 240^{\circ}\text{E}$ ) storm-track regions (Appendix C).

Across both baroclinicity metrics, all simulations show distinct trends between the full post-industrial period versus the satellite-era. This difference is most pronounced for the Northern Hemisphere. For the satellite-era ERA5 period all models generally reproduce the broad spatial characteristics of the ERA5 summer baroclinicity trends and mean patterns, despite substantial regional spread (Figures 5, 6, 7 and 8, mean maps not shown). Comparable trend structures are obtained using  
 315 both Eady Growth Rate and baroclinic MAPE, although the Eady Growth Rate trend maps exhibit greater small-scale spatial variability, especially at high latitudes. Baroclinic MAPE, however, highlights more coherent trends towards the subtropics. To express the connection between the baroclinicity and the storm-track trends, we also calculated the trends in SLP variance (Figures 14 and 15) and EKE (Figures E1 and E2) for the two periods. Additionally, to provide an initial intuition for the cause of the different trend patterns across the different models we also study the trends in the aerosol optical depth (AOD), the  
 320 aerosol absorption optical depth (AAOD), and the single scattering albedo (SSA) at the 550nm wavelength, and in sea surface temperature (SST) across the models for the two periods (Figures 9, 10, 11, 12 and 13 respectively).

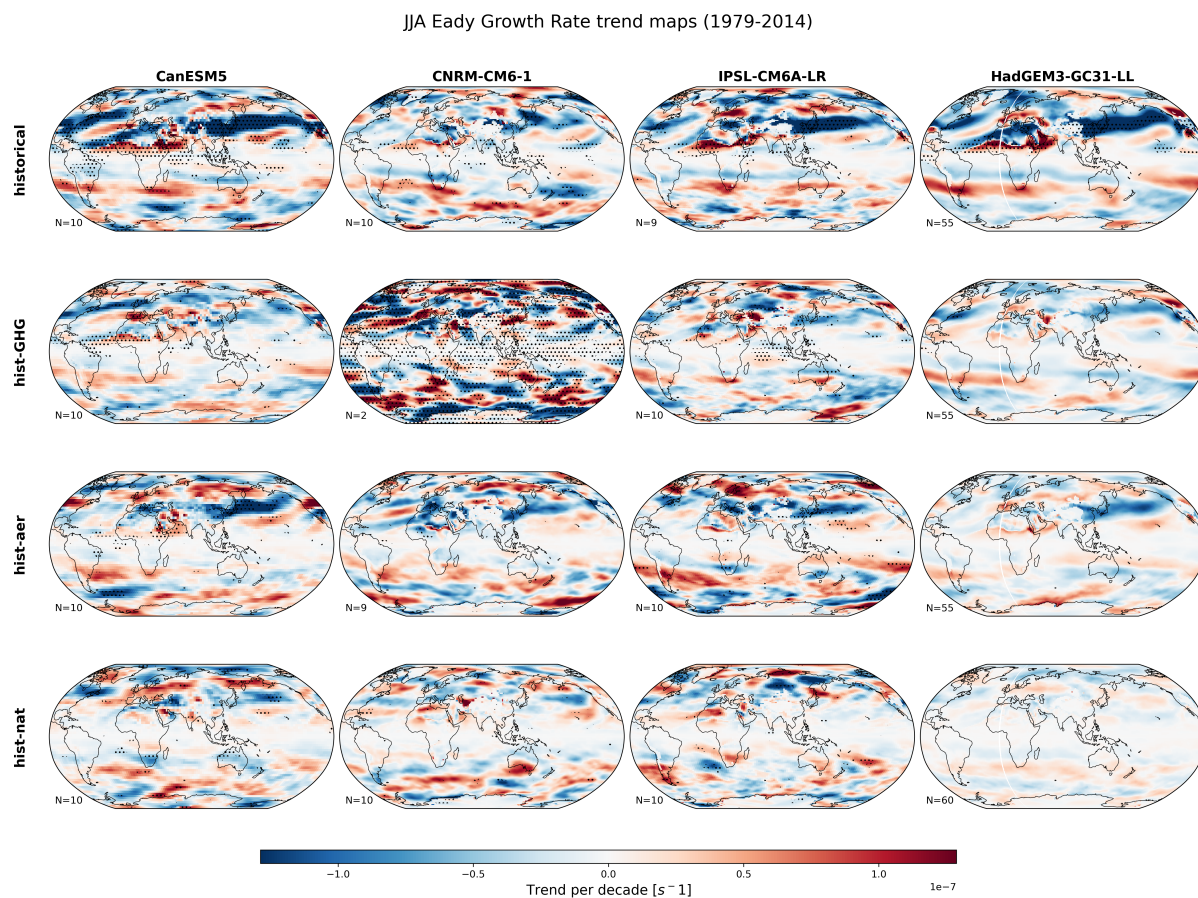
Observing the differences in the aerosol perturbation response between the models, as represented by trends in AOD and AAOD and the derived single scattering albedo (SSA), we find substantial inter-model variability in both the magnitude and spatial distribution of aerosol changes (Figures 9 and 10). During the full industrial period (1850–2014), all models exhibit  
 325 positive AOD and AAOD trends over the major industrialised regions of the Northern Hemisphere, although the spatial extent





**Figure 5.** Spatial maps of trends in Eady Growth Rate across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

and magnitude of these trends differ considerably across models. In contrast, the satellite-era trends (1979–2014) display a more coherent large-scale pattern, characterised by decreasing AOD and AAOD over Europe and North America and increasing values over South and East Asia, reflecting the redistribution of anthropogenic aerosol emissions during the late twentieth and early twenty-first centuries. While the AAOD trends broadly mirror the total AOD response, they exhibit substantially larger inter-model differences in magnitude, particularly between CanESM5 and HadGEM3-GC31-LL and the weaker responses simulated by CNRM-CM6-1 and IPSL-CM6A-LR. The derived SSA trends indicate that these changes are accompanied by differences in the relative contributions of scattering and absorbing aerosols across models. In particular, the pronounced satellite-era reductions in total AOD over Europe and North America are substantially weaker in AAOD, leading to generally negative SSA trends, i.e. aerosol becoming more absorbing, over these regions. This was primarily driven by de-sulfurisation of fuels in response to acid rain and corresponding policy changes. This suggests that changes in aerosol composition accompany

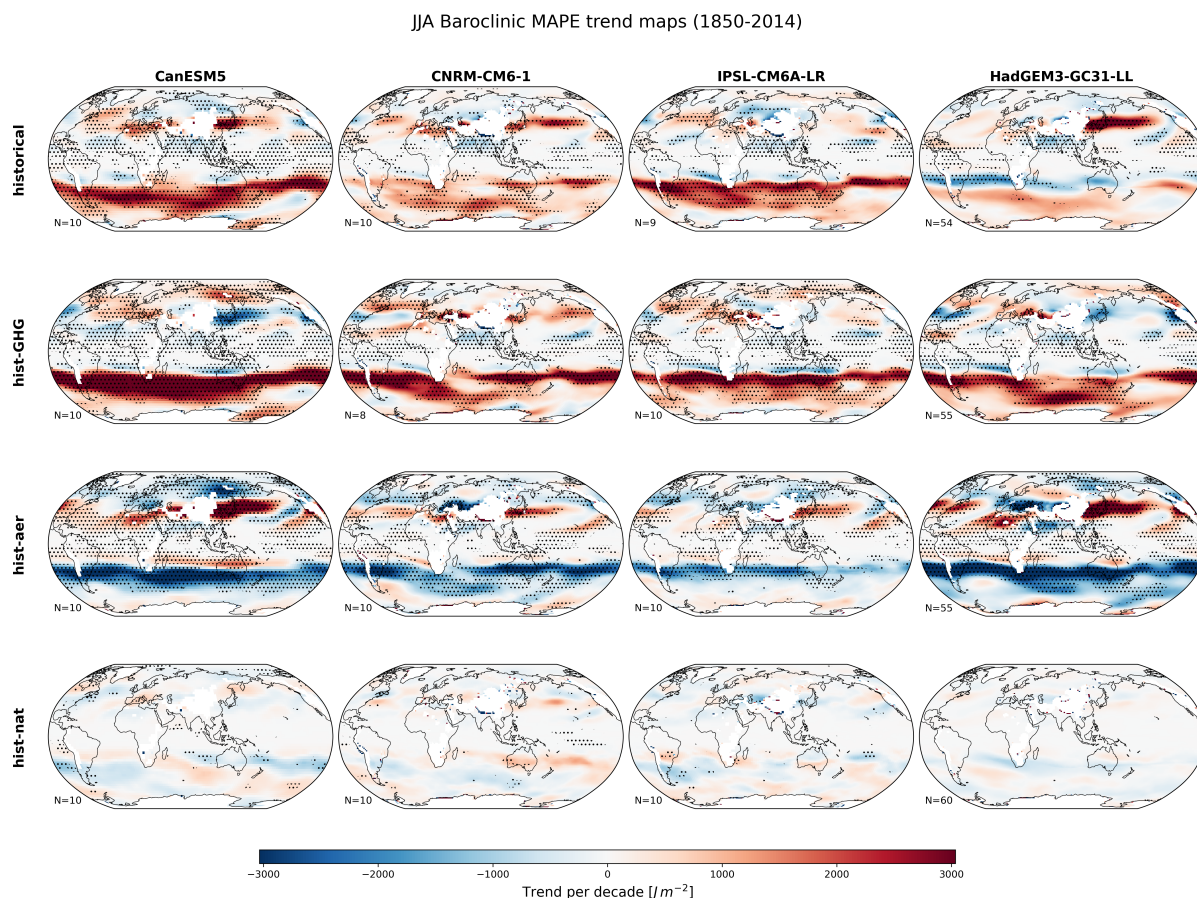


**Figure 6.** Spatial maps of trends in Eady Growth Rate across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

changes in aerosol loading, with potentially different radiative impacts on the simulated circulation. These satellite era trends are largely in agreement with recent trends derived from satellite observations. A more comprehensive discussion regarding recent aerosol emission changes can be found in Quaas et al. (2022).

Corresponding differences in the simulated aerosol perturbations are reflected in the simulated sea surface temperature (SST) trends (Figures 12 and 13). The historical and hist-GHG experiments show widespread warming across most ocean basins for both periods, with particularly strong warming at high latitudes in the Northern Hemisphere. In contrast, the hist-aer simulations across models produce more spatially heterogeneous SST trends, including widespread cooling across parts of the Southern Ocean during the full industrial period and pronounced regional contrasts across the Northern Hemisphere during the satellite era. These aerosol-driven SST responses broadly resemble the spatial structure of the corresponding baroclinicity trends, particularly over the North Pacific and Southern Ocean. Given that changes in the meridional temperature gradient



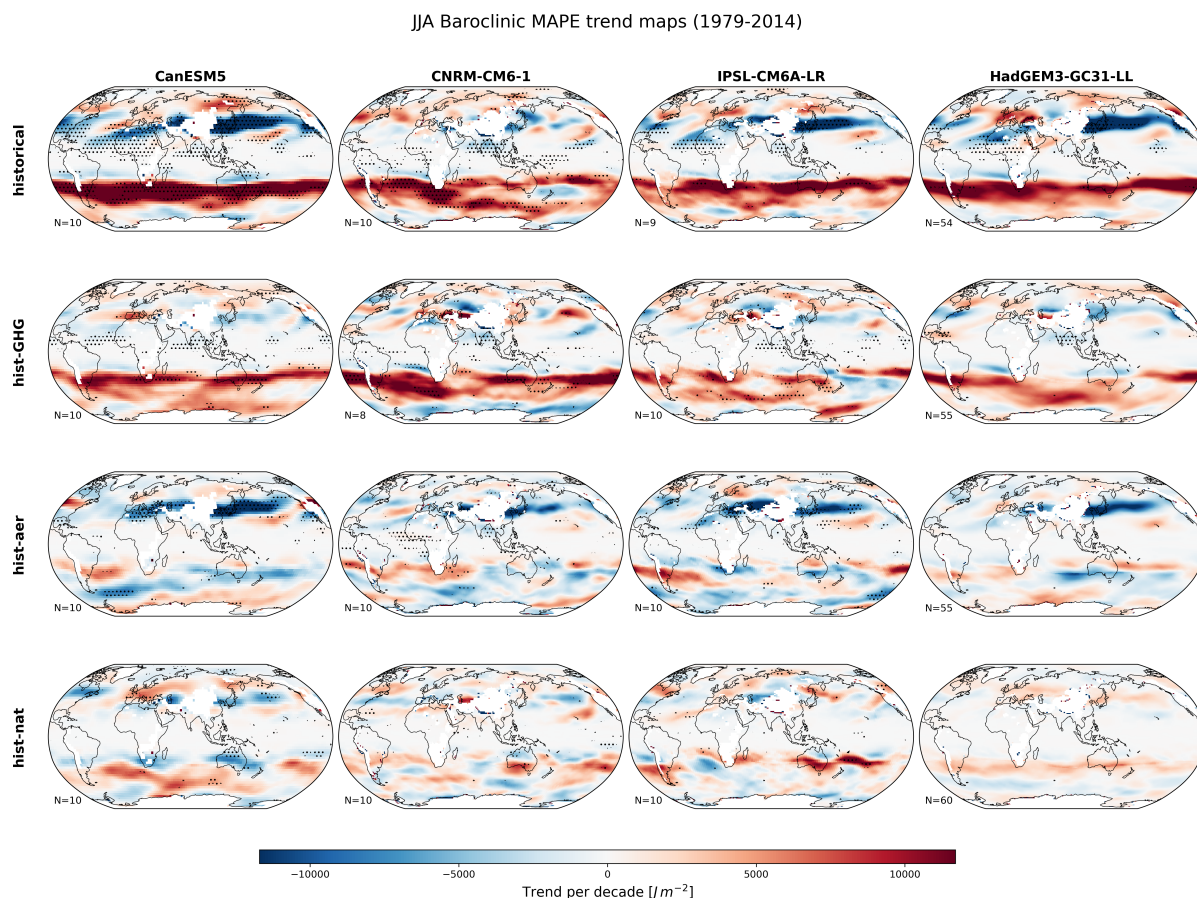


**Figure 7.** Spatial maps of trends in baroclinic MAPE across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

provide the dominant contribution to the MAPE trends, these results suggest that differences in aerosol forcing influence the simulated circulation response primarily through their impact on large-scale temperature gradients.

The similarities between the AOD, AAOD, SST and baroclinicity trend patterns also help explain part of the inter-model spread in the circulation response. Models exhibiting stronger and more spatially diverse AOD and AAOD trends also tend to produce larger SST and baroclinicity responses in the hist-aer experiments, particularly in the North Pacific and Southern Hemisphere mid-latitudes (Figures 9, 10, 11, 12 and 13). Specifically, CanESM5 and HadGEM3-GC31-LL generally exhibit the largest AOD and AAOD responses, together with stronger aerosol-induced SST changes, and consequently produce some of the strongest baroclinicity responses in the hist-aer experiments. This relationship is particularly evident over the North Pacific and Southern Ocean, where stronger aerosol-induced temperature gradient changes are associated with larger circulation responses. While the precise regional response differs between models, the broad correspondence between aerosol perturbations,

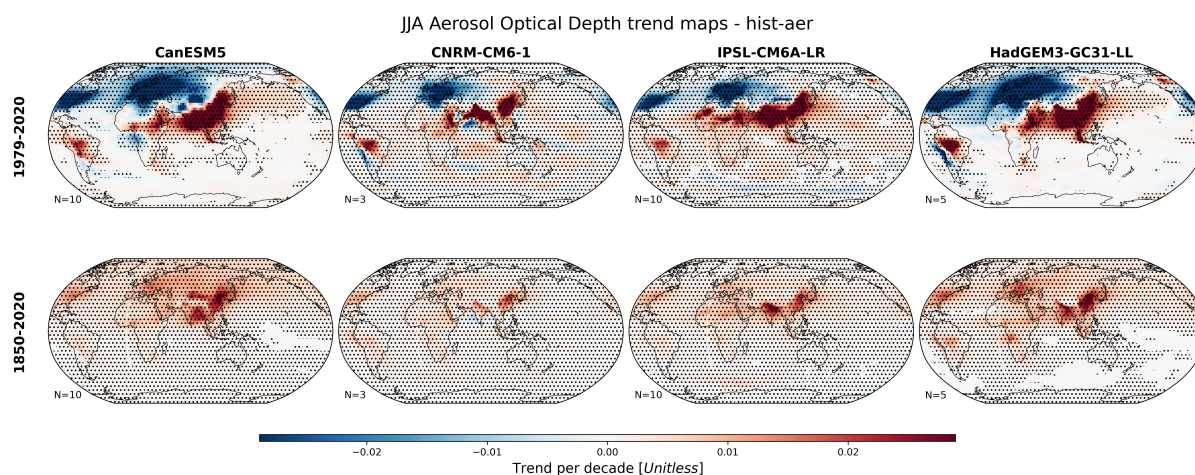




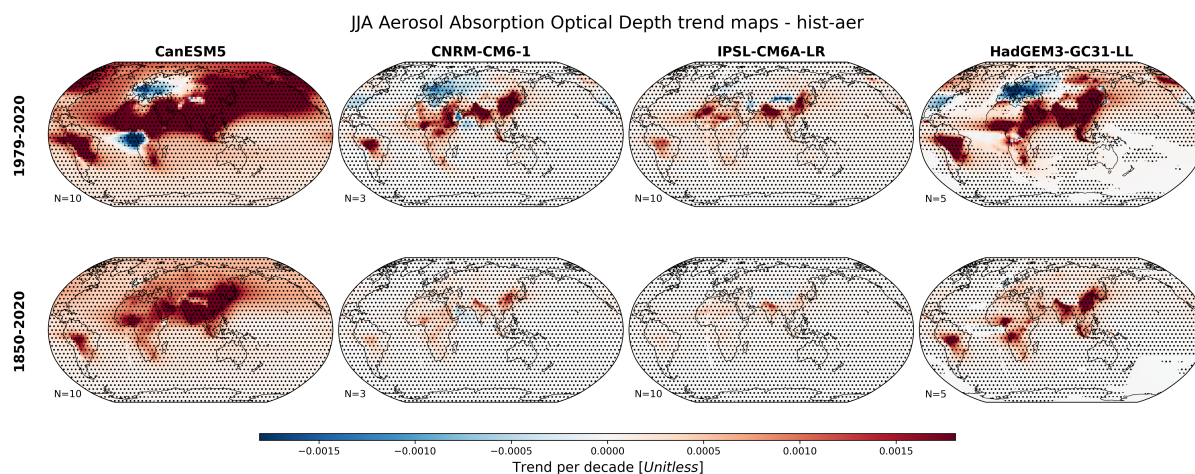
**Figure 8.** Spatial maps of trends in baroclinic MAPE across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

SST gradients and baroclinicity trends suggests that differences in the representation of aerosol-radiation and aerosol-cloud interactions contribute substantially to the spread in simulated summer baroclinicity and storm-track trends, although the relative contributions of these processes cannot be isolated from the current experiments used.

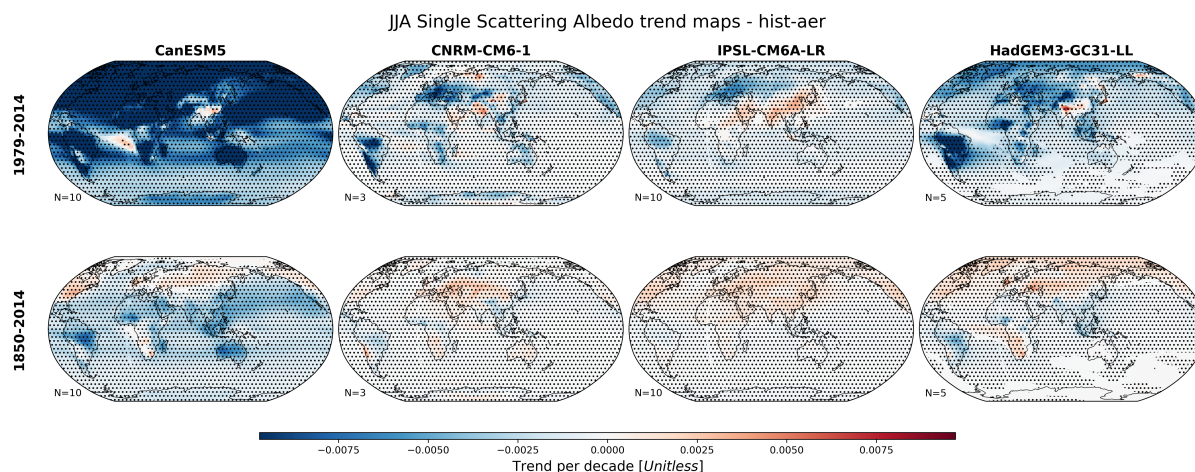
The clearest robust baroclinicity feature in baroclinic MAPE across the models and experiments is a positive trend in Southern Hemisphere mid-latitude baroclinicity, particularly over the Southern Ocean, which is evident in both the historical and hist-GHG simulations for the 1850–2014 and 1979–2014 periods (Figures 7 and 8). These Southern Hemisphere trend patterns are also evident, but tend to be less significant, for Eady Growth Rate over the industrial era, and are largely absent from the satellite era Eady Growth Rate trend patterns (Figures 5 and 6). These trends are largely absent in the hist-nat experiments, and are generally negative in the hist-aer experiments over the industrial era and weak in the satellite era, indicating that the long-term Southern Hemisphere winter (JJA) baroclinicity increase is primarily driven by anthropogenic greenhouse gas



**Figure 9.** Spatial maps of trends in aerosol optical depth in the 550nm wavelength (AOD) across the industrial and the satellite periods in the single forcing experiments. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.



**Figure 10.** Spatial maps of trends in aerosol absorption optical depth in the 550nm wavelength (AAOD) across the industrial and the satellite periods in the single forcing experiments. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.



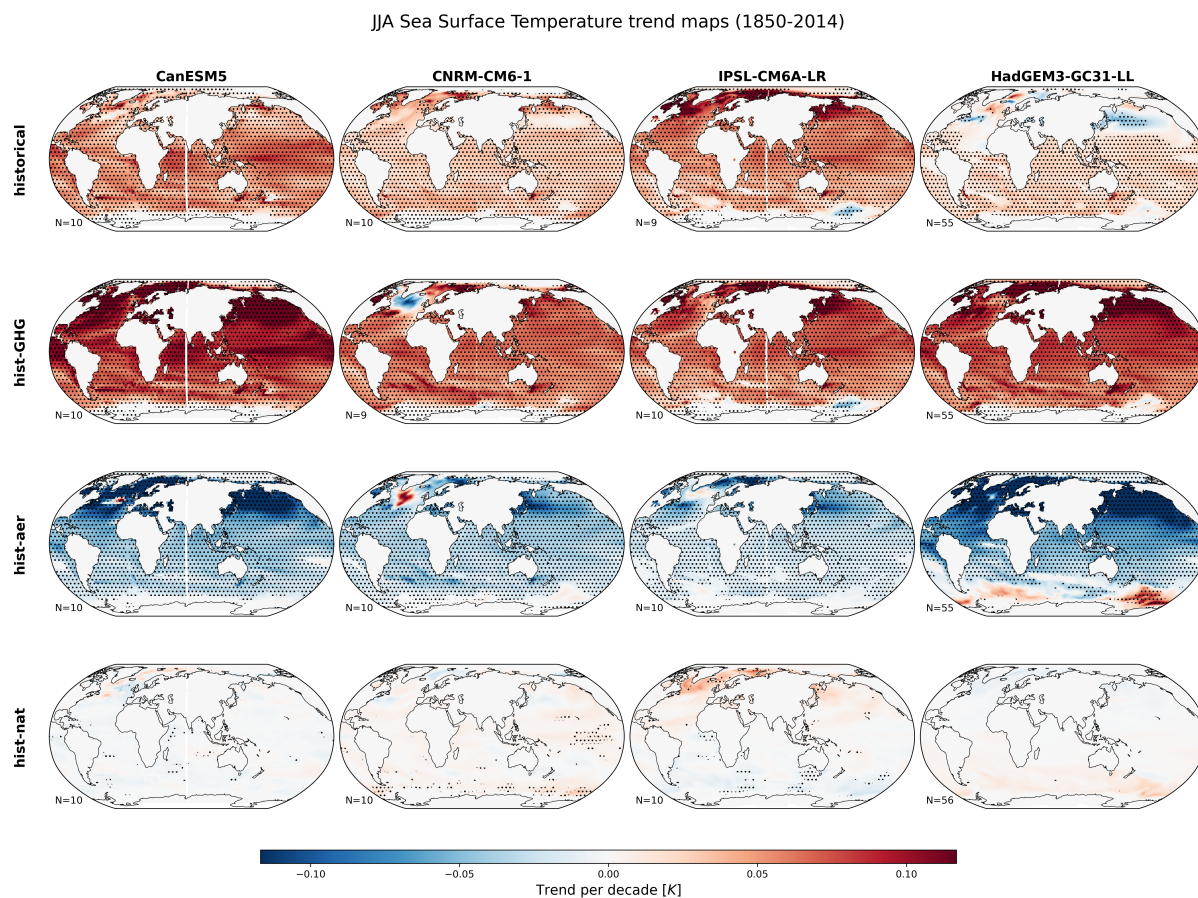
**Figure 11.** Spatial maps of trends in single scattering albedo (SSA) across the industrial and the satellite periods in the single forcing experiments. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

forcing. The Southern Hemisphere baroclinic MAPE response also exhibits relatively strong inter-model agreement compared to the Northern Hemisphere, seen in the zonally consistent positive baroclinic MAPE trends in the historical and hist-GHG experiments located in the Southern Hemisphere between approximately  $40^{\circ}S$  and  $60^{\circ}S$ .

In contrast, Northern Hemisphere summer trends are substantially more heterogeneous and exhibit varied sensitivities to both forcing and period. During the satellite era (1979–2014), the historical experiments show widespread negative baroclinicity trends over the North Pacific storm-track region, while model trends over the North Atlantic are generally weaker, don't fully capture the SNAO pattern, and divert from reanalysis trends in the region (Figures 8 and 6, Harvey et al., 2023). These negative satellite-era North Pacific trends are strongest in the hist-aer experiments and are weak or absent in the hist-GHG and hist-nat experiments for both Eady Growth Rate and baroclinic MAPE. The close correspondence between the aerosol-driven North Pacific SST trends and the baroclinicity response further suggests that aerosol-induced SST changes and their impact on the meridional temperature gradients contribute substantially to the recent weakening of North Pacific summer baroclinicity.

The comparison between the post-industrial and satellite-era trends further highlights the specific baroclinicity response. The 1850–2014 trends are generally zonally smooth, particularly in the Southern Hemisphere, whereas the 1979–2014 trends exhibit substantially larger regional amplitudes and stronger zonal asymmetries (Figures 5, 6, 7 and 8). This behaviour is especially evident in the hist-aer experiments, suggesting that shorter-timescale aerosol forcing changes exert a stronger influence on satellite era June–August baroclinicity trends. Specifically, in the hist-aer experiments, the aerosol forcings seem to have a relatively low influence on the Southern Hemisphere in the satellite era compared to the entire industrial era (Figures 5, 6, 7 and 8). This could be partially explained by the concentration of the significant aerosol emission trends over the satellite era in the Northern Hemisphere.

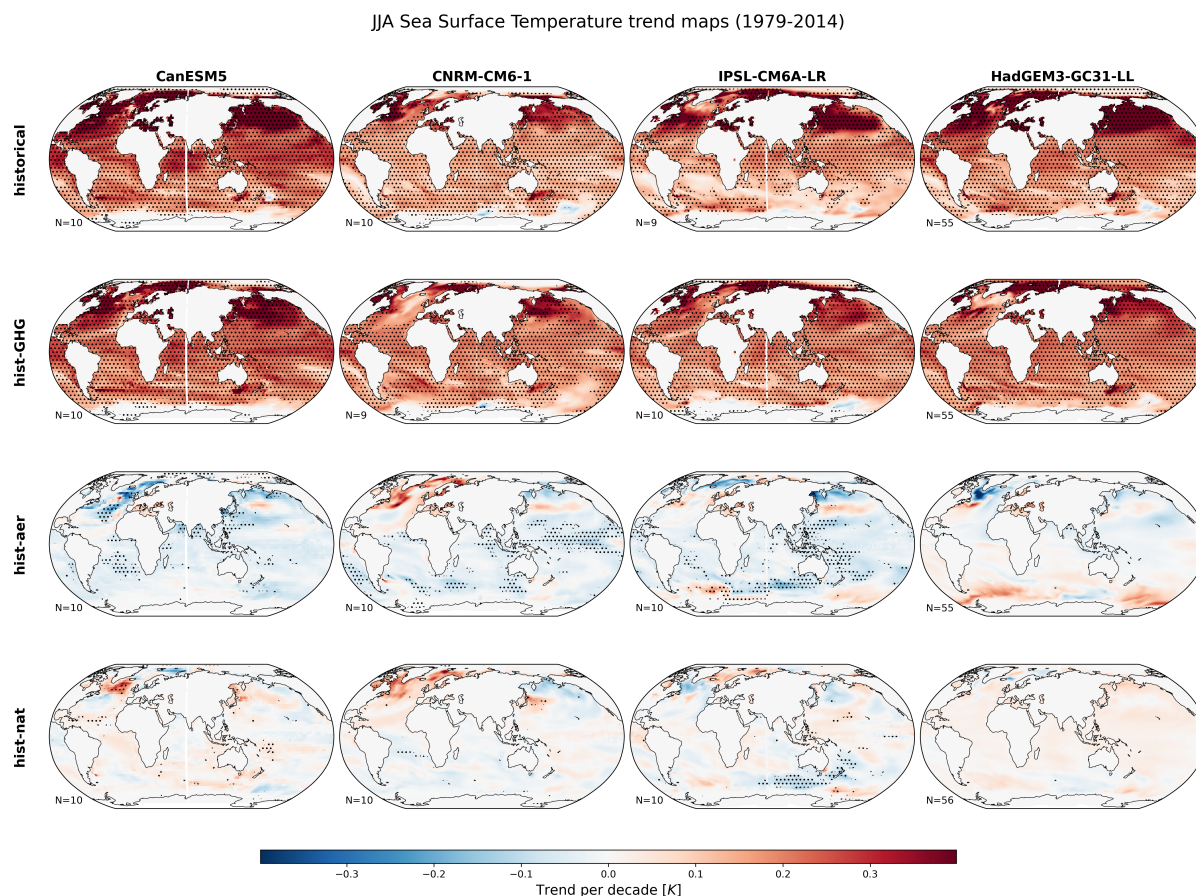




**Figure 12.** Spatial maps of trends in sea surface temperature (SST) across the models and experiments used in the single forcing experiments for the 1850-2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

385 Contrasting behaviour is evident between the North Atlantic and Pacific regions (regional means are given in appendix C for convenience). Across most models, the North Pacific exhibits robust negative historical baroclinicity trends during the satellite era (1979–2014), with the strongest reductions occurring in the hist-aer experiments. By contrast, North Atlantic mean trends are weaker and often remain near-neutral for baroclinic MAPE, and tend to be negative but weaker than the North Pacific ones for Eady Growth Rate. The contrasting North Pacific and North Atlantic responses are consistent with the different aerosol perturbations simulated over the two basins. In particular, the opposite-signed AOD and AAOD trends between the North  
 390 Pacific and North Atlantic during the satellite era are accompanied by contrasting SST and baroclinicity responses, suggesting that regional aerosol forcing contributes to the observed basin-scale differences (Figures 9, 10, 12 and 13).

To better understand the physical drivers underlying the baroclinicity trends, we also analyse the decomposition of Eady Growth Rate and baroclinic MAPE into their contributing factors in the single-forcing experiments (Appendix B and D). In



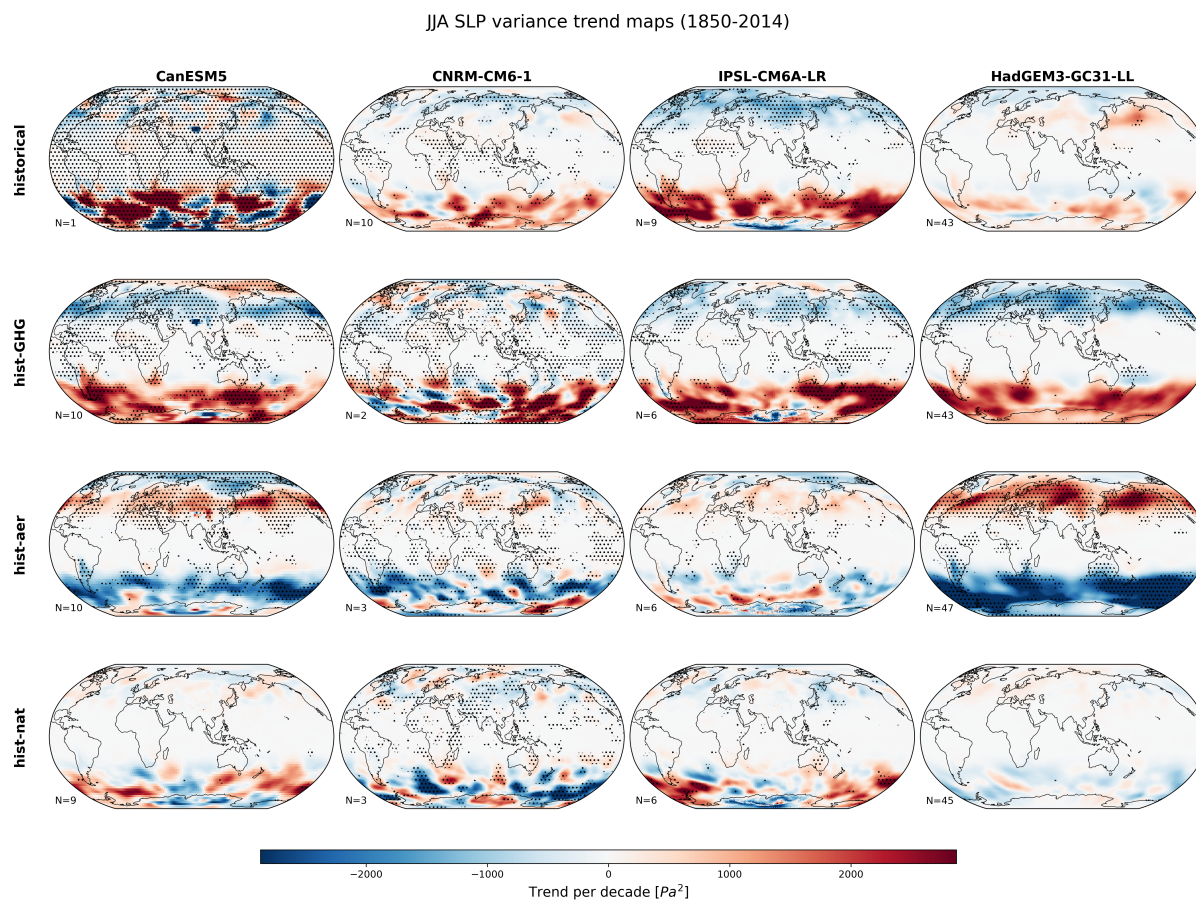
**Figure 13.** Spatial maps of trends in sea surface temperature (SST) across the models and experiments used in the single forcing experiments for the 1979-2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

395 agreement with the ERA5 trends over the satellite-era, across experiments and eras, the dominant contribution to the summer baroclinicity trends arises from changes in the meridional temperature gradient and the vertical wind shear terms (Figures B3, 6, D5 and D6), while the static stability and tropospheric depth contributions are weaker and more local (Figures D3, D4, D1 and D2). This is particularly evident within the aerosol-forced North Pacific response, where reductions in the vertically averaged meridional temperature gradient and vertical wind shear closely resemble the total baroclinicity trend pattern (Figures

400 D5 and D6).

To assess the impact of these baroclinicity trends on the storm tracks, we also calculated the trend maps for the SLP variance (Figures 14 and 15) and EKE (Figures E1 and E2) across the periods and compared them to the baroclinicity trends. These calculations were limited by the fewer members available at the daily temporal resolution, required for the calculation of SLP variance and EKE, and are thus considered to be less robust. More members included the surface fields needed to calculate the

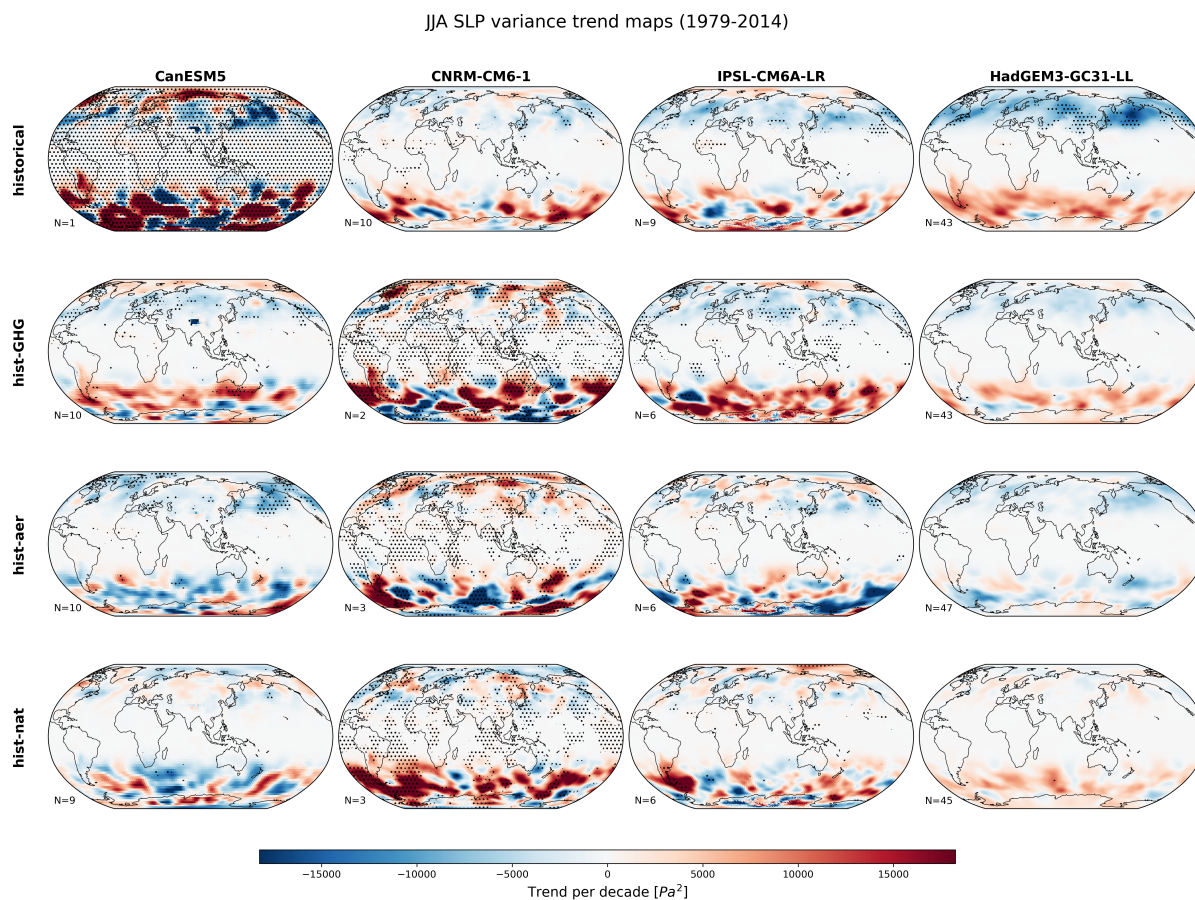




**Figure 14.** Spatial maps of trends in SLP variance across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

405 SLP variance at daily resolution, and so we focus on SLP variance trends in the main text, and present the trends in EKE in Appendix E. As expected, the SLP variance trends tend generally to resemble the baroclinicity trend patterns. Specifically, for the industrial era, most model experiments depict a positive trend in the Southern Hemisphere for the historical experiments with a more mixed trend in the Northern Hemisphere (Figure 14). Furthermore, the SLP variance trends in the hist-aer and hist-GHG experiments are also similar to the baroclinicity trends for those experiments, depicting a positive Northern Hemisphere and a negative Southern Hemisphere trend for the hist-aer experiment, and the opposite trend pattern for the hist-GHG experiment (Figure 14).

The satellite-era SLP variance trends in the historical experiments also generally agree with the corresponding baroclinicity trends seen in Eady Growth Rate and barclinic MAPE, depicting a generally weak negative trend across the Northern Hemisphere and a positive trend across the Southern Hemisphere (Figure 15). Similarly, the hist-aer and hist-GHG experiments



**Figure 15.** Spatial maps of trends in SLP variance across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

415 exhibit negative and positive SLP variance trends in the Southern Hemisphere, respectively, while the Northern Hemisphere responses are more spatially heterogeneous. Consistent with the baroclinicity trends, these SLP variance responses suggest that greenhouse gases and aerosols exert competing influences on storm-track behaviour over the industrial period. During the satellite era, however, this contrast becomes less pronounced, reflecting the substantial redistribution of anthropogenic aerosol emissions during the late twentieth century.

## 420 4 Discussion

The analysis of the Eady Growth Rate and baroclinic MAPE decompositions indicates that the observed summer baroclinicity trends are primarily driven by changes in the meridional temperature gradient and the associated vertical wind shear,



highlighting its dominant role in shaping June–August circulation changes (Figure 4). In ERA5, both diagnostics identify robust weakening over the North Pacific and strengthening across much of the Southern Hemisphere mid latitudes, although  
 425 the Northern Hemisphere satellite-era response is more mixed and Eady Growth Rate additionally exhibits stronger negative trends at higher latitudes. In both diagnostics, the strongest and most robust Northern Hemisphere weakening occurs on the subtropical side of the Pacific storm-track region, suggesting that changes in the meridional temperature gradient play a key role in the recent decline in summer baroclinicity.

Although the two diagnostics produce broadly similar large-scale baroclinicity responses, they differ in the spatial expression  
 430 of the Northern Hemisphere satellite-era trends. Eady Growth Rate exhibits a somewhat more dominant Northern Hemisphere weakening, including stronger high-latitude negative trends, whereas baroclinic MAPE emphasises stronger regional differences, particularly between the North Pacific and North Atlantic and has a weaker Arctic response. These differences likely reflect the different mathematical formulations of the diagnostics rather than fundamentally different physical mechanisms. Eady Growth Rate depends approximately linearly on the meridional temperature gradient through its impact on the vertical  
 435 wind shear. In contrast, baroclinic MAPE is proportional to the square of the meridional temperature gradient. Consequently, baroclinic MAPE places greater emphasis on regions with large climatological temperature gradients and large regional perturbations, while Eady Growth Rate is more sensitive to local changes in wind shear, including at higher latitudes.

The CMIP6 single forcing experiments’ results presented here suggest that summer baroclinicity and storm-track trends are strongly influenced by the competing forcings of greenhouse gases and anthropogenic aerosols. Across the CMIP6 single-  
 440 forcing experiments, both greenhouse gas and aerosol forcings produce significant and sometimes opposite baroclinicity and storm-track responses in both hemispheres, while the comparatively weak trends in the natural forcings experiments (hist-nat) support the dominant role of anthropogenic forcings in shaping the observed trends. However, the aerosol-forced responses exhibit strong regional asymmetries and substantial temporal sensitivity, particularly between the post-industrial (1850–2014) and satellite-era (1979–2014) periods. Interestingly, the aerosol single forcing experiment suggests that changes in aerosol  
 445 emissions, located mainly in the Northern Hemisphere, produce significant baroclinicity and storm-track trends in the Southern Hemisphere, suggesting their large-scale impact on storm track behaviour.

The inter-model comparison suggests that differences in the simulated aerosol forcing response contribute substantially to the spread in the diagnosed baroclinicity and storm-track trends. Models exhibiting larger changes in aerosol optical depth (AOD), aerosol absorption optical depth (AAOD), and sea surface temperature (SST) generally produce stronger baroclinicity  
 450 and storm-track responses during June–August, particularly over the North Pacific and Southern Hemisphere mid-latitudes. Across the industrial period, the hist-aer experiments exhibit positive baroclinic MAPE and storm-track trends over parts of the North Pacific and North Atlantic, together with negative trends across much of the Southern Hemisphere mid-latitudes. These responses are accompanied by corresponding changes in SST gradients, representing enhanced meridional temperature gradients over parts of the Northern Hemisphere oceans and weakened gradients across much of the Southern Ocean. In  
 455 contrast, the greenhouse-gas-only forcing experiments generally produce opposite responses, suggesting that aerosol forcing partially offsets components of the greenhouse-gas-driven circulation response through its influence on large-scale temperature gradients.



The aerosol-forced response during the satellite era differs substantially from the longer-term industrial era response. Reductions in aerosol emissions over Europe and North America (and particularly a reduction in scattering aerosols) following the implementation of air quality regulations, contrasted with continued increases over parts of South-East Asia (dominated by absorbing aerosols as seen in the trends in SSA), are associated with markedly different baroclinicity and storm-track trends compared to those found over the full industrial period. In particular, strong negative baroclinicity trends emerge over the North Pacific in the aerosol-only experiments, while the North Atlantic response remains comparatively weak. The consistency between these satellite-era trends in the historical simulations and ERA5 reanalysis suggests that recent aerosol emission reductions may be muting the circulation response to anthropogenic greenhouse-gas warming. The stronger North Pacific response is consistent with the larger aerosol perturbations simulated over this basin, which are accompanied by larger SST and meridional temperature gradient changes than over the North Atlantic, helping to explain the pronounced asymmetry between the North Pacific and North Atlantic summer baroclinicity trends. However, the mechanisms responsible for these regional differences remain uncertain and require further investigation.

## 5 Summary and conclusions

In this paper, we analyse temporal trends in Northern Hemisphere summer (June–August) baroclinicity in ERA5 reanalysis during the satellite era, together with baroclinicity and storm-track trends in CMIP6 single-forcing experiments over the industrial and satellite periods. Significant baroclinicity trends are identified in both hemispheres since 1979, in agreement with previous studies. In the satellite era ERA5 data, negative Eady Growth Rate and baroclinic MAPE trends are found over the North Pacific, mixed trend patterns resembling the summer North Atlantic Oscillation (SNAO) are identified over the North Atlantic, and positive baroclinicity trends occur across much of the Southern Hemisphere mid-latitudes during the 1979–2024 period (Figures 4 and A1). The decomposition of Eady Growth Rate and baroclinic MAPE indicates that changes in the meridional temperature gradient provide the dominant contribution to the observed baroclinicity trends, while changes in static stability and tropospheric depth play comparatively minor roles.

Motivated by these identified satellite-era baroclinicity trends, we incorporate four CMIP6 single-forcing large ensemble experiments to examine the impacts of different anthropogenic forcings on baroclinicity trends over both the post-industrial and satellite-era periods. The results suggest that both greenhouse gases and aerosol forcings produce significant and comparable baroclinicity and storm-track responses in both hemispheres, while the weak trends in the hist-nat simulations indicate a limited role for natural forcings alone in producing the observed temporal trends. The results also suggest that aerosol emissions have a significant influence on baroclinicity and storm-track trends in the Southern Hemisphere, even though the majority of the aerosol emissions and trends are located within the Northern Hemisphere, indicating that aerosol emission shifts can influence circulation changes on the global scale. The aerosol-only forcing experiments additionally exhibit large differences in the calculated trends between the 1850–2014 and 1979–2014 periods, suggesting that major changes in anthropogenic aerosol emissions over recent decades have significantly influenced the baroclinicity and storm-track response in both hemispheres.





490 Overall, the results suggest that recent summer baroclinicity trends are strongly shaped by the balance between greenhouse-  
gas warming and aerosol emissions, and their competing impacts on meridional temperature gradients. Greenhouse-gas forcing  
provides a relatively smooth large-scale radiative perturbation, whereas aerosol forcing is inherently regional because aerosol  
emissions are concentrated over industrialised regions. Despite these different forcing patterns, the resulting baroclinicity re-  
sponses are often similar in structure but opposite in sign, reflecting their competing influences on the sea surface temperature  
495 gradients and the resulting meridional temperature gradients. This competition is particularly important over the North Pa-  
cific, where aerosol forcing significantly contributes to the recent negative baroclinicity response. The marked differences  
between the industrial and satellite-era aerosol responses further indicate that changes in aerosol emissions over recent decades  
have modified the circulation response to anthropogenic warming. These findings highlight the importance of considering  
both greenhouse-gas and aerosol forcings when interpreting historical storm-track changes, and when projecting their future  
500 behaviour in different emission scenarios.

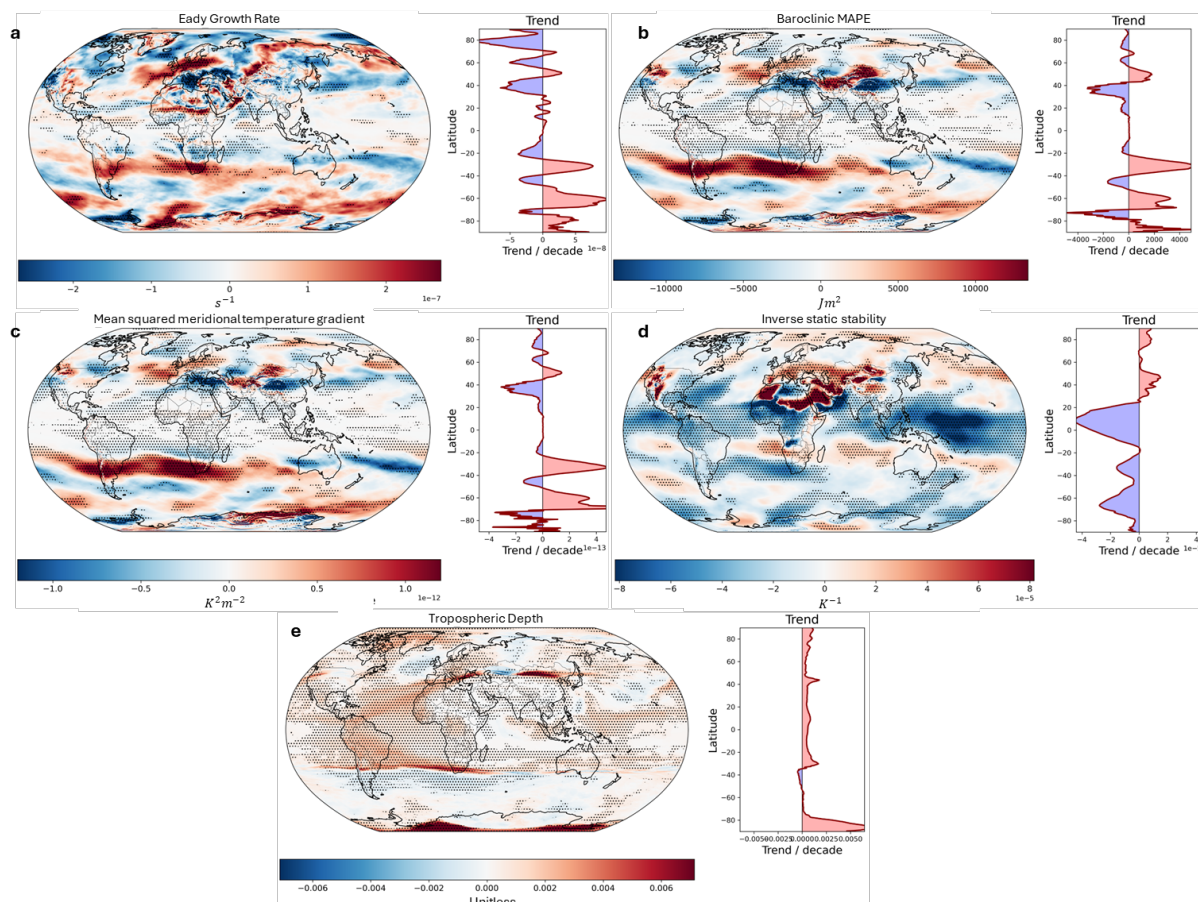
Future analysis will aim to better understand the competing physical impacts of greenhouse gas and aerosol emission changes  
on the observed baroclinicity and storm-track trends identified here, and to better explain the physical mechanisms by which  
aerosol forcing influences baroclinicity and storm-track behaviour in both hemispheres and across different seasons and pe-  
riods. In particular, a more detailed investigation into the relative roles of aerosol-radiation and aerosol-cloud interactions, as  
505 well as assessing the storm-track changes under different aerosol emission scenarios, would likely provide further insight into  
the processes driving the identified responses. Extending the analysis to additional seasons, reanalysis products and climate  
model experiments would also improve the robustness of the identified trends and assist in understanding model biases as-  
sociated with mid-latitude baroclinicity and storm-track variability. Finally, investigating the future evolution of these trend  
patterns under different future emission scenarios would provide insight into potential future storm-track changes and their  
510 associated impacts on society and improve the efficiency of mitigation and adaptation efforts.

*Code availability.* The analysis code could be obtained upon request from the authors in a GitHub repository used for this project.

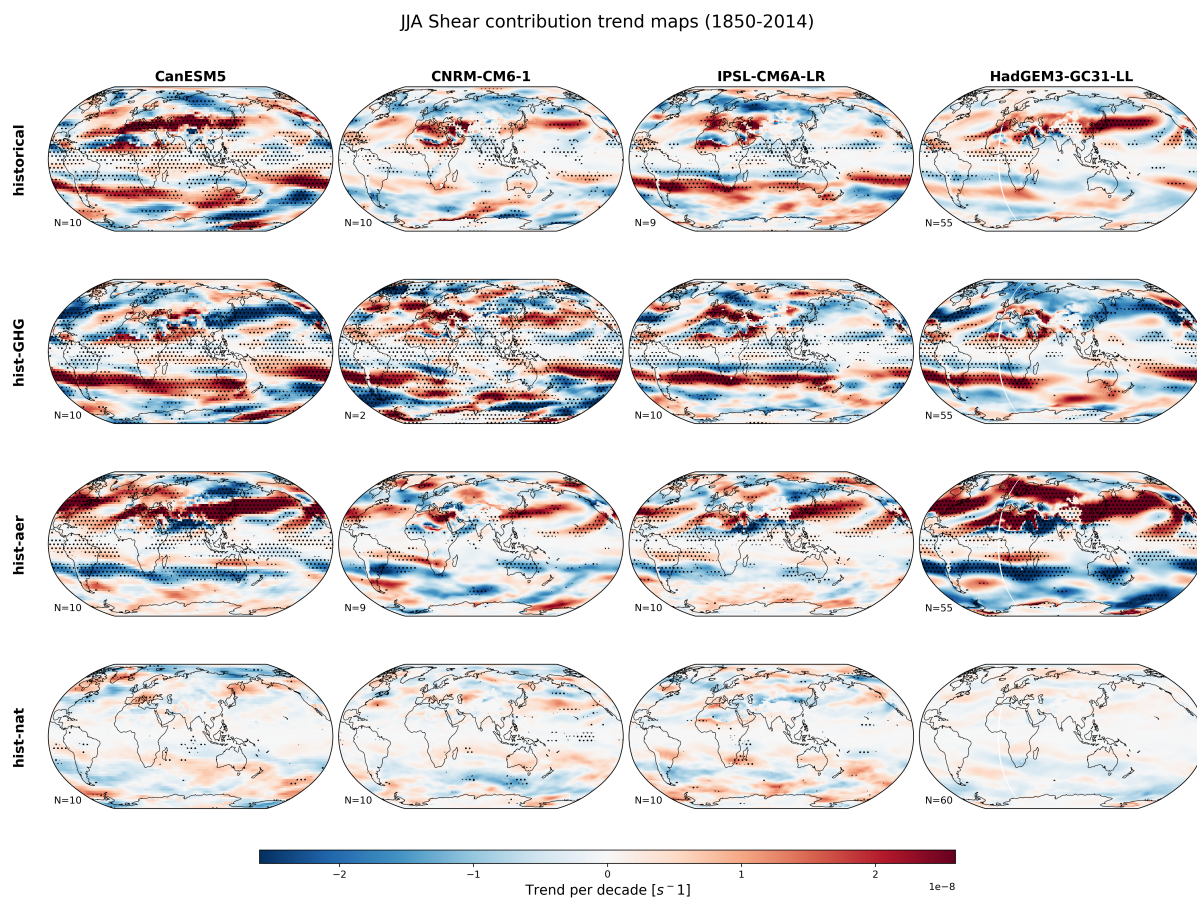
*Data availability.* All data used in this analysis is open-source and freely distributed online. ERA5 data can be found on the climate data  
store in the following link: <https://cds.climate.copernicus.eu/>. All single forcing CMIP6 data were used on the Jasmin cluster in connection  
with the CEDA archive. Explanation about the data structure and download can be found here: <https://wcrp-cmip.org/cmip-data-access/>.



## 515 Appendix A: Extended ERA5 baroclinicity trends

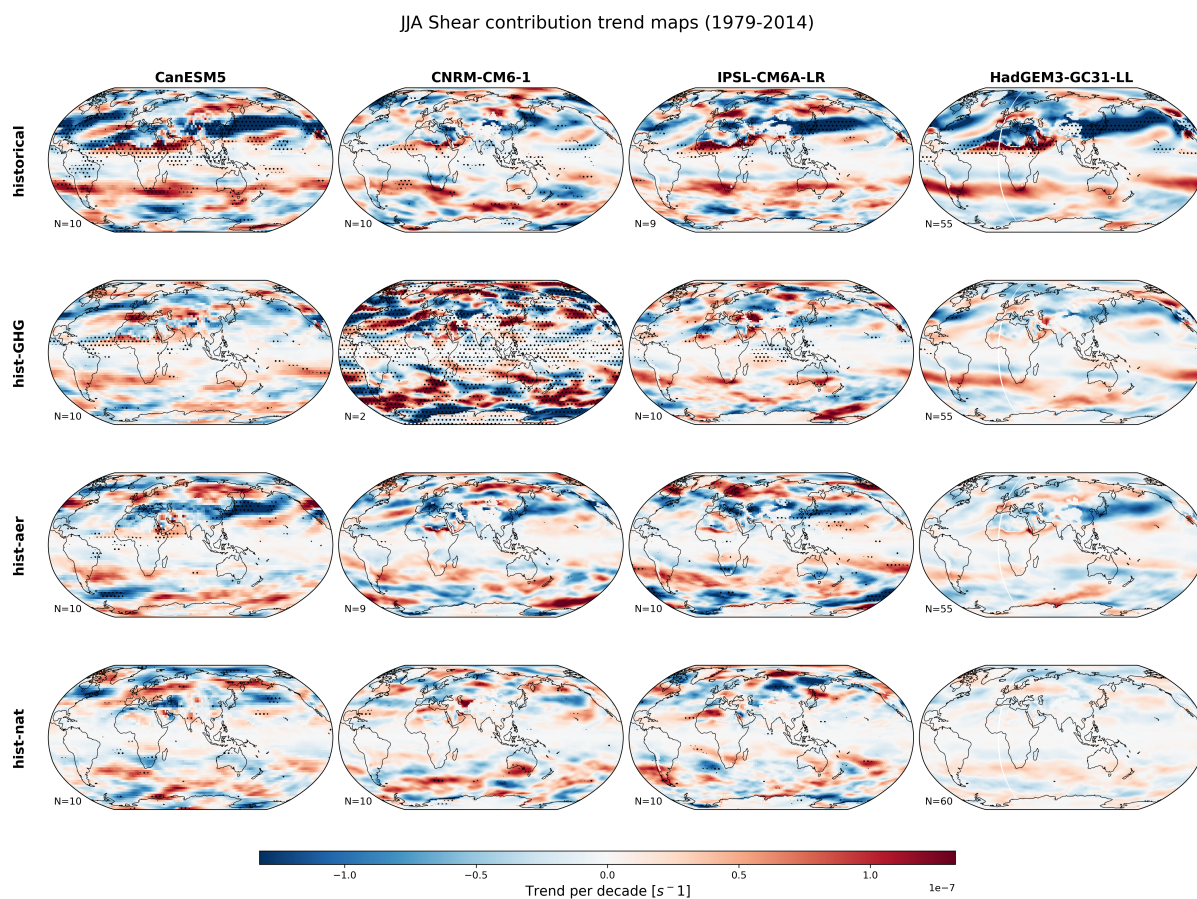


**Figure A1.** June-August trend maps and zonal mean trends for Eady Growth rate (a), baroclinic MAPE (b), mean squared meridional temperature gradient (c), inverse static stability (d) and tropospheric depth (e). Means were calculated using ERA5 reanalysis data from 1979 to 2024. Stippling indicates a significant trend above the 95% confidence bounds using the Student's t-test method.



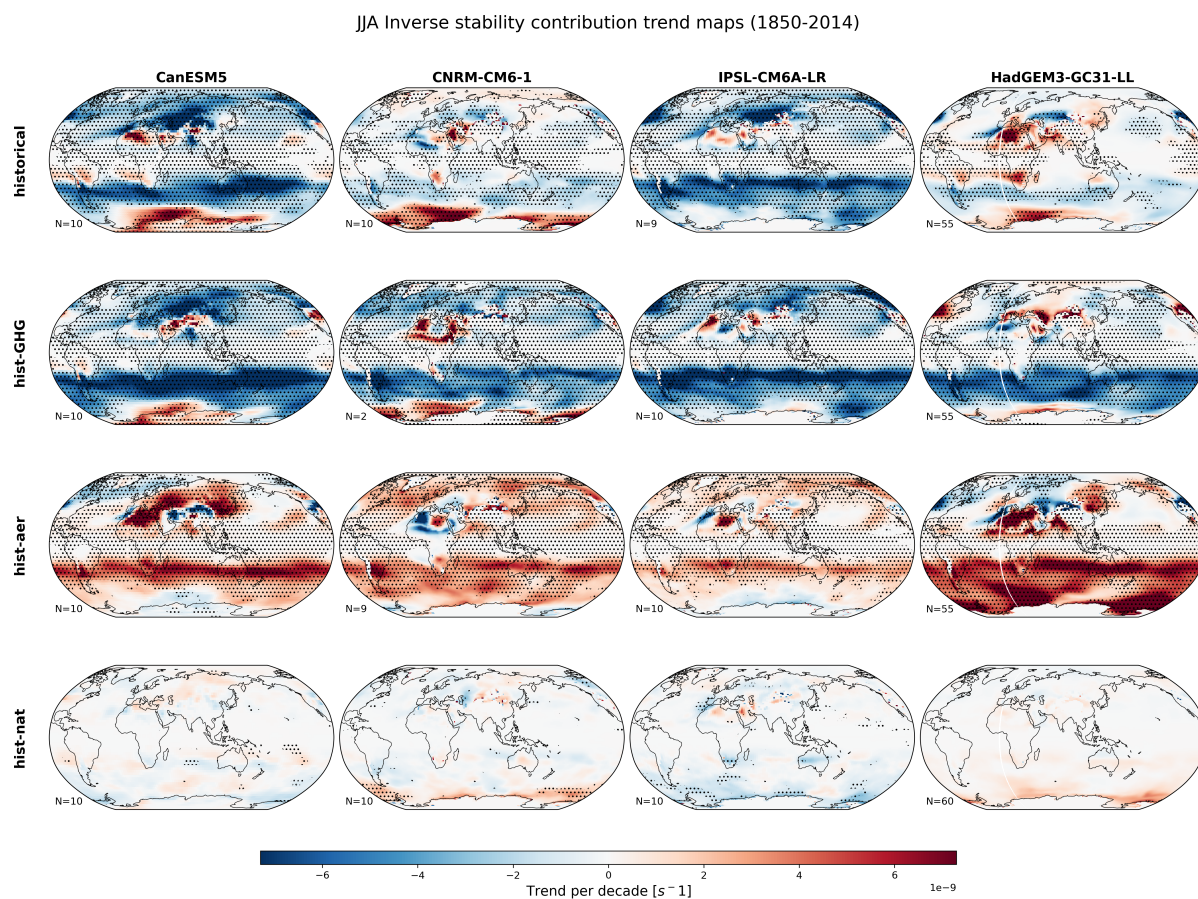
**Figure B1.** Spatial maps of trends in the shear contribution of Eady Growth Rate across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

## Appendix B: Eady Growth Rate decomposition trends in the single forcing experiments

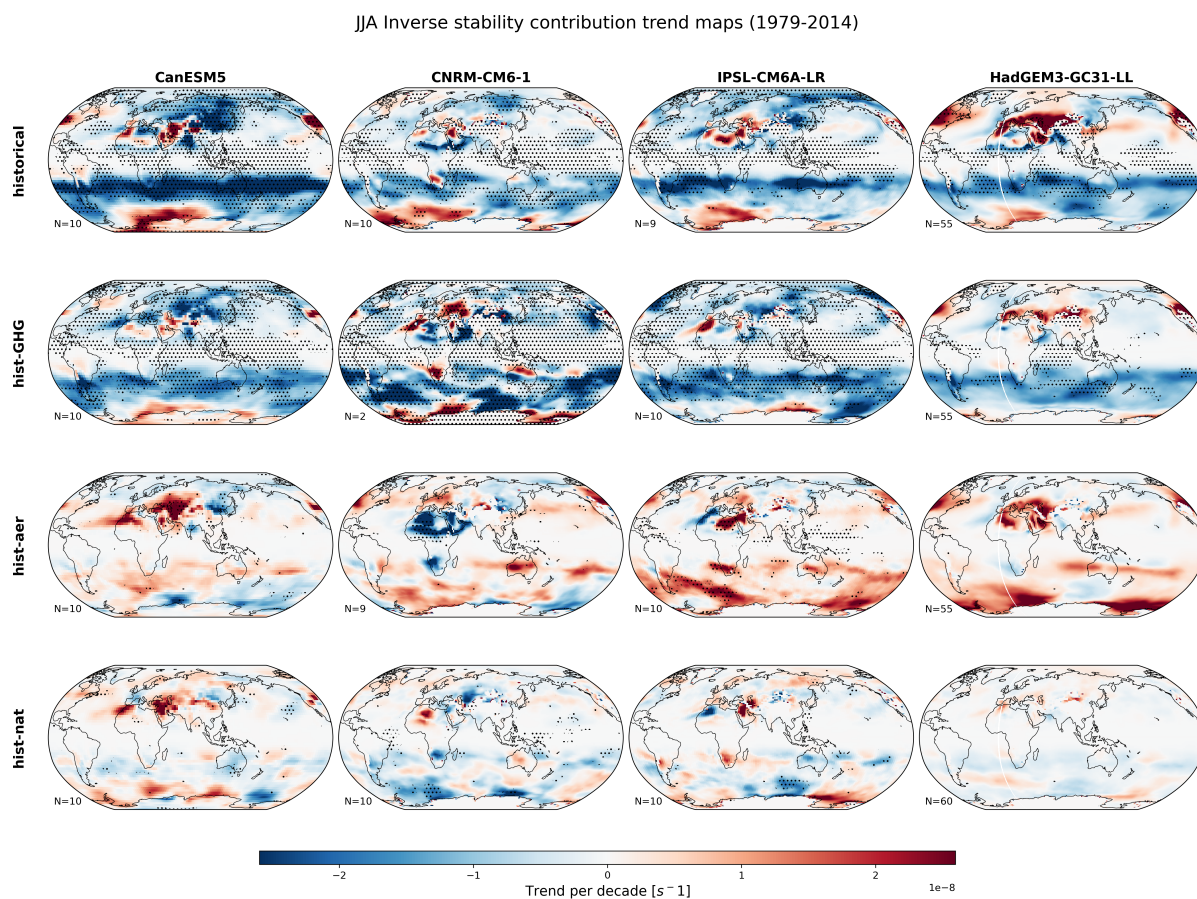


**Figure B2.** Spatial maps of trends in the shear contribution of Eady Growth Rate across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.





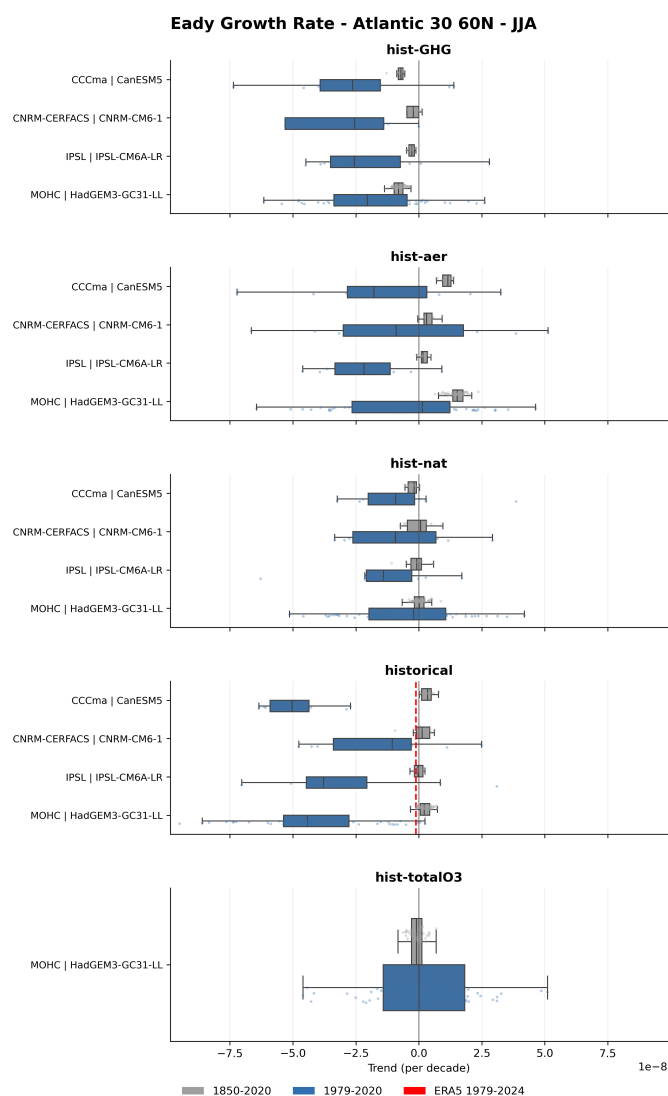
**Figure B3.** Spatial maps of trends in the shear contribution of Eady Growth Rate across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.



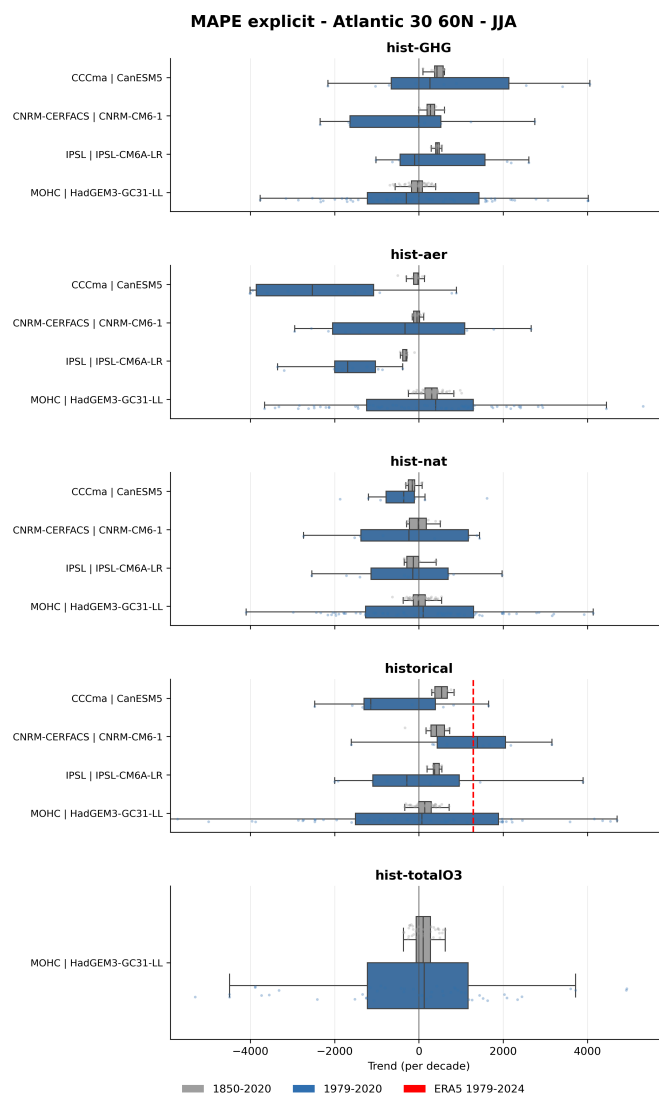
**Figure B4.** Spatial maps of trends in the shear contribution of Eady Growth Rate across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.



## Appendix C: regional mean baroclinicity trends over the North Atlantic and North Pacific

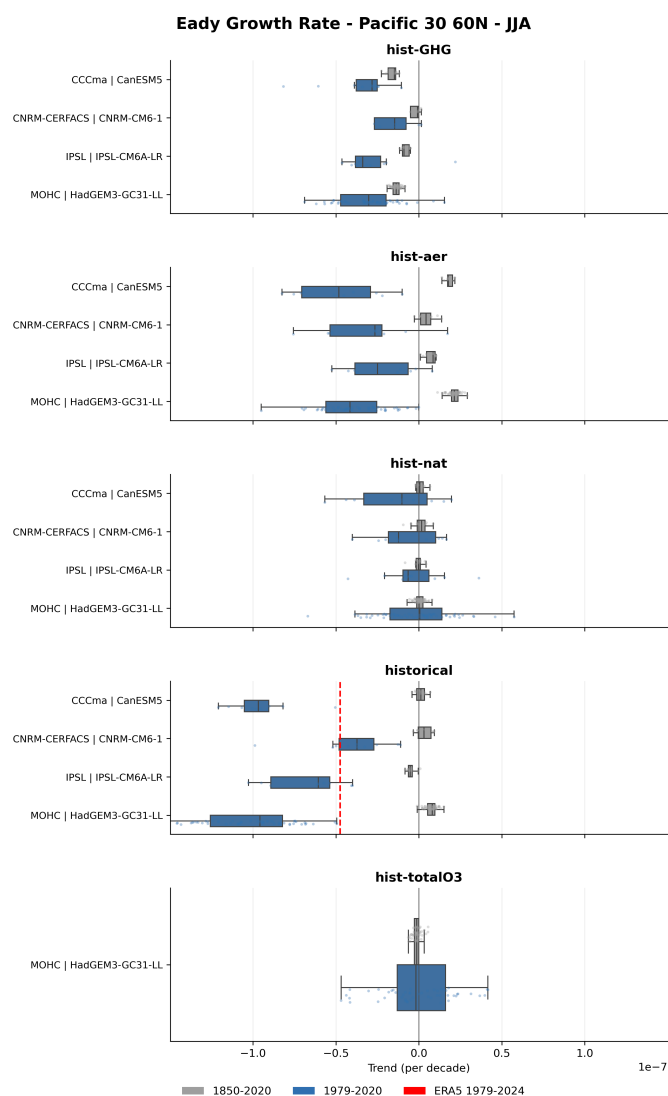


**Figure C1.** Regional mean Eady Growth Rate trends in the North Atlantic (between  $30^{\circ} - 60^{\circ}N$  and  $280^{\circ} - 350^{\circ}E$ ) across the single forcing models and experiments used.

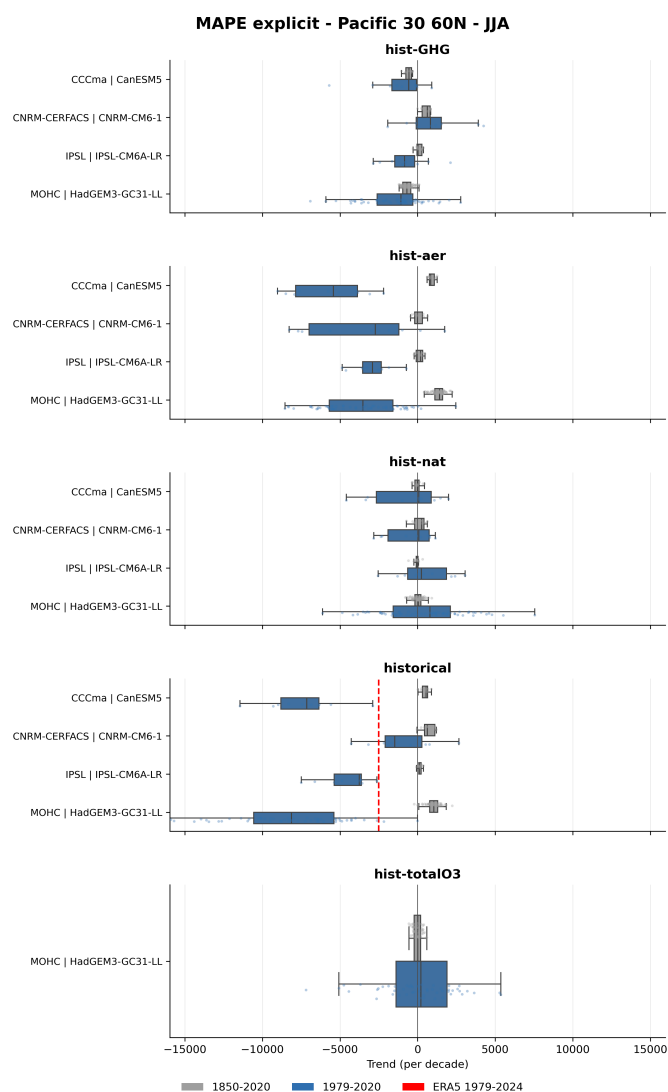


**Figure C2.** Regional mean baroclinic MAPE trends in the North Atlantic (between  $30^{\circ} - 60^{\circ}N$  and  $280^{\circ} - 350^{\circ}E$ ) across the single forcing models and experiments used.

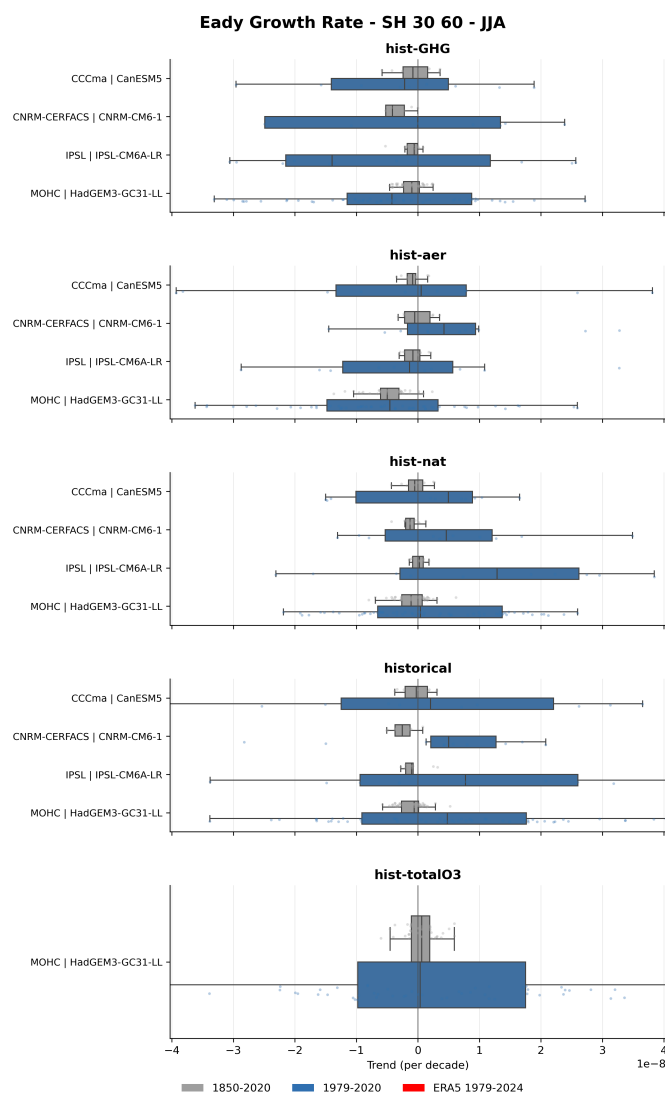




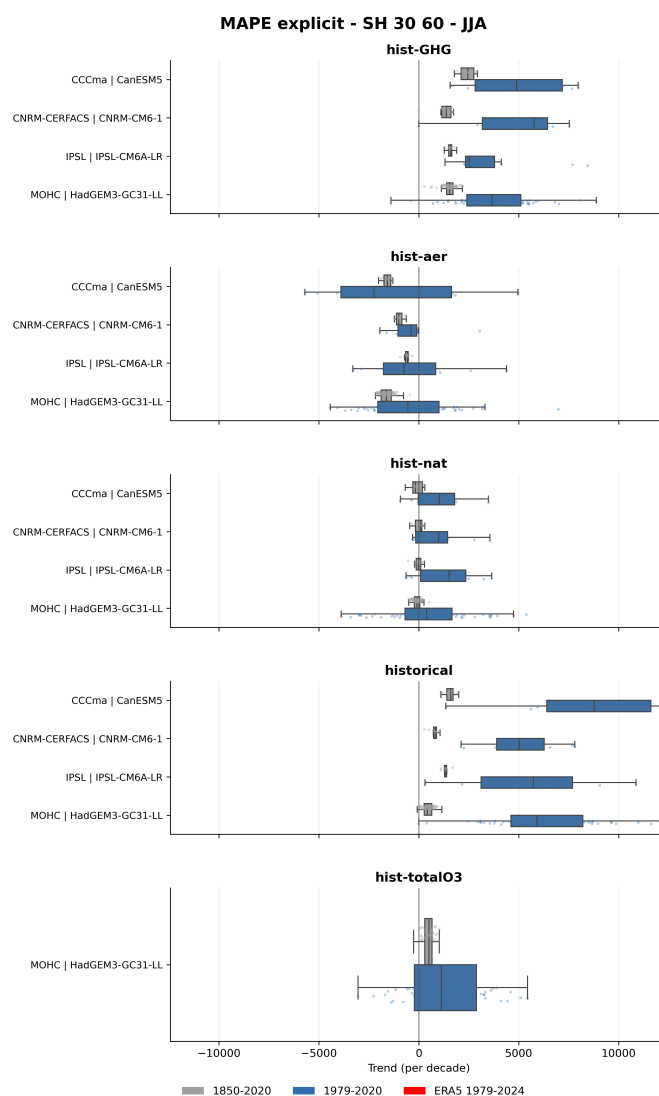
**Figure C3.** Regional mean Eady Growth Rate trends in the North Pacific (between  $30^{\circ} - 60^{\circ} N$  and  $280^{\circ} - 350^{\circ} E$ ) across the single forcing models and experiments used.



**Figure C4.** Regional mean baroclinic MAPE trends in the North Pacific (between  $30^{\circ} - 60^{\circ} N$  and  $280^{\circ} - 350^{\circ} E$ ) across the single forcing models and experiments used.



**Figure C5.** Regional mean Eady Growth Rate trends in the SH mid-latitudes (between  $30^{\circ}$  –  $60^{\circ}$ S) across the single forcing models and experiments used.

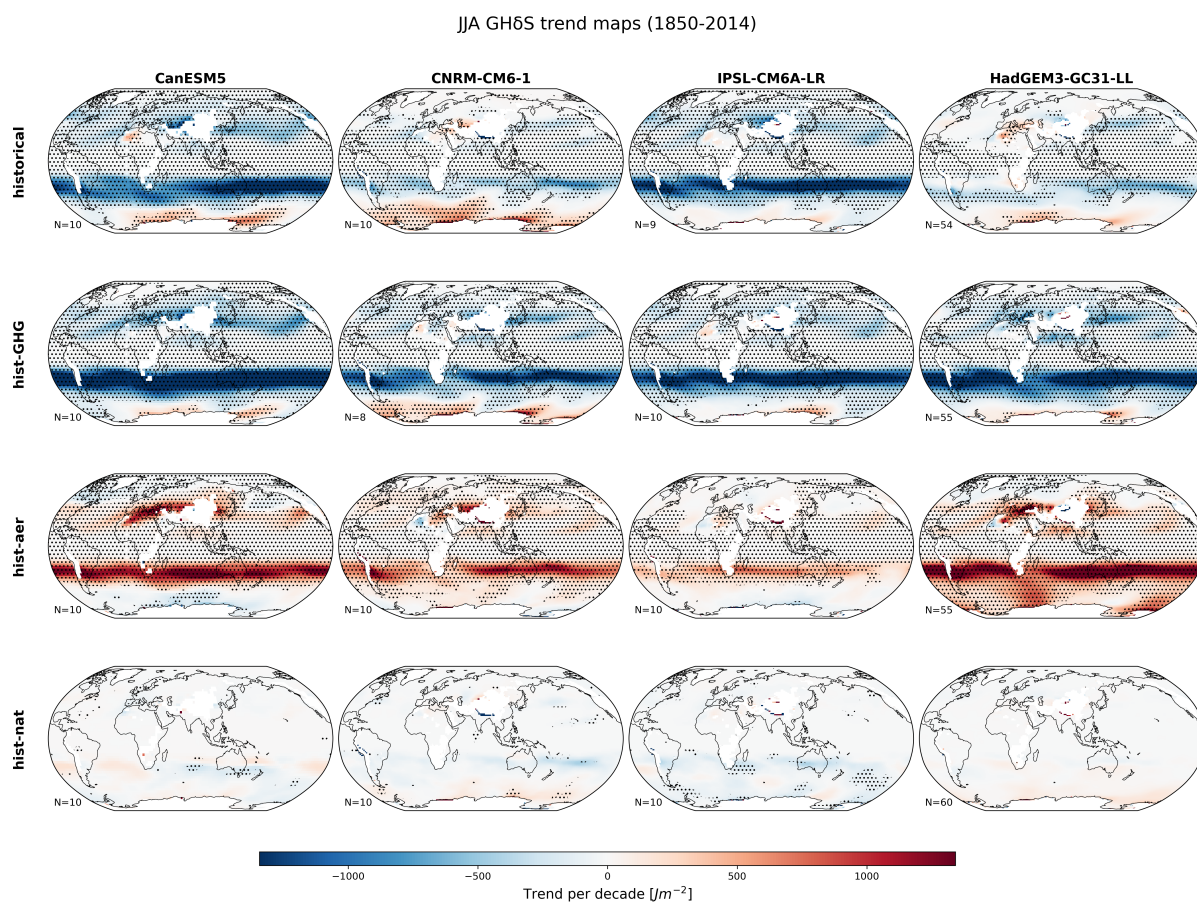


**Figure C6.** Regional mean baroclinic MAPE trends in the SH mid-latitudes (between  $30^{\circ}$  –  $60^{\circ}$ S) across the single forcing models and experiments used.

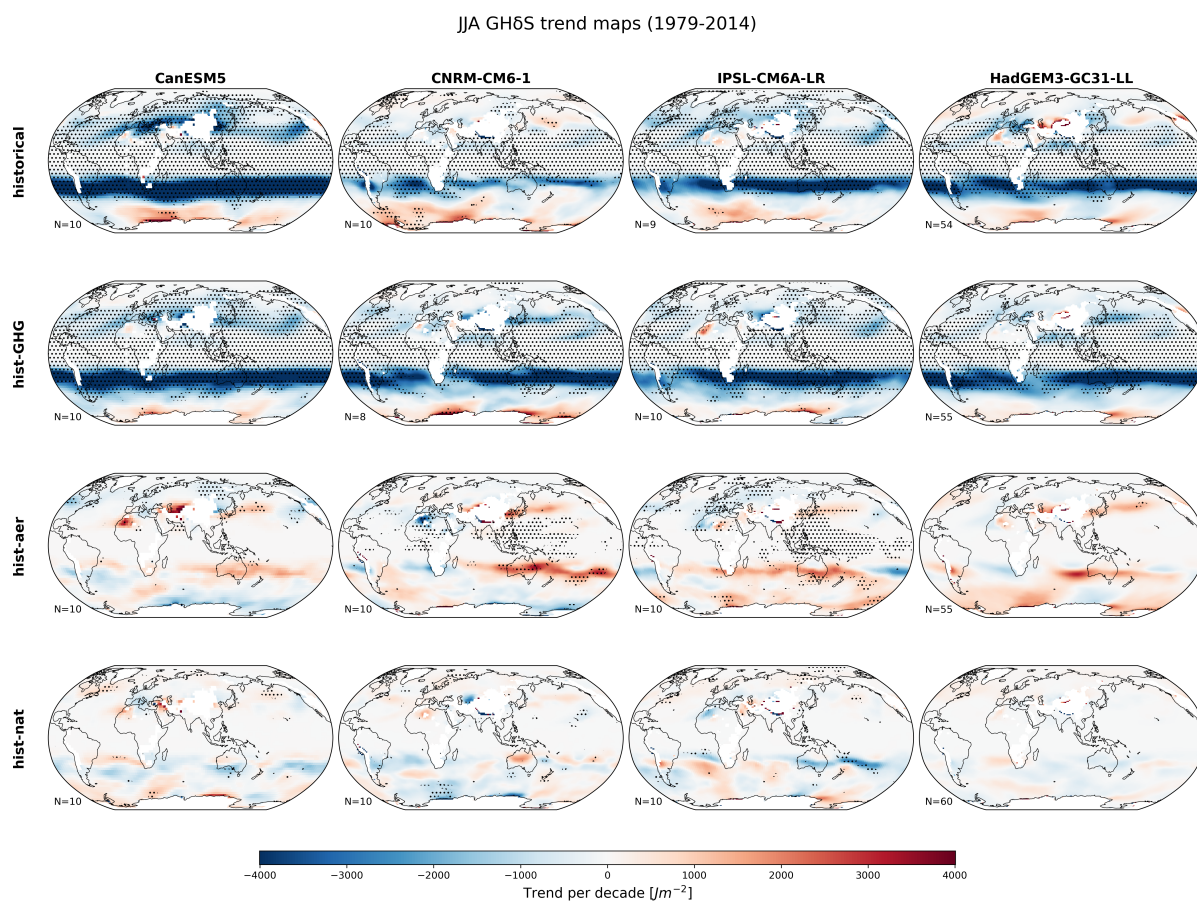




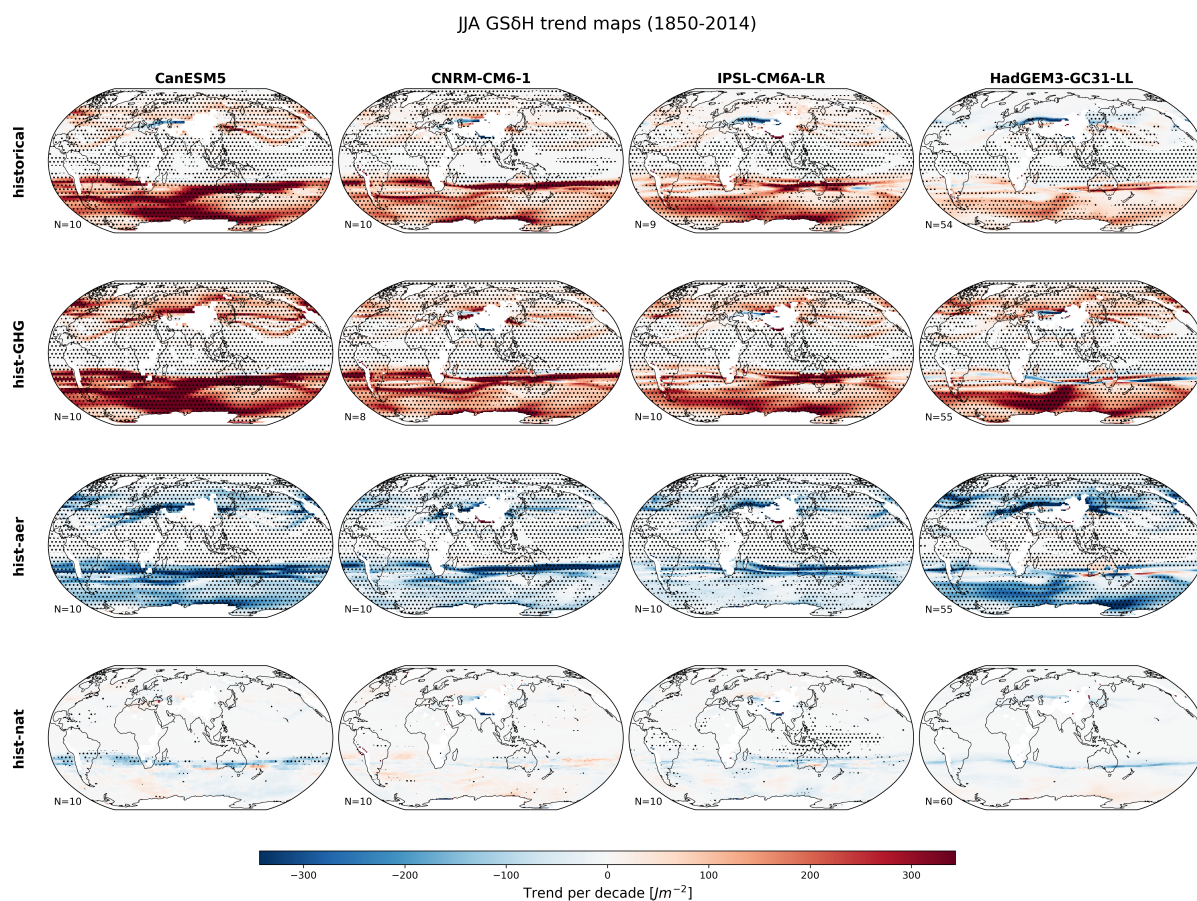
## Appendix D: Baroclinic MAPE decomposition's trends in the single forcing experiments



**Figure D1.** Spatial maps of trends in  $GH\delta S$  across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

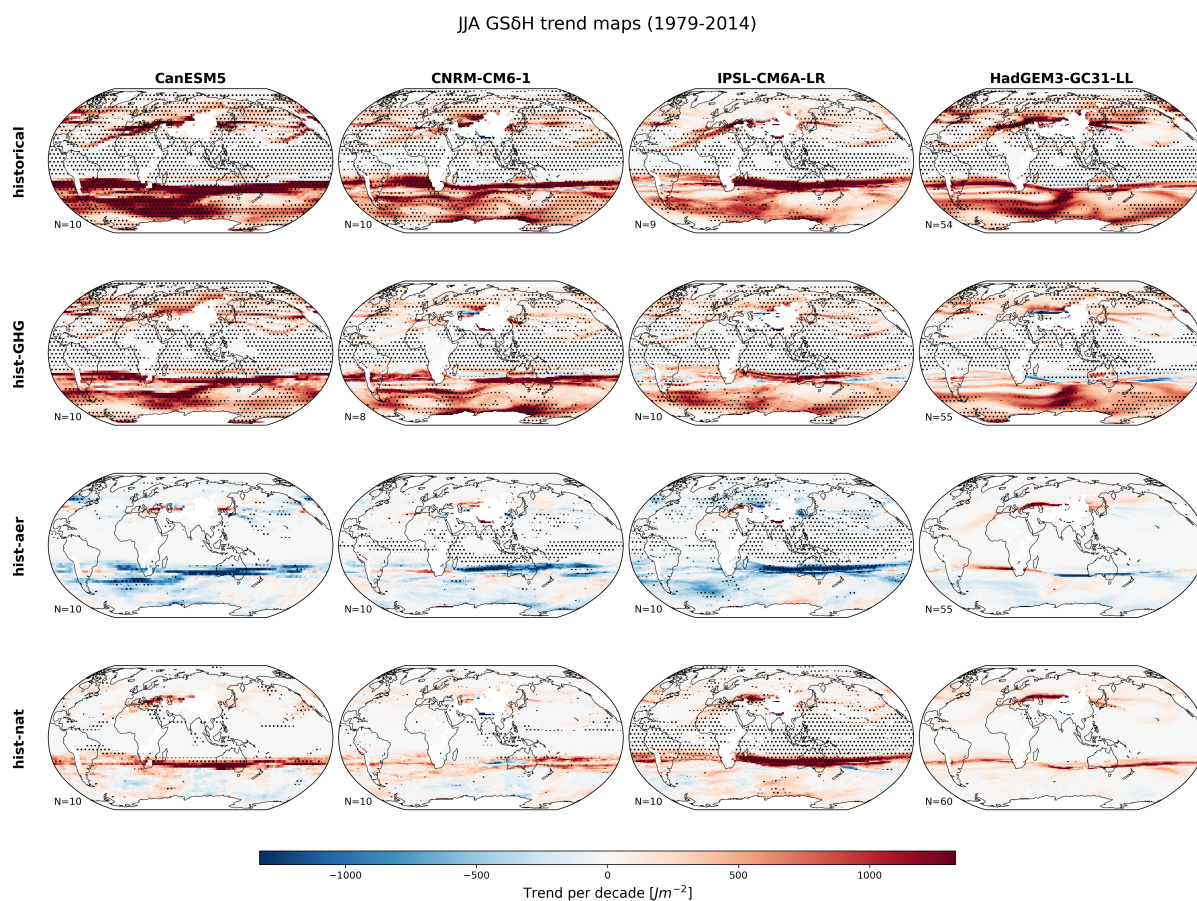


**Figure D2.** Spatial maps of trends in  $\text{GH}\delta\text{S}$  across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.



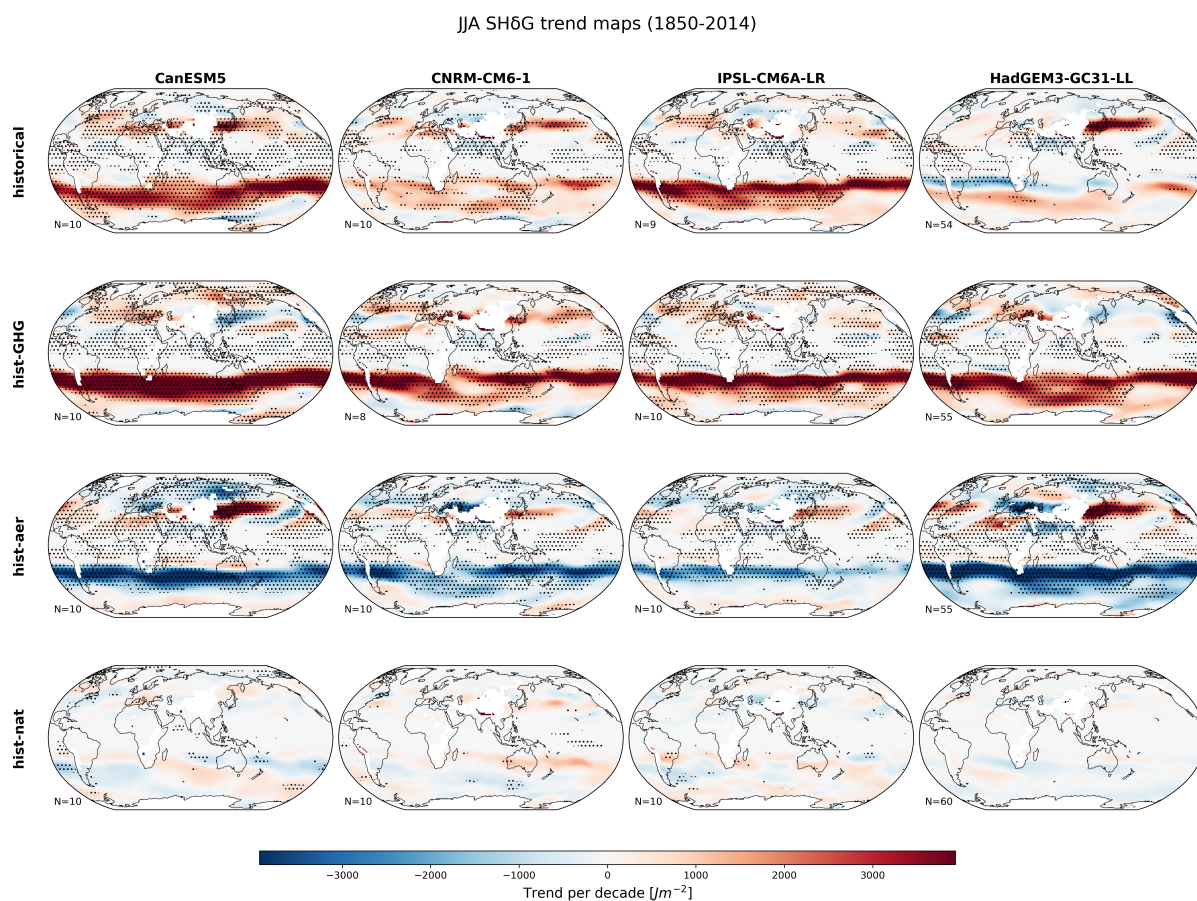
**Figure D3.** Spatial maps of trends in  $GS\delta H$  across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.



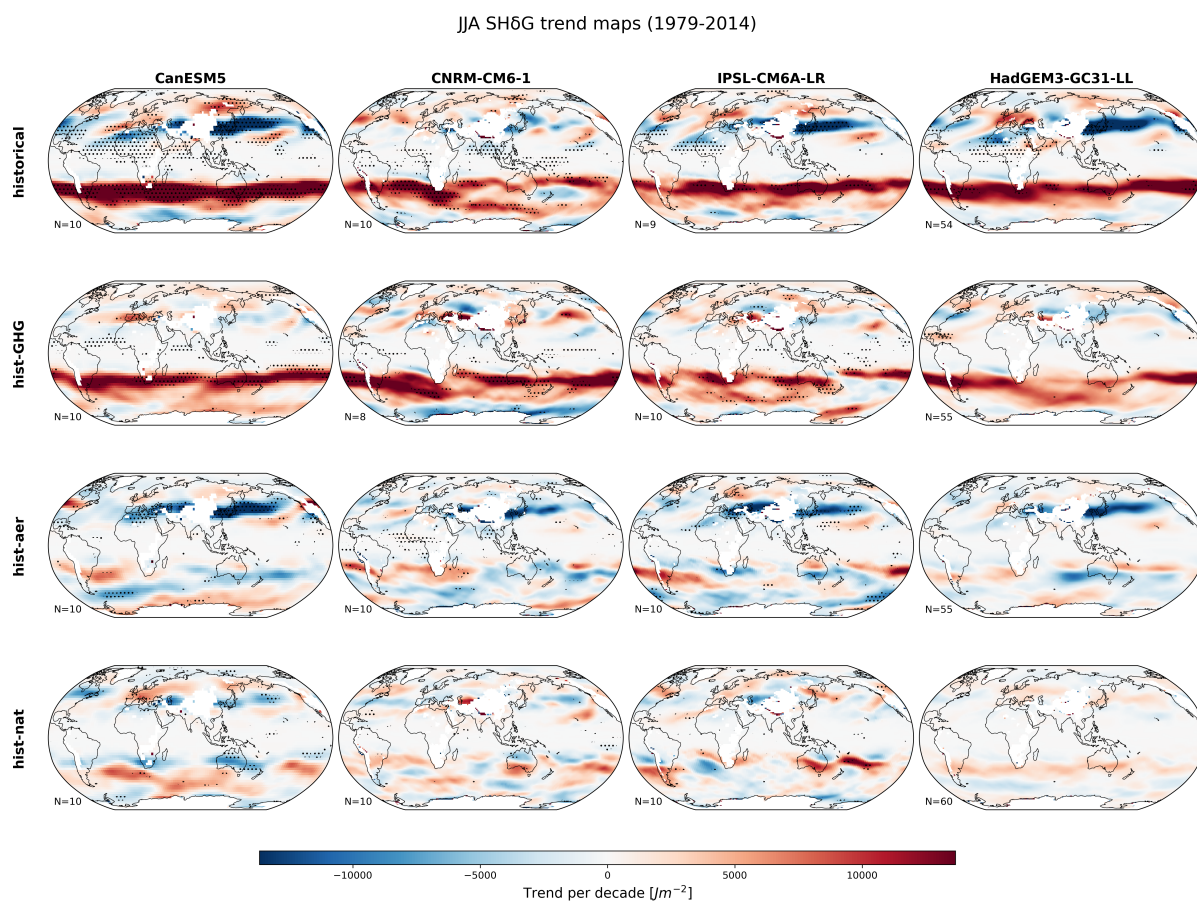


**Figure D4.** Spatial maps of trends in  $GS\delta H$  across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.





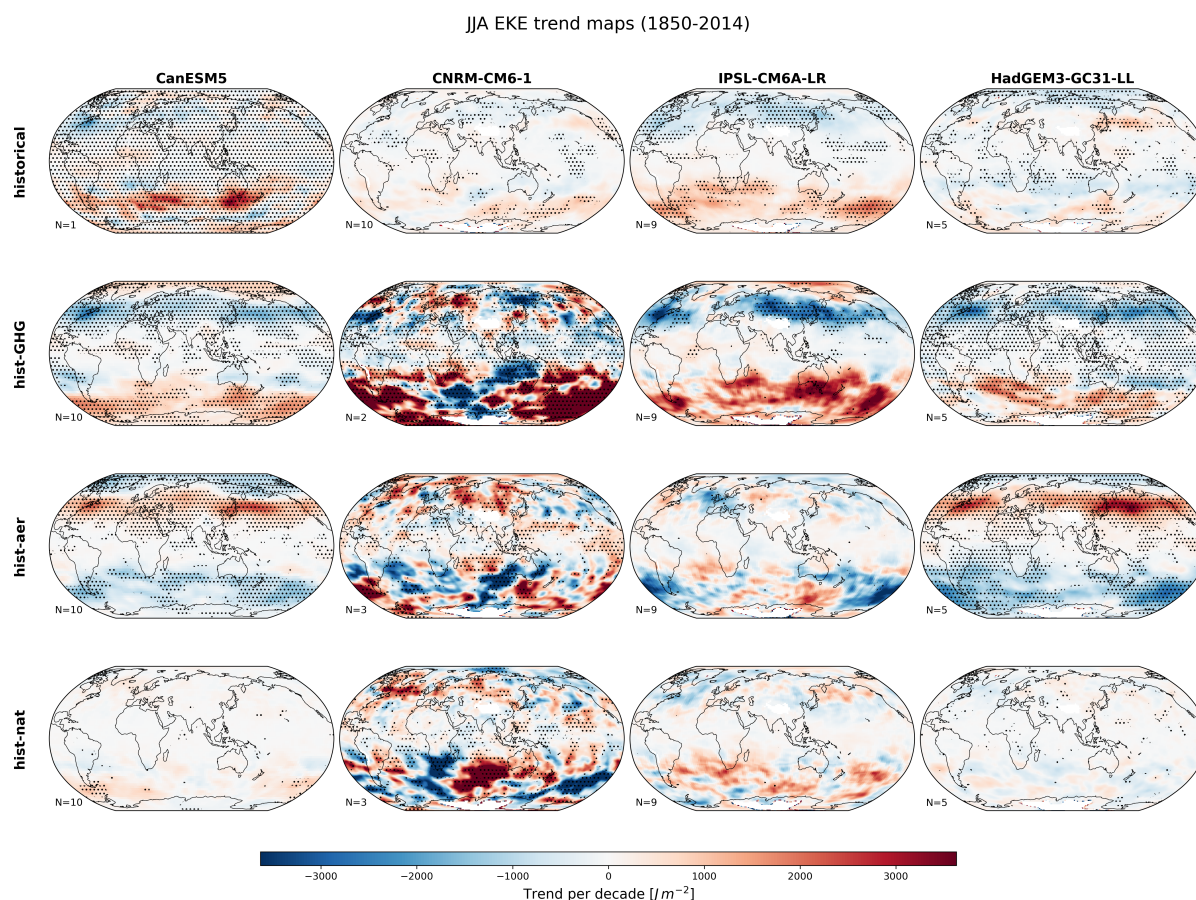
**Figure D5.** Spatial maps of trends in  $SH\delta G$  across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.



**Figure D6.** Spatial maps of trends in  $SH\delta G$  across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.



## Appendix E: Eddy Kinetic Energy trends in the single forcing experiments

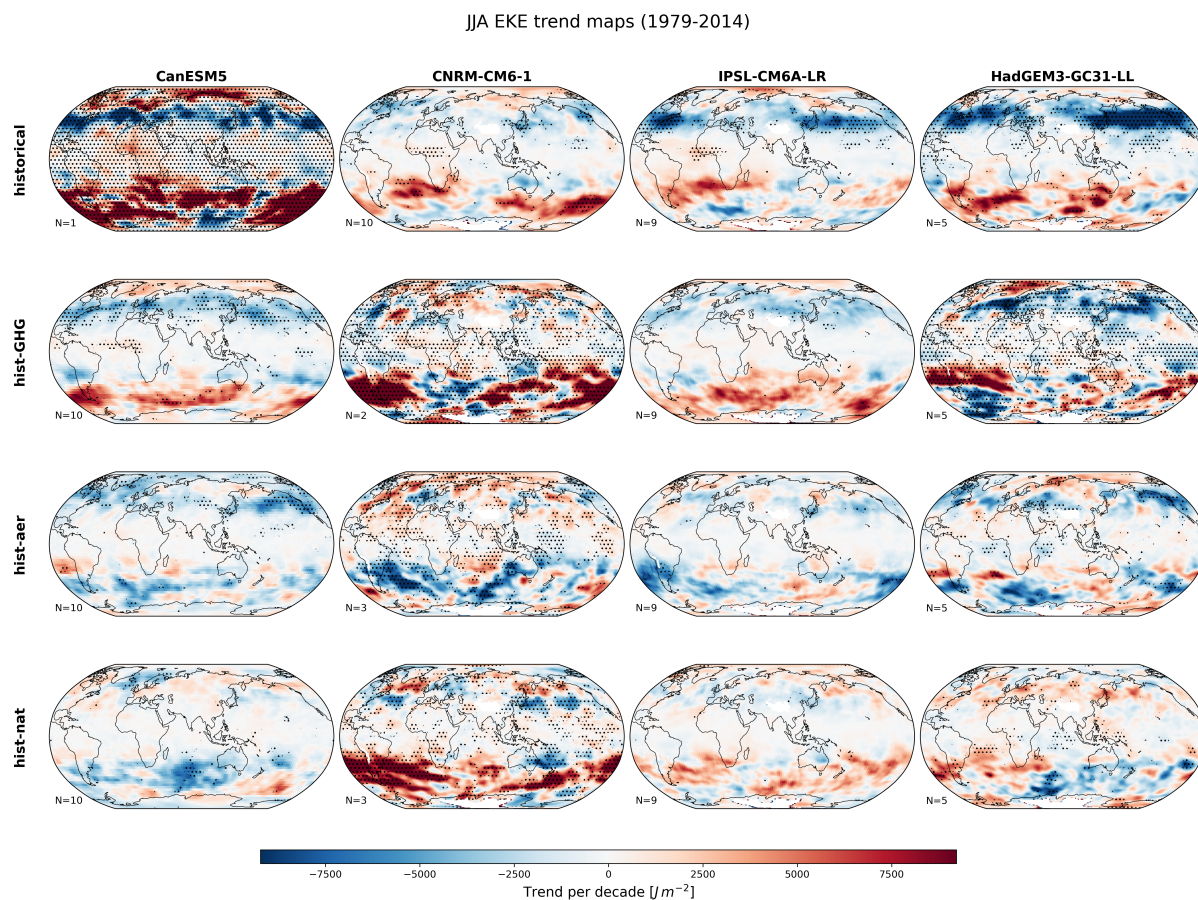


**Figure E1.** Spatial maps of trends in EKE across the models and experiments used in the single forcing experiments for the 1850–2014 period. Stippling indicates agreement of  $> 80\%$  of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

520 *Author contributions.* OC conducted the analysis and main writing of the manuscript. TW, NH, SO and PS aided in the derivation of the methodology, helped explain the results, and contributed to the discussion and writing.

*Competing interests.* At least one of the (co-)authors is a member of the editorial board of Weather and Climate Dynamics.





**Figure E2.** Spatial maps of trends in EKE across the models and experiments used in the single forcing experiments for the 1979–2014 period. Stippling indicates agreement of > 80% of the members on the sign of the trend. To the lower left of each panel, the number of members available for this diagnostic is stated.

*Acknowledgements.* This work was supported by funding from the Biotechnology and Biological Sciences Research Council and the Natural Environment Research Council (UKRI-BBSRC/NERC) [grant number UKRI1352]. OC is also supported by Reuben College through a Reuben-Oxford scholarship for doctoral studies. SO is also supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) through the Advanced Studies of Climate Change Projection (JPMXD0722680395) and by the Japan-UK Fellowship of the University of Reading. NCGH from acknowledges support UKRI FLF MR/W011379/1. Generative AI tools, including ChatGPT EDU and GitHub Copilot, were used to assist in identifying and correcting errors in the analysis code and improving code organisation and readability. All analysis and interpretation were reviewed and verified by the authors.





## 530 References

- Adam, O., Schneider, T., and Harnik, N.: Role of Changes in Mean Temperatures versus Temperature Gradients in the Recent Widening of the Hadley Circulation, *Journal of Climate*, 27, 7450–7461, <https://doi.org/10.1175/JCLI-D-14-00140.1>, 2014.
- Alexander, M. A., Scott, J. D., Friedland, K. D., Mills, K. E., Nye, J. A., Pershing, A. J., and Thomas, A. C.: Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of Northern Oceans, *Elementa: Science of the Anthropocene*, 6, 9, <https://doi.org/10.1525/elementa.191>, 2018.
- 535 Andrews, M. B., Ridley, J. K., Wood, R. A., Andrews, T., Blockley, E. W., Booth, B., Burke, E., Dittus, A. J., Florek, P., Gray, L. J., Haddad, S., Hardiman, S. C., Hermanson, L., Hodson, D., Hogan, E., Jones, G. S., Knight, J. R., Kuhlbrodt, T., Misios, S., Mizieliński, M. S., Ringer, M. A., Robson, J., and Sutton, R. T.: Historical Simulations With HadGEM3-GC3.1 for CMIP6, *Journal of Advances in Modeling Earth Systems*, 12, e2019MS001995, <https://doi.org/10.1029/2019MS001995>, 2020a.
- 540 Andrews, M. B., Ridley, J. K., Wood, R. A., Andrews, T., Blockley, E. W., Booth, B., Burke, E., Dittus, A. J., Florek, P., Gray, L. J., Haddad, S., Hardiman, S. C., Hermanson, L., Hodson, D., Hogan, E., Jones, G. S., Knight, J. R., Kuhlbrodt, T., Misios, S., Mizieliński, M. S., Ringer, M. A., Robson, J., and Sutton, R. T.: Historical Simulations With HadGEM3-GC3.1 for CMIP6, *Journal of Advances in Modeling Earth Systems*, 12, e2019MS001995, <https://doi.org/10.1029/2019MS001995>, [\\_eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019MS001995](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019MS001995), 2020b.
- 545 Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D’Andrea, F., Davini, P., de Lavergne, C., Denvil, S., Deshayes, J., Devilliers, M., Ducharne, A., Dufresne, J.-L., Dupont, E., Éthé, C., Fairhead, L., Falletti, L., Flavoni, S., Foujols, M.-A., Gardoll, S., Gastineau, G., Ghattas, J., Grandpeix, J.-Y., Guenet, B., Guez, Lionel, E., Guilyardi, E., Guimberteau, M., Hauglustaine, D., Hourdin, F., Idelkadi, A., Joussaume, S., Kageyama, M., Khodri, M., Krinner, G., Lebas, N., Levavasseur, G., Lévy, C., Li, L., Lott, F.,
- 550 Lurton, T., Luyssaert, S., Madec, G., Madeleine, J.-B., Maignan, F., Marchand, M., Marti, O., Mellul, L., Meurdesoif, Y., Mignot, J., Musat, I., Ottlé, C., Peylin, P., Planton, Y., Polcher, J., Rio, C., Rochetin, N., Rousset, C., Sepulchre, P., Sima, A., Swingedouw, D., Thiéblemont, R., Traore, A. K., Vancoppenolle, M., Vial, J., Vialard, J., Viovy, N., and Vuichard, N.: Presentation and Evaluation of the IPSL-CM6A-LR Climate Model, *Journal of Advances in Modeling Earth Systems*, 12, e2019MS002010, <https://doi.org/10.1029/2019MS002010>, [\\_eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019MS002010](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019MS002010), 2020.
- 555 Chang, E. K. M., Ma, C.-G., Zheng, C., and Yau, A. M. W.: Observed and Projected Decrease in Northern Hemisphere Extratropical Cyclone Activity in Summer and Its Impacts on Maximum Temperature, *Geophysical Research Letters*, 43, 2200–2208, <https://doi.org/10.1002/2016GL068172>, 2016.
- Chemke, R.: Centennial-Scale Recovery of the North Atlantic Summer Storm Track Weakening, *Geophysical Research Letters*, 51, e2024GL109801, <https://doi.org/10.1029/2024GL109801>, 2024.
- 560 Chemke, R. and Coumou, D.: Human Influence on the Recent Weakening of Storm Tracks in Boreal Summer, *npj Climate and Atmospheric Science*, 7, 86, <https://doi.org/10.1038/s41612-024-00640-2>, 2024.
- Chemke, R. and Yuval, J.: Human-Induced Weakening of the Northern Hemisphere Tropical Circulation, *Nature*, 617, 529–532, <https://doi.org/10.1038/s41586-023-05903-1>, 2023.
- Chemke, R. and Yuval, J.: Climate Change Shifts the North Pacific Storm Track Polewards, *Nature*, 649, 626–630, <https://doi.org/10.1038/s41586-025-09895-y>, 2026.
- 565



- Chen, C. and Wang, G.: Role of North Pacific Mixed Layer in the Response of SST Annual Cycle to Global Warming, *Journal of Climate*, 28, 9451–9458, <https://doi.org/10.1175/JCLI-D-14-00349.1>, 2015.
- Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., and Jones, J.: Recent Arctic Amplification and Extreme Mid-Latitude Weather, *Nature Geoscience*, 7, 627–637, <https://doi.org/10.1038/ngeo2234>, 2014.
- Coumou, D., Lehmann, J., and Beckmann, J.: The weakening summer circulation in the Northern Hemisphere mid-latitudes, <https://doi.org/10.1126/science.1261768>, 2015.
- Dong, B. and Sutton, R. T.: Recent Trends in Summer Atmospheric Circulation in the North Atlantic/European Region: Is There a Role for Anthropogenic Aerosols?, *Journal of Climate*, 34, 6777–6795, <https://doi.org/10.1175/JCLI-D-20-0665.1>, 2021.
- 575 Dong, B., Sutton, R. T., Woollings, T., and Hodges, K.: Variability of the North Atlantic summer storm track: mechanisms and impacts on European climate, *Environmental Research Letters*, 8, 034 037, <https://doi.org/10.1088/1748-9326/8/3/034037>, 2013.
- Dong, B., Sutton, R. T., Shaffrey, L., and Harvey, B.: Recent Decadal Weakening of the Summer Eurasian Westerly Jet Attributable to Anthropogenic Aerosol Emissions, *Nature Communications*, 13, 1148, <https://doi.org/10.1038/s41467-022-28816-5>, 2022.
- Folland, C. K., Knight, J., Linderholm, H. W., Fereday, D., Ineson, S., and Hurrell, J. W.: The Summer North Atlantic Oscillation: Past, 580 Present, and Future, *Journal of Climate*, 22, 1082–1103, <https://doi.org/10.1175/2008JCLI2459.1>, 2009.
- Francis, J. A. and Vavrus, S. J.: Evidence Linking Arctic Amplification to Extreme Weather in Mid-Latitudes, *Geophysical Research Letters*, 39, <https://doi.org/10.1029/2012GL051000>, 2012.
- Gertler, C. G. and O’Gorman, P. A.: Changing Available Energy for Extratropical Cyclones and Associated Convection in Northern Hemisphere Summer, *Proceedings of the National Academy of Sciences*, 116, 4105–4110, <https://doi.org/10.1073/pnas.1812312116>, 2019.
- 585 Gillett, N. P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B. D., Stone, D., and Tebaldi, C.: The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) Contribution to CMIP6, *Geoscientific Model Development*, 9, 3685–3697, <https://doi.org/10.5194/gmd-9-3685-2016>, 2016.
- Hall, N. M. J., Hoskins, B. J., Valdes, P. J., and Senior, C. A.: Storm tracks in a high-resolution GCM with doubled carbon dioxide, *Quarterly Journal of the Royal Meteorological Society*, 120, 1209–1230, <https://doi.org/10.1002/qj.49712051905>, <https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.49712051905>, 1994.
- 590 Harvey, B., Hawkins, E., and Sutton, R.: Storylines for Future Changes of the North Atlantic Jet and Associated Impacts on the UK, *International Journal of Climatology*, 43, 4424–4441, <https://doi.org/10.1002/joc.8095>, 2023.
- Harvey, B. J., Shaffrey, L. C., and Woollings, T. J.: Equator-to-pole temperature differences and the extra-tropical storm track responses of the CMIP5 climate models, *Climate Dynamics*, 43, 1171–1182, <https://doi.org/10.1007/s00382-013-1883-9>, 2014.
- 595 Held, I. M. and Soden, B. J.: Robust Responses of the Hydrological Cycle to Global Warming, *Journal of Climate*, 19, 5686–5699, <https://doi.org/10.1175/JCLI3990.1>, 2006.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., 600 Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N.: The ERA5 Global Reanalysis, *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.



- Hoffmann, L. and Spang, R.: An Assessment of Tropopause Characteristics of the ERA5 and ERA-Interim Meteorological Reanalyses, *Atmospheric Chemistry and Physics*, 22, 4019–4046, <https://doi.org/10.5194/acp-22-4019-2022>, 2022.
- 605 Hoskins, B. J. and Valdes, P. J.: On the Existence of Storm-Tracks, *Journal of the Atmospheric Sciences*, 47, 1854–1864, [https://doi.org/10.1175/1520-0469\(1990\)047<1854:OTEOST>2.0.CO;2](https://doi.org/10.1175/1520-0469(1990)047<1854:OTEOST>2.0.CO;2), 1990.
- Jo, A. R., Lee, J.-Y., Timmermann, A., Jin, F.-F., Yamaguchi, R., and Gallego, A.: Future Amplification of Sea Surface Temperature Seasonality Due To Enhanced Ocean Stratification, *Geophysical Research Letters*, 49, e2022GL098 607, <https://doi.org/10.1029/2022GL098607>, [\\_eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2022GL098607](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2022GL098607), 2022.
- 610 Kang, J. M., Shaw, T. A., and Sun, L.: Arctic Sea Ice Loss Weakens Northern Hemisphere Summertime Storminess but Not Until the Late 21st Century, *Geophysical Research Letters*, 50, e2022GL102 301, <https://doi.org/10.1029/2022GL102301>, 2023.
- Kang, J. M., Shaw, T. A., Kang, S. M., Simpson, I. R., and Yu, Y.: Revisiting the reanalysis-model discrepancy in Southern Hemisphere winter storm track trends, *npj Climate and Atmospheric Science*, 7, 252, <https://doi.org/10.1038/s41612-024-00801-3>, 2024a.
- Kang, J. M., Shaw, T. A., and Sun, L.: Anthropogenic Aerosols Have Significantly Weakened the Regional Summertime Circulation in the Northern Hemisphere During the Satellite Era, *AGU Advances*, 5, e2024AV001 318, <https://doi.org/10.1029/2024AV001318>, 2024b.
- 615 Kang, J. M., Thomas, R., Dunstone, N., Shaw, T. A., and Woollings, T.: Robust Impact of Tropical Pacific SST Trends on Global and Regional Circulation in Boreal Winter, *npj Climate and Atmospheric Science*, 8, 315, <https://doi.org/10.1038/s41612-025-01192-9>, 2025.
- Lehmann, J., Coumou, D., Frieler, K., Eliseev, A. V., and Levermann, A.: Future changes in extratropical storm tracks and baroclinicity under climate change, *Environmental Research Letters*, 9, 084 002, <https://doi.org/10.1088/1748-9326/9/8/084002>, 2014.
- 620 Lindzen, R. S. and Farrell, B.: A Simple Approximate Result for the Maximum Growth Rate of Baroclinic Instabilities, *Journal of the Atmospheric Sciences*, 37, 1648–1654, [https://doi.org/10.1175/1520-0469\(1980\)037<1648:ASARFT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1980)037<1648:ASARFT>2.0.CO;2), 1980.
- Lorenz, D. J. and DeWeaver, E. T.: Tropopause Height and Zonal Wind Response to Global Warming in the IPCC Scenario Integrations, *Journal of Geophysical Research: Atmospheres*, 112, <https://doi.org/10.1029/2006JD008087>, 2007.
- Lorenz, E. N.: Available Potential Energy and the Maintenance of the General Circulation, *Tellus*, 7, 157–167, <https://doi.org/10.3402/tellusa.v7i2.8796>, 1955.
- 625 Lu, J., Vecchi, G. A., and Reichler, T.: Expansion of the Hadley Cell under Global Warming, *Geophysical Research Letters*, 34, <https://doi.org/10.1029/2006GL028443>, 2007.
- Mbengue, C. and Schneider, T.: Storm Track Shifts under Climate Change: What Can Be Learned from Large-Scale Dry Dynamics, *Journal of Climate*, 26, 9923–9930, <https://doi.org/10.1175/JCLI-D-13-00404.1>, 2013.
- 630 Mbengue, C. and Schneider, T.: Storm-Track Shifts under Climate Change: Toward a Mechanistic Understanding Using Baroclinic Mean Available Potential Energy, <https://doi.org/10.1175/JAS-D-15-0267.1>, 2017a.
- Mbengue, C. and Schneider, T.: Storm-Track Shifts under Climate Change: Toward a Mechanistic Understanding Using Baroclinic Mean Available Potential Energy, *Journal of the Atmospheric Sciences*, 74, 93–110, <https://doi.org/10.1175/JAS-D-15-0267.1>, 2017b.
- Mbengue, C. and Schneider, T.: Linking Hadley Circulation and Storm Tracks in a Conceptual Model of the Atmospheric Energy Balance, <https://doi.org/10.1175/JAS-D-17-0098.1>, 2018.
- 635 Mbengue, C. O., Woollings, T., Dacre, H. F., and Hodges, K. I.: The Roles of Static Stability and Tropical–Extratropical Interactions in the Summer Interannual Variability of the North Atlantic Sector, *Climate Dynamics*, 52, 1299–1315, <https://doi.org/10.1007/s00382-018-4192-5>, 2019.
- O’Gorman, P. A.: Understanding the Varied Response of the Extratropical Storm Tracks to Climate Change, *Proceedings of the National Academy of Sciences*, 107, 19 176–19 180, <https://doi.org/10.1073/pnas.1011547107>, 2010.
- 640



- O’Gorman, P. A. and Schneider, T.: Energy of Midlatitude Transient Eddies in Idealized Simulations of Changed Climates, <https://doi.org/10.1175/2008JCLI2099.1>, 2008.
- Quaas, J., Jia, H., Smith, C., Albright, A. L., Aas, W., Bellouin, N., Boucher, O., Doutriaux-Boucher, M., Forster, P. M., Grosvenor, D., Jenkins, S., Klimont, Z., Loeb, N. G., Ma, X., Naik, V., Paulot, F., Stier, P., Wild, M., Myhre, G., and Schulz, M.: Robust evidence for reversal of the trend in aerosol effective climate forcing, *Atmospheric Chemistry and Physics*, 22, 12 221–12 239, <https://doi.org/10.5194/acp-22-12221-2022>, 2022.
- Reichler, T., Dameris, M., and Sausen, R.: Determining the Tropopause Height from Gridded Data, *Geophysical Research Letters*, 30, <https://doi.org/10.1029/2003GL018240>, 2003.
- Ridley, J., Menary, M., Kuhlbrodt, T., Andrews, M., and Andrews, T.: MOHC HadGEM3-GC31-LL Model Output Prepared for CMIP6 CMIP, <https://doi.org/10.22033/ESGF/CMIP6.419>, 2018.
- Rivière, G.: A Dynamical Interpretation of the Poleward Shift of the Jet Streams in Global Warming Scenarios, *Journal of the Atmospheric Sciences*, 68, 1253–1272, <https://doi.org/10.1175/2011JAS3641.1>, 2011.
- Shaw, T. A.: Mechanisms of Future Predicted Changes in the Zonal Mean Mid-Latitude Circulation, *Current Climate Change Reports*, 5, 345–357, <https://doi.org/10.1007/s40641-019-00145-8>, 2019.
- Shaw, T. A., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C. I., Hwang, Y.-T., Li, C., O’Gorman, P. A., Rivière, G., Simpson, I. R., and Voigt, A.: Storm Track Processes and the Opposing Influences of Climate Change, *Nature Geoscience*, 9, 656–664, <https://doi.org/10.1038/ngeo2783>, 2016.
- Shaw, T. A., Barpanda, P., and Donohoe, A.: A Moist Static Energy Framework for Zonal-Mean Storm-Track Intensity, *Journal of the Atmospheric Sciences*, 75, 1979–1994, <https://doi.org/10.1175/JAS-D-17-0183.1>, 2018.
- Smith, C. J., Kramer, R. J., Myhre, G., Alterskjær, K., Collins, W., Sima, A., Boucher, O., Dufresne, J.-L., Nabat, P., Michou, M., Yukimoto, S., Cole, J., Paynter, D., Shiogama, H., O’Connor, F. M., Robertson, E., Wiltshire, A., Andrews, T., Hannay, C., Miller, R., Nazarenko, L., Kirkevåg, A., Olivé, D., Fiedler, S., Lewinschal, A., Mackallah, C., Dix, M., Pincus, R., and Forster, P. M.: Effective radiative forcing and adjustments in CMIP6 models, *Atmospheric Chemistry and Physics*, 20, 9591–9618, <https://doi.org/10.5194/acp-20-9591-2020>, 2020.
- Smith, D. M., Gillett, N. P., Simpson, I. R., Athanasiadis, P. J., Baehr, J., Bethke, I., Bilge, T. A., Bonnet, R., Boucher, O., Findell, K. L., Gastineau, G., Gualdi, S., Hermanson, L., Leung, L. R., Mignot, J., Müller, W. A., Osprey, S., Otterå, O. H., Persad, G. G., Scaife, A. A., Schmidt, G. A., Shiogama, H., Sutton, R. T., Swingedouw, D., Yang, S., Zhou, T., and Ziehn, T.: Attribution of Multi-Annual to Decadal Changes in the Climate System: The Large Ensemble Single Forcing Model Intercomparison Project (LESFMP), *Frontiers in Climate*, 4, <https://doi.org/10.3389/fclim.2022.955414>, 2022.
- Stier, P.: Limitations of passive remote sensing to constrain global cloud condensation nuclei, *Atmospheric Chemistry and Physics*, 16, 6595–6607, <https://doi.org/10.5194/acp-16-6595-2016>, 2016.
- Swart, N. C., Cole, J. N. S., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., Anstey, J., Arora, V., Christian, J. R., Hanna, S., Jiao, Y., Lee, W. G., Majaess, F., Saenko, O. A., Seiler, C., Seinen, C., Shao, A., Sigmond, M., Solheim, L., von Salzen, K., Yang, D., and Winter, B.: The Canadian Earth System Model version 5 (CanESM5.0.3), *Geoscientific Model Development*, 12, 4823–4873, <https://doi.org/10.5194/gmd-12-4823-2019>, 2019.
- Voltaire, A., Saint-Martin, D., Sénési, S., Decharme, B., Alias, A., Chevallier, M., Colin, J., Guérémy, J.-F., Michou, M., Moine, M.-P., Nabat, P., Roehrig, R., Salas y Méliá, D., Séférián, R., Valcke, S., Beau, I., Belamari, S., Berthet, S., Cassou, C., Cattiaux, J., Deshayes, J., Douville, H., Ethé, C., Franchistéguy, L., Geoffroy, O., Lévy, C., Madec, G., Meurdesoif, Y., Msadek, R., Ribes, A., Sanchez-Gomez, E., Terray, L., and Waldman, R.: Evaluation of CMIP6 DECK Experiments With





- 680 CNRM-CM6-1, *Journal of Advances in Modeling Earth Systems*, 11, 2177–2213, <https://doi.org/10.1029/2019MS001683>, \_eprint:  
<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019MS001683>, 2019.
- Woollings, T.: Storm Tracks, Blocking, and Climate Change: A Review, in: *Dynamics and Predictability of Large-Scale, High-Impact Weather and Climate Events*, edited by Volkert, H., Li, J., Grotjahn, R., and Swinbank, R., Special Publications of the International Union of Geodesy and Geophysics, pp. 113–121, Cambridge University Press, Cambridge, <https://doi.org/10.1017/CBO9781107775541.009>, 2016.
- 685 Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., Klein, S. A., and Taylor, K. E.: Causes of Higher Climate Sensitivity in CMIP6 Models, *Geophysical Research Letters*, 47, e2019GL085782, <https://doi.org/10.1029/2019GL085782>, \_eprint:  
<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019GL085782>, 2020.