

*Enhanced climate change response of wintertime North Atlantic circulation, cyclonic activity and precipitation in a 25 km-resolution global atmospheric model*

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Baker, A. J. ORCID: <https://orcid.org/0000-0003-2697-1350>, Schiemann, R. ORCID: <https://orcid.org/0000-0003-3095-9856>, Hodges, K. I. ORCID: <https://orcid.org/0000-0003-0894-229X>, Demory, M.-E., Mizieliński, M. S., Roberts, M. J., Shaffrey, L. C. ORCID: <https://orcid.org/0000-0003-2696-752X>, Strachan, J. and Vidale, P. L. ORCID: <https://orcid.org/0000-0002-1800-8460> (2019) Enhanced climate change response of wintertime North Atlantic circulation, cyclonic activity and precipitation in a 25 km-resolution global atmospheric model. *Journal of Climate*, 32 (22). pp. 7763-7781. ISSN 1520-0442 doi: <https://doi.org/10.1175/JCLI-D-19-0054.1> Available at <https://centaur.reading.ac.uk/86133/>

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# Enhanced climate change response of wintertime North Atlantic circulation, cyclonic activity and precipitation in a 25 km-resolution global atmospheric model



Alexander J. Baker<sup>1,\*</sup>, Reinhard Schiemann<sup>1</sup>, Kevin I. Hodges<sup>1</sup>, Marie-Estelle Demory<sup>1</sup>,  
Matthew S. Mizieliński<sup>2</sup>, Malcolm J. Roberts<sup>2</sup>, Len C. Shaffrey<sup>1</sup>, Jane Strachan<sup>2</sup>, and Pier  
Luigi Vidale<sup>1</sup>

<sup>1</sup> National Centre for Atmospheric Science and Department of Meteorology, University of Reading, Reading, Berkshire, UK

<sup>2</sup> Met Office Hadley Centre, Exeter, Devon, UK

\* alexander.baker@reading.ac.uk

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## 1 **Abstract**

2 Wintertime mid-latitude cyclone activity and precipitation are projected to increase across  
3 northern Europe and decrease over southern Europe, particularly over the western  
4 Mediterranean. Greater confidence in these regional projections may be established by their  
5 replication in state-of-the-art, high-resolution global climate models that resolve synoptic-  
6 scale dynamics. We evaluated the representation of the wintertime eddy-driven and  
7 subtropical jet streams, extratropical cyclone activity and precipitation across the North  
8 Atlantic and Europe under historical (1985-2011) and RCP8.5 sea surface temperature  
9 forcing in an ensemble of atmosphere-only HadGEM3-GA3.0 simulations, where horizontal  
10 atmospheric resolution is increased from 135 to 25 km. Under RCP8.5, increased (decreased)  
11 frequency of northern (southern) eddy-driven jet occurrences and a basin-wide poleward shift  
12 in the upper-level westerly flow are simulated. Increasing atmospheric resolution  
13 significantly enhances these climate change responses. At 25 km resolution, these enhanced  
14 changes in large-scale circulation amplify increases (decreases) in extratropical cyclone track  
15 density and mean intensity across the northern (southern) Euro-Atlantic region under  
16 RCP8.5. These synoptic changes with resolution impact the overall climate change response  
17 of mean and heavy winter precipitation: wetter (drier) conditions in northern (southern)  
18 Europe are also amplified at 25 km resolution. For example, the reduction in heavy  
19 precipitation simulated over the Iberian Peninsula under RCP8.5 is ~15% at 135 km, but  
20 ~30% at 25 km resolution. Conversely, a shift to more frequent high ETC-associated  
21 precipitation rates is simulated over Scandinavia under RCP8.5, which is enhanced at 25 km.  
22 This study provides evidence that global atmospheric resolution may be a crucial  
23 consideration in European winter climate change projections.

24

## 25 **1. Introduction**

26 Across the Euro-Atlantic region, hazardous weather – particularly heavy precipitation and  
27 wind extremes – is primarily related to extratropical storm occurrence (e.g., Huntingford et  
28 al. 2014), which is modulated by variability in the westerly flow over the North Atlantic  
29 basin. Model projections of the behaviour of such dynamical phenomena under climate  
30 change are uncertain, but greater confidence could be established by running global climate  
31 models at resolutions sufficient to resolve weather-scale processes, and thereby internally-  
32 driven climate variability (Roberts et al. 2018), increasing understanding of Europe’s future  
33 exposure to climate risk.

34

35 Synoptic conditions over the North Atlantic are governed by two jet streams: the upper-  
36 tropospheric subtropical jet, which arises from angular momentum transport by the Hadley  
37 circulation (Schneider 2006), and the lower-tropospheric eddy-driven jet, induced by eddy  
38 momentum flux from baroclinic waves (Hoskins 1983). The wintertime eddy-driven jet  
39 exhibits an observed tri-modal regime behaviour that is most pronounced during winter:  
40 southern (~35-40 °N), central (~42-58 °N) and northern (~53-60 °N) positions are occupied  
41 preferentially because transient eddy forcing acts to maintain the eddy-driven jet at a given  
42 latitude, and variability in this forcing causes meridional jet shifts (Woollings et al. 2010).  
43 Variability in this large-scale, zonal-mean circulation modulates weather regime frequency  
44 (Madonna et al. 2017) and steers mid-latitude, extratropical cyclone (ETC) tracks (Bengtsson  
45 et al. 2006; Della-Marta and Pinto 2009; Masato et al. 2016; Pfahl et al. 2017; Pinto et al.  
46 2009; Zappa and Shepherd 2017). ETCs are synoptic-scale, low-pressure systems whose  
47 cyclogenesis, propagation (generally poleward and eastward), decay and cyclolysis occur  
48 within the mid-latitude storm track regions. ETC cyclogenesis occurs frequently over North  
49 America, where a strong meridional temperature gradient and thus high baroclinicity exists at

50 the interface of subtropical and polar air masses (polar front). Subsequently, these synoptic  
51 disturbances develop into mature ETCs over the North Atlantic basin (Pinto et al. 2009).  
52 ETCs are important for the poleward transport of heat, moisture and momentum in the  
53 atmospheric general circulation, reducing the equator-to-pole energy imbalance (Kaspi and  
54 Schneider 2013; Schneider 2006; Shaw et al. 2016), but are also responsible for a substantial  
55 component of variability in winter precipitation and wind conditions across mid- and mid-to-  
56 high-latitude regions (Pfahl and Wernli 2012). The climatological mean contribution of ETCs  
57 to European winter precipitation is ~70% (Hawcroft et al. 2012) and model simulations  
58 indicate increased ETC-associated precipitation by the end of the 21<sup>st</sup> century (Hawcroft et al.  
59 2018). Storm track processes are therefore crucial for European hydroclimate and extreme  
60 event variability.

61

62 On seasonal to decadal timescales, the North Atlantic Oscillation (NAO), the leading mode of  
63 natural variability in large-scale atmospheric circulation, storminess and precipitation across  
64 the Euro-Atlantic region (Pinto et al. 2009; Wallace and Gutzler 1981; Zveryaev 2004, 2006),  
65 is dominated by positional variability of the North Atlantic jet and storm track (Woollings et  
66 al. 2018). Therefore, the ability of global climate models to capture variability in North  
67 Atlantic zonal-mean flow and ETC occurrence is critical for climate impact studies and  
68 projections at the regional scale. However, many CMIP5 models are unable to capture the tri-  
69 modality of the North Atlantic eddy-driven jet (Iqbal et al. 2018). This highlights the  
70 importance of resolution sufficiency and of performing climate simulations at a horizontal  
71 resolution sufficient to resolve weather systems and their feedback on large-scale circulation  
72 and variability.

73

74 There is evidence from both global and regional modelling studies that global atmospheric  
75 model resolution is important for representing the North Atlantic storm track, cyclonic  
76 activity and precipitation, indicating that resolution is an important modelling consideration  
77 in the climate change projection of these phenomena. Multi-model climate change  
78 projections from the 5<sup>th</sup> phase of the Coupled Model Intercomparison Project (CMIP5) show  
79 a decline in winter cyclonic activity and precipitation over southern Europe, particularly the  
80 western Mediterranean, and an increase over north-western Europe (Zappa et al. 2013b).  
81 Shepherd (2014) highlighted the non-robustness of the winter circulation response to climate  
82 change over the North Atlantic in global CMIP5 models, hypothesising that differing  
83 atmospheric model resolution is an important factor. Zappa et al. (2013a) showed that CMIP5  
84 models with the best representation of the North Atlantic storm track are those of highest  
85 resolution within the CMIP5 ensemble, indicating that high atmospheric resolution is  
86 necessary to accurately capture the position and tilt of the North Atlantic storm track, as well  
87 as variability in the downstream impacts of North Atlantic storminess. Global EC-Earth  
88 simulations performed at resolutions of ~112 and ~25 km revealed resolution sensitivity of  
89 European precipitation due to the resolution sensitivity of the simulated North Atlantic storm  
90 track, particularly its more realistic tilt (van Haren et al. 2015). Global historical and future  
91 climate ECHAM5 simulations at equivalent resolutions of ~60 and ~40 km show that the  
92 responses of ETC intensity and wind speed maxima to warming are partly dependent on  
93 model resolution and, for both climates, the impact of resolution exceeds the climate change  
94 response at either resolution (Champion et al. 2011). These studies provide evidence that  
95 increases in atmospheric resolution improve simulated storm track dynamics.

96

97 To improve mean and extreme climate predictions, a quantitative assessment of the ability of  
98 global climate models to simulate weather-scale processes is required, but such processes are

99 driven by relatively uncertain circulation dynamics (Woollings 2010; Zappa and Shepherd  
100 2017). High model resolution is particularly important for Europe, a populous region where  
101 synoptic systems interact with complex coastlines, orography and the Mediterranean Sea.  
102 Global and regional modelling studies simulating present-climate precipitation have  
103 demonstrated the resolution sensitivity of mean and extreme European precipitation due to  
104 orography (Delworth et al. 2012; Prein et al. 2016; Schiemann et al. 2018) and models'  
105 representation of the North Atlantic storm track (van Haren et al. 2015). Clearly, high-fidelity  
106 model representations of boundary conditions, large-scale atmospheric circulation, storm  
107 track processes, and synoptic phenomena are all key to simulating climate change patterns  
108 across the Euro-Atlantic region, highlighting the value of global models. Current high-  
109 performance computing and data management facilities now allow multi-decadal simulations  
110 at effective resolutions adequate to resolve synoptic phenomena (Mizielinski et al. 2014; van  
111 Haren et al. 2015; Zhang et al. 2016).

112

113 Overall, global and regional modelling efforts highlight the need to quantify the impact of  
114 atmospheric resolution on North Atlantic circulation and hydroclimate in isolation by the  
115 analysis of global climate model experiments designed to quantify the impact of resolution.  
116 In this study, we have quantified the impact of increasing global atmospheric model  
117 resolution on the response of Euro-Atlantic circulation, storminess and precipitation to  
118 climate change. We focus on boreal winter (December-February; DJF), when mid-latitude  
119 storm tracks are most active and the majority of precipitation occurs over the mid-latitude  
120 North Atlantic. The representation of wintertime dynamics in climate models is important for  
121 their simulation of other canonical seasons. For example, models' ability to capture  
122 extratropical winter precipitation impacts their ability to simulate spring and summer soil  
123 moisture levels and, in turn, droughts and heatwaves, highlighting the importance of

124 accurately reproducing climatological cold season precipitation, its variability, and the  
125 dynamical phenomena with which it is associated (Hawcroft et al. 2016; Vidale et al. 2007).  
126 The aims of this study are: (i) to compare large-scale circulation, ETC activity and  
127 precipitation over the Euro-Atlantic domain simulated at 135 km, a resolution typical of  
128 CMIP5 GCMs, with that simulated at 60 and 25 km resolution; (ii) to identify regions where  
129 resolution impacts both the historical mean state and climate change response; (iii) to  
130 consider the implications for climate change impact studies for this region ahead of the 6<sup>th</sup>  
131 phase of the Coupled Model Intercomparison Project (CMIP6), particularly HighResMIP  
132 (Haarsma et al. 2016). To make this contribution, we analyse an ensemble of global historical  
133 and future climate model simulations from a single model, where only horizontal atmospheric  
134 resolution is increased. This allows us to isolate the role of atmospheric resolution without  
135 needing to account for inter-model disparities in formulation, complexity, or tuning, all issues  
136 that hinder resolution sensitivity studies (Matsueda and Palmer 2011). This paper continues  
137 with a description of the model ensemble, North Atlantic jet analysis techniques, and ETC  
138 tracking and analysis in section 2. Sequentially, we examine the impact of increased  
139 atmospheric model resolution under historical and RCP8.5 forcings on the North Atlantic  
140 zonal-mean circulation (section 3), ETC activity (section 4) and precipitation (section 5). We  
141 discuss these results in section 6 and summarise our conclusions in section 7.

142

143

## 144 **2. Data and methods**

### 145 *2.1 Model ensemble*

146 We analysed an ensemble of global atmosphere-only simulations performed with Hadley  
147 Centre Global Environmental Model (version 3) Global Atmosphere 3.0 (hereafter  
148 HadGEM3-GA3.0; Walters et al. 2011). These simulations are part of the UPSCALE (UK on

149 PRACE: weather-resolving Simulations for global Environmental risk) project (Mizielinski  
150 et al. 2014), which offers an opportunity to evaluate the sensitivity of aspects of global and  
151 regional climate and their physical drivers to horizontal atmospheric resolution. UPSCALE  
152 simulations were performed for the period 1985-2011 at N96, N216 and N512 resolutions,  
153 where 'Nx' denotes global latitude and longitude grid of  $1.5x+1$  and  $2x$  cells, respectively.  
154 Corresponding nominal mid-latitude grid spacings (at  $50^\circ$  latitude) are 135, 60 and 25 km,  
155 respectively. All simulations have 85 vertical levels and are forced by daily Met Office  
156 Operational SST and Sea Ice Analysis (OSTIA) data (Donlon et al. 2012), which were  
157 regridded from their native resolution of  $1/20^\circ$  to the three atmospheric resolutions (Fig. S1),  
158 and time-varying forcings were defined following AMIP-II protocols (Mizielinski et al.  
159 2014). The historical climate ensemble size for the N96, N216 and N512 resolutions is five,  
160 three and five members, respectively. Future (end of the 21st century) climate change  
161 simulations were configured using a time-slice methodology forced by the OSTIA historical  
162 SST field plus the SST change between the periods 1990-2010 and 2090-2110 simulated by  
163 the HadGEM2 Earth System under the IPCC Representative Concentration Pathway 8.5  
164 (RCP8.5) scenario. For regions experiencing sea ice loss under RCP8.5 forcing, SST values  
165 were interpolated from HadGEM2. At each resolution, three future climate ensemble  
166 members were run. Beyond minor adjustments to ensure numerical stability at each  
167 resolution, which are given in Mizielinski et al. (2014), no model retuning was performed  
168 (Demory et al. 2014).

169

170 For high-resolution global models, there is necessarily a trade-off between resolution and  
171 ensemble size, constrained by computational expense. Nevertheless, the UPSCALE project's  
172 experimental design – the combination of model resolution range, simulation length,  
173 availability of multiple ensemble members for better event sampling, and the lack of model

174 retuning – allowed us to isolate the role of atmospheric resolution in the simulated historical  
175 climate and under RCP8.5.

176

## 177 *2.2 Eddy-driven jet variability analysis*

178 The action of transient eddy forcing to accelerate westerly winds occurs throughout the depth  
179 of the troposphere, but is particularly strong at low levels (Hoskins et al. 1983). The regime  
180 behaviour of the North Atlantic eddy-driven jet is examined in HadGEM3-GA3.0 following  
181 the method of Woollings et al. (2010). Daily zonal wind data were averaged over the 925,  
182 850 and 700 hPa levels, then averaged zonally over a North Atlantic longitudinal sector (15-  
183 75 °N, 0-60 °W). The use of three rather than four levels does not significantly affect our  
184 results (see Supplementary information, section S1). A low-pass Lanczos filter (Duchon  
185 1979) was applied with a cut-off value of 10 days to remove wind features associated with  
186 synoptic systems. The latitudes at which maxima of the resulting zonal-mean westerly wind  
187 profiles occur are defined as jet latitudes. Grid cells where orography exceeds 750 m were  
188 masked to avoid the inclusion of spurious sub-surface winds (e.g., over southernmost  
189 Greenland) in this analysis, particularly at the lowest isobaric level of 925 hPa (see  
190 Supplementary information). We also examined the inverse relationship between jet latitude  
191 variance and jet speed. Following Woollings et al. (2018), we computed the standard  
192 deviation of jet latitude binned by jet speed. We computed jet speed as the square root of the  
193 sum of the squares of the zonal and meridional winds, which accounts for instances when the  
194 magnitude of jet speed is dominated by the meridional component (e.g., due to jet  
195 meandering). To maximise sampling in these analyses, the low-pass-filtered wind time series  
196 for all ensemble members were concatenated for each resolution, taking advantage of the  
197 UPSCALE ensemble size. We compared model results for both of these analyses with the  
198 ERA5, ERA-Interim (Dee et al. 2011) and NCEP-CFSR (Saha et al. 2010) reanalyses for the

199 period 1979-2016. All data were regridded to the N96 grid to isolate resolution sensitivity  
200 from any improved sampling at higher resolution.

201

### 202 *2.3 Extratropical cyclone tracking*

203 To identify and track the evolution of ETCs in this study, we used the objective feature-  
204 tracking algorithm – *TRACK* – of Hodges (1995, 1999), previously applied to reanalyses  
205 (Dacre and Gray 2013; Hawcroft et al. 2012; e.g., Hoskins and Hodges 2002) and model  
206 simulations of both present (e.g., Catto et al. 2010; Hawcroft et al. 2016) and future climates  
207 (e.g., Zappa et al. 2015; Zappa et al. 2013a). The Lagrangian *TRACK* algorithm was applied  
208 to 6-hourly, spectrally-filtered vorticity maxima at the 850 hPa level. Wavenumbers 0-5 and  
209 >42 are filtered out (i.e., truncation to T42 resolution, retaining wavenumbers 6-42), which  
210 excludes large-scale planetary motion and small-scale noise, respectively. Final ETC tracks  
211 represent only those identified features that propagate at least 1000 km and whose vorticity  
212 maxima exceed  $1.0 \times 10^{-5} \text{ s}^{-1}$  and lifetime exceeds 2 days. These post-processing criteria  
213 exclude spurious stationary features in the vorticity field. Statistical ETC track density and  
214 mean intensity (as measured by vorticity) metrics were computed according to Hoskins and  
215 Hodges (2002) and compared with ERA-Interim reanalysis data for the period 1979-2016  
216 (Dee et al. 2011).

217

### 218 *2.4. Quantification of cyclone-associated precipitation*

219 To associate precipitation to tracked ETCs, a radial cap was defined around each ETC centre  
220 at each 6-hourly timestep and precipitation within this cap is defined as cyclone-associated.  
221 The sensitivity of this analysis to cap radius was investigated by Hawcroft et al. (2012), who  
222 established the need to define cap radius according to the season and ocean basin in question.  
223 Accordingly, following Hawcroft et al. (2012) and Zappa et al. (2015; 2013a), we employed

224 a constant cap radius of  $10^\circ$  in our analysis of wintertime North Atlantic ETCs, which is  
225 close to that used by Hawcroft et al. (2012) and minimises overlap between caps at a given  
226 timestep.

227

## 228 *2.5 Significance testing*

229 The statistical significance (above the 95 % level) of model-observation or inter-resolution  
230 (i.e., high- minus low-resolution) differences was determined with respect to interannual  
231 variability by applying Welch's unequal variances *t*-test.

232

233

## 234 **3. Resolution sensitivity of Euro-Atlantic zonal-mean circulation under historical** 235 **climate and RCP8.5**

236 In this section, we evaluate the mean state of the eddy-driven and subtropical components of  
237 North Atlantic westerly flow simulated by HadGEM3-GA3.0 under historical and RCP8.5  
238 SST forcings, focussing on the impact of increased atmospheric resolution.

239

### 240 *3.1 North Atlantic eddy-driven jet*

241 We compare the representation of the tri-modal regime behaviour of the wintertime North  
242 Atlantic eddy-driven jet latitude across the historical climate simulations with the ERA5,  
243 ERA-Interim and NCEP-CFSR reanalyses (Fig. 1). Overall, the tri-modal behaviour of the  
244 eddy-driven jet is captured by the historical HadGEM3-GA3.0 simulations at each of the  
245 three resolutions considered here. However, increasing resolution from N96 to N512  
246 decreases the southern jet regime frequency (matching all three reanalyses more closely),  
247 increases the central regime frequency (exceeding the reanalyses), and causes a double-peak  
248 in the northern regime frequency, which is not present in the lower-resolution reanalyses or

249 N96 simulations (Fig. 1, upper panel). This double-peak is, however, present in the latest  
250 ERA5 reanalysis, whose resolution (30 km) is comparable to N512, and is likely related to a  
251 better representation of orographic boundary conditions (i.e., Greenland and Iceland  
252 orography), known to influence where peaks in the wintertime frequency of low-level  
253 westerly jet events occur over the North Atlantic (Woollings et al. 2010). Despite the  
254 presence of a central peak bias at N512, increased resolution improves the overall frequency  
255 distribution of eddy-driven jet latitude and refines our view of northern regime behaviour  
256 arising from interaction with orography. Moreover, the observed inverse relationship between  
257 jet latitude variance and jet speed is well-captured (compared with all three reanalyses) across  
258 each model resolution under historical SST forcing (Fig. 2).

259

260 The latitudinal response of the eddy-driven jet to RCP8.5 in HadGEM3-GA3.0 is a  
261 pronounced poleward shift, shown clearly by zonally-averaged jet latitude probability density  
262 (Fig. 1, middle panel). At N96, the tri-modal jet latitude distribution is significantly different  
263 from the historical simulations, with a smoothing-out of the southern regime, a decrease in  
264 the peak frequency of the central regime, which also exhibits a broader shape, and an increase  
265 in the frequency of the northern regime. The southern regime response is further reduced at  
266 N216 and N512 resolutions. The northern regime response is increased markedly at N512  
267 and also exhibits a double peak. Moreover, the inverse relationship between jet latitude  
268 variance and jet speed changes under RCP8.5 (Fig. 2). Jet latitude variability is reduced  
269 across all jet speed percentiles, with the largest such change simulated at N512. Overall, the  
270 probability density function of eddy-driven jet latitude is redistributed poleward (Fig. 1) and  
271 is less variable (Fig. 2) under RCP8.5, both responses forced by increased SST, which  
272 dominates jet shift in the Northern Hemisphere (Grise and Polvani 2014). These results  
273 indicate that increasing atmospheric resolution amplifies these behaviours under climate

274 change, further discussion and interpretation of which is presented in the subsequent sections.  
275 Additionally, our results are consistent with Matsueda and Palmer (2011), who used the  
276 JMA-GSM model to show that coarse resolution (180 km) may underestimate the magnitude  
277 of the climate change response of North Atlantic westerly flow at 850 hPa, which is increased  
278 significantly by increasing resolution to 20 km.

279

### 280 *3.2 North Atlantic subtropical jet*

281 Historical HadGEM3-GA3.0 simulations capture the wintertime climatological upper-  
282 tropospheric (250 hPa) zonal wind field over the North Atlantic basin. Biases of up to  $\sim 4 \text{ ms}^{-1}$   
283 (versus ERA-Interim) over this region are statistically insignificant with respect to  
284 interannual variability, and particularly low over the poleward flank of the subtropical jet  
285 (Fig. S2). Additionally, a localised positive bias east of the Mediterranean Sea at N96 is  
286 reduced in spatial extent at N512. At N512, North Atlantic zonal flow exhibits a southwest-  
287 northeast tilt compared with the more zonal orientation simulated at N96 (Fig 3), which is  
288 likely due to the improved representation of orographic boundary conditions at this resolution  
289 (Fig. S3) allowing more realistic simulation of westerly flow incident on the Rocky  
290 Mountains. Increasing resolution also enhances the zonal wind over northern Europe and  
291 reduces it over south-eastern Europe, resembling a positive winter NAO-like pattern (Fig. 3).  
292 Over the North Atlantic, dipolar patterns of opposite sign are seen in the N216-N96 and  
293 N512-N216 difference maps, but these differences are largely statistically insignificant at the  
294 95 % level.

295

296 The RCP8.5 response of the upper-tropospheric zonal wind field over the North Atlantic  
297 simulated by HadGEM3-GA3.0 is a pronounced basin-wide poleward shift and eastward  
298 extension (Fig. 4). This response is enhanced when resolution is increased in HadGEM-

299 GA3.0 from N96 to N512, particularly over the eastern North Atlantic and Mediterranean  
300 basin. This spatial pattern of resolution sensitivity for N512-N96 resembles that of the  
301 historical climate (Fig. 3), indicating that the resolution sensitivity of the mean state zonal  
302 flow may impact that of the climate change response. Vertical (latitude-height) sections of  
303 the zonal wind field, averaged over the eastern Atlantic (0-40 °W), show this northward shift  
304 is simulated throughout the troposphere (Fig. 5). Under RCP8.5, the region wherein zonal  
305 wind speed at 250 hPa exceeds  $30 \text{ ms}^{-1}$  extends further east over the north-eastern North  
306 Atlantic than under historical climate forcing. At N216 and N512, this north-eastward  
307 extension towards northern Europe is enhanced; that is to say, these high wind speeds are  
308 projected to occur further east over Europe at increased resolution (Fig. S4), indicating upper-  
309 level, subtropical jet extension as resolution is increased from N96 to N512.

310

311 We undertook a correlation analysis to establish whether changes in the wintertime tropical  
312 Atlantic Hadley circulation response to RCP8.5 with resolution could provide more insight  
313 into the resolution-dependence of the subtropical jet response under RCP8.5. Specifically, we  
314 correlated inter-seasonal variability in tropical Atlantic vertical velocity (i.e., Lagrangian  
315 tendency of atmospheric air pressure,  $\omega$ , at 500 hPa) with zonal wind. However, this analysis  
316 (not shown) revealed no evidence for a tropical cause of the resolution-dependent behaviour  
317 of North Atlantic zonal flow seen in these HadGEM3-GA3.0 integrations. While this analysis  
318 alone does not rule out any influence of the tropics, we limit the scope of this study to an  
319 examination of the consequences of a resolution-dependent flow response to warming for  
320 storm track phenomena and precipitation, focussing on significant differences between N96  
321 and N512 resolutions.

322

323

324 **4. Resolution sensitivity of extratropical cyclone activity under historical climate and**  
325 **RCP8.5**

326 ETCs, steered by the atmospheric flow over the North Atlantic, are primarily responsible for  
327 high-impact weather – namely, strong wind and heavy precipitation events – downstream  
328 over Europe (Madonna et al. 2017). Strengthened upper-level winds over the North Atlantic  
329 may increase the meridional propagation of mid-latitude cyclonic systems (Tamarin-Brodsky  
330 and Kaspi 2017) and, given the results presented in section 3, we therefore expect ETC  
331 activity simulated by HadGEM3-GA3.0 to change with resolution. To quantify this, we  
332 evaluated Euro-Atlantic ETC activity simulated by HadGEM3-GA3.0 under historical and  
333 RCP8.5 SST forcings.

334

335 An ensemble-mean HadGEM3-GA3.0 bias in ETC track density (versus ERA-Interim data;  
336 Fig. S5) of ~15% at N96 resolution is statistically significant only in a confined region of the  
337 North and Norwegian Seas, and this bias is reduced to ~7% at N512. This improvement of  
338 simulated ETC activity with increased resolution highlights the necessity of resolving  
339 synoptic phenomena in studies of wintertime European hydroclimate. For the historical  
340 climate, HadGEM3-GA3.0 simulates higher ETC track density at N512 across the  
341 downstream region of the North Atlantic storm track, Scandinavia and the Iberian Peninsula  
342 than at N96 (Fig. 6). Climatologically, ~1 to ~3 additional cyclones per month per unit area  
343 ( $5^\circ$  radial cap) are simulated over these regions at N512 compared with N96. The increases  
344 with resolution over Iberia and northwest Africa, where absolute values at N96 are low ( $<3$   
345 cyclones month<sup>-1</sup>), are significant. There is evidence from idealised experiments (Brayshaw  
346 et al. 2011) and GCM simulations (O'Reilly et al. 2017; Small et al. 2019) linking the  
347 absolute SST and the Gulf Stream SST front sharpness to increased downstream eddy  
348 activity. In HadGEM3-GA3.0, the track density increase with resolution is concentrated

349 downstream over the north-eastern North Atlantic and likely driven by the increased  
350 sharpness of the OSTIA SST gradients from N96 to N512 (Fig. S1). Increased track density  
351 is also simulated over the subtropical Atlantic and northwest Africa at N512, reflecting the  
352 detection of vorticity maxima over these lower-latitude regions, where absolute densities are  
353 relatively low. A reduction of ETC track density is simulated downstream of orography at  
354 N512 compared with N96, particularly over the Northern Mediterranean (downstream of the  
355 Alps) and east of southern Greenland (Fig. 6), which is attributable to N512 orography (Fig.  
356 S3).

357

358 Under RCP8.5, the ensemble-mean spatial response of ETC track density simulated at N96  
359 resolution qualitatively resembles that of the CMIP5 multi-model ensemble (Zappa et al.  
360 2013b): a tri-polar pattern in the track density response is projected over the Euro-Atlantic  
361 region, with a decrease over the Mediterranean, increased activity over Northern Europe,  
362 particularly the UK and Scandinavia, and decreased track density in high Arctic latitudes  
363 (Fig. 7, upper row). Similar responses over northern Europe were simulated by Bengtsson et  
364 al. (2006) using ECHAM5. At N512, the magnitude of the ETC track density response is  
365 enhanced over northern-western Europe, the western Mediterranean, and the western North  
366 Atlantic (Fig. 7, upper row). Under RCP8.5, the ensemble-mean spatial response of ETC  
367 mean intensity simulated at N96 resolution is a dipolar pattern, with decreased intensity over  
368 the central North Atlantic, western Europe and the Mediterranean, and an increase over the  
369 north-eastern North Atlantic and Scandinavia (Fig. 7, lower row). This dipolar spatial  
370 structure in ETC intensity response to RCP8.5 is also simulated at N512, but the magnitudes  
371 of these responses are enhanced, particularly west of Iberia and north of the United Kingdom  
372 and over Scandinavia (Fig. 7, lower row). Consistent with this is an enhanced response in  
373 upward vertical velocity (i.e., negative  $\omega$ ) simulated north of  $\sim 60^\circ\text{N}$  over the north-eastern

374 North Atlantic under RCP8.5 at N512 (Fig. S6), which we attribute to more frequent ETC  
375 transits over this region at N512 compared with the lower resolutions based on evidence for  
376 moisture-driven  $\omega$  asymmetry (Tamarin-Brodsky and Hadas 2019).

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378

## 379 **5. Resolution sensitivity of Euro-Atlantic precipitation under historical climate and** 380 **RCP8.5**

381 Given that ETCs are the primary contributor to winter precipitation, particularly over  
382 Northern Europe (Hawcroft et al. 2012), the resolution-dependence of the simulated ETC  
383 track density and mean intensity responses to RCP8.5 is expected to impact projected  
384 precipitation. Schiemann et al. (2018) showed that present-climate mean and extreme  
385 European precipitation are better represented at N512 (see Supplementary information,  
386 section S2, Fig. S7 and Fig. S8), enabling examination of differences in projected  
387 precipitation under climate change at each model resolution. To this end, we quantified the  
388 impact of increased resolution on ETC-associated and total mean and extreme precipitation in  
389 the historical and RCP8.5 HadGEM3-GA3.0 simulations.

390

### 391 *5.1 Extratropical cyclone-associated precipitation*

392 Based on tracked ETCs, we decomposed Euro-Atlantic precipitation into cyclone- and non-  
393 cyclone-associated components, where the former is determined according to the Hawcroft et  
394 al. (2012) method and the latter defined as total minus cyclone-associated precipitation. For  
395 the historical climate, as expected, HadGEM3-GA3.0 simulates the highest ETC-associated  
396 precipitation values over the storm track region and lower values on the poleward and  
397 equatorward flanks of the storm track (Fig. 8). This spatial pattern is consistent across the  
398 resolution hierarchy and closely resembles that computed from ERA-Interim (Fig. S9, top

399 panel). A negative bias in the magnitude of ensemble-mean ETC-associated precipitation  
400 exists over the North Atlantic storm track, which is progressively reduced at N216 and N512  
401 resolution, particularly over the downstream storm track region (Fig. S9), highlighting the  
402 value of 25 km-resolution in improving the fidelity of simulated precipitation associated with  
403 synoptic systems. There are limitations in using ERA-Interim precipitation, which is a  
404 forecast, rather than analysed, field. However, Pfahl and Wernli (2012) compared ERA-  
405 Interim precipitation flux data with satellite-derived estimates, concluding that, excepting  
406 high-intensity events, precipitation sufficiently-well captured by the ERA-Interim forecast  
407 model to allow analysis of cyclone-associated precipitation. Use of 6-hourly ERA-Interim  
408 precipitation avoids the need to either evaluate HadGEM3-GA3.0 only over the tropical and  
409 subtropical regions covered by satellite products or degrade 6-hourly ETC track data to a  
410 daily frequency for comparison with global observed precipitation datasets (e.g., GPCP).

411

412 At N512 resolution, significantly higher ETC-associated precipitation is simulated over much  
413 of the North Atlantic compared with N96 (Fig. 8), reflecting the spatial pattern of resolution  
414 sensitivity in track density (Fig. 6) and corresponding to the region of reduced ETC-  
415 associated precipitation bias (Fig. S9). This is also seen over Iberia, the UK, and orographic  
416 regions (Scandinavian Mountains and Alps). Significantly reduced ETC-associated  
417 precipitation is simulated at N512 over continental mainland Europe and downstream of  
418 orography, particularly east of Greenland, the Alps, the Apennines, and the eastern  
419 Mediterranean basin (Fig. 8, upper row). The contribution of ETC-associated precipitation to  
420 total precipitation in the downstream North Atlantic storm track region and Norwegian Sea is  
421 ~5% greater at N512 (Fig. 8, lower row), again reflecting the spatial pattern of resolution  
422 sensitivity in ETC track density (Fig. 6) and corresponding to the region of reduced ETC-  
423 associated precipitation bias (Fig. S9).

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Under RCP8.5, CMIP5 models project approximately a doubling of 99<sup>th</sup> percentile ETC-associated precipitation over eastern North America and northern Europe, but changes over the Mediterranean are comparatively uncertain (Hawcroft et al. 2018). In HadGEM3-GA3.0, ETC-associated precipitation increases under RCP8.5 across north-eastern North America, northern Europe and high-latitude regions, and a significant decrease is simulated over the Mediterranean (Fig. 9). However, increased resolution has little overall impact on these ensemble-mean projections for the North Atlantic, except for orographic European regions (Fig. 9, upper row). The projected contribution of ETC-associated precipitation to total precipitation is reduced across central and southern Europe under RCP8.5 at each resolution (Fig. 9, lower row). Interestingly, a less negative response is simulated over Scandinavia at N512 resolution (Fig. 9) due to the enhanced track density increase under RCP8.5 simulated over this region (Fig. 7). Overall, the ensemble-mean RCP8.5 response is greater than the resolution sensitivity of ETC-associated precipitation by a factor of approximately two. Areas of statistical significance are highly localised, which is a firm indication that, at least in these integrations, ETC track density shifts, rather than changes in mean ETC-associated precipitation, explain spatial patterns of resolution sensitivity in the climate change response of Euro-Atlantic precipitation discussed in section 5.2.

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The role of resolution in the simulated response of ETC-associated precipitation to RCP8.5 emerges at smaller spatial scales and when a range of precipitation rates is considered. We quantified the impact of increased resolution on area-averaged ETC-associated precipitation rates over regions where statistically significant changes are projected by CMIP5 as well as in our HadGEM3-GA3.0 simulations: Scandinavia, the UK, Iberia and the Mediterranean. The frequency of ETC-associated precipitation over Scandinavia and the UK simulated at

449 N96 increases under RCP8.5, and a larger increase is simulated at N512 (Fig. 10) for  
450 precipitation rates exceeding  $\sim 10 \text{ mm day}^{-1}$ . These results are consistent with the ECHAM5  
451 simulations of Champion et al. (2011), which showed an increase in the frequency of area-  
452 averaged, ETC-associated heavy precipitation events in response to climate change simulated  
453 at an atmospheric resolution of 60 km, increasing further at 40 km. However, our results,  
454 which span a larger range in resolution, provide evidence that the impact of increasing  
455 atmospheric resolution on enhancing the ETC-associated precipitation response over northern  
456 Europe is spatially variable. Conversely, the projected decrease in ETC-associated  
457 precipitation over Iberia and the Mediterranean under RCP8.5 is indistinguishable between  
458 the resolutions considered here. A recent analysis of the added value of high-resolution in  
459 simulating present-climate daily precipitation indicates that the coarsest best resolution for  
460 the Mediterranean region is uncertain and compounded by observational uncertainty (Roberts  
461 et al. 2018).

462

### 463 *5.2 Response of European total precipitation to RCP8.5*

464 The CMIP5 multi-model mean response of wintertime mean precipitation to RCP8.5 exhibits  
465 a large-scale dipolar pattern of drying across the Mediterranean and southern Europe and  
466 wetter conditions across northern Europe (Zappa et al. 2013a). HadGEM3-GA3.0 simulates a  
467 similar spatial pattern in both mean and heavy winter precipitation at N96 resolution, which,  
468 as expected, resembles that of ETC-associated precipitation (Fig. 11) because ETCs are  
469 primarily responsible for mid-latitude precipitation. Increasing resolution from N96 to N216  
470 enhances the RCP8.5 precipitation increase over the Scandinavian mountains and the  
471 reduction projected over the Iberian Peninsula and over an area of ocean west of Europe (not  
472 shown). Further increasing resolution to N512 enhances this overall dipolar climate change  
473 response pattern, particularly over the Norwegian Sea and Iberia (Fig. 11). This enhancement

474 of the RCP8.5 response with resolution is significant when tested against interannual  
475 variability. Averaged over European sub-regions, interannual variability in total heavy  
476 precipitation simulated by HadGEM3-GA3.0 under RCP8.5 is significantly and positively  
477 correlated with ETC track density over the eastern North Atlantic at each resolution (Fig.  
478 S10), indicating that patterns of resolution-dependence in total precipitation relate directly to  
479 changes in upstream ETC activity with resolution. However, this cannot be fully explained by  
480 the ETC-associated component of precipitation alone because (i) ETCs are the dominant, but  
481 not the only, source of Euro-Atlantic precipitation and (ii) the contribution of ETC-associated  
482 precipitation to the total decreases under RCP8.5 in HadGEM3-GA3.0 (Fig. 9). Nevertheless,  
483 the mean and heavy precipitation responses simulated at each resolution match those of ETC  
484 activity.

485

486 Finally, we computed area-average percentage changes in ETC track density and associated  
487 precipitation as well as mean and 95<sup>th</sup> percentile precipitation (P95) over Scandinavia, the  
488 Iberian Peninsula, the Mediterranean, and the UK (Fig. 12). For these regions, we find that  
489 area-averaged responses in these quantities simulated at N96 and N512 are generally distinct,  
490 but the separation between these resolutions and the intermediate N216 is more variable. For  
491 example, the mean precipitation response over Scandinavia shows little change with  
492 resolution (Fig. 12a), but responses in P95, ETC frequency and ETC-associated precipitation  
493 all increase with resolution (Fig. 12c, d). The track density response for Scandinavia is  
494 slightly negative (~-3%) at N96 but positive (~10%) at N512. For Iberia, the RCP8.5  
495 response is greater for mean precipitation than P95, but the separation between resolutions is  
496 greater for P95. The Iberian P95 change is particularly sensitive to resolution: -12% at N96  
497 and -27% at N512. Projected decreases in track density over the Iberia and the Mediterranean  
498 at N96 decrease further at N512. These results (i) indicate that ETC-associated precipitation

499 cannot fully explain the overall resolution-dependent precipitation responses to RCP8.5 and  
500 (ii) illustrate the complexity of the role of resolution in sub-regional-scale hydroclimate,  
501 suggesting the impact-relevance of increased resolution varies spatially.

502

503 To summarise, the responses of ETC activity and precipitation to RCP8.5 in HadGEM3-  
504 GA3.0 exhibit dipolar spatial patterns generally consistent with CMIP5, but which are  
505 enhanced significantly at N512 resolution. This resolution-dependence results from an  
506 enhanced poleward shift and downstream, north-eastward extension of both the eddy-driven  
507 and subtropical components of the North Atlantic zonal-mean westerly flow simulated at 25  
508 km atmospheric resolution.

509

510

## 511 **6. Discussion**

512 In HadGEM3-GA3.0, the simulated latitudinal distribution of the North Atlantic eddy-driven  
513 jet shifts poleward in response to RCP8.5, with corresponding decreases in southern jet  
514 occurrences. This poleward shift is more pronounced at N512 compared with N96 (Fig. 1).  
515 Eddy-driven jet latitude variability as a function of jet speed decreases under RCP8.5, which  
516 is again more pronounced at N512 (Fig. 2). RCP8.5 also engenders a basin-wide, poleward  
517 shift in the upper-tropospheric, subtropical component of North Atlantic mean zonal flow  
518 (Fig. 4 and Fig. 5). The amplitude of this climate change response is amplified and the  
519 eastward jet extension into Europe enhanced by increasing atmospheric model resolution.  
520 These large-scale changes have societally-relevant consequences for ETC activity and  
521 precipitation over the North Atlantic storm track and Europe.

522

523 Under RCP8.5, increased (decreased) ETC track density and mean ETC intensity are  
524 projected over northern (southern) Europe (Fig. 7). Particularly pronounced changes are  
525 projected over Scandinavia and the Iberian Peninsula. Increasing resolution to N512  
526 enhances these regional responses in ETC activity in both the simulated historical (Fig. 6)  
527 and future (Fig. 7) climate states. Overall, these spatial patterns of resolution sensitivity in  
528 ETC activity under RCP8.5 forcing are explained by the significant poleward shift and  
529 eastward extension of the eddy-driven and subtropical components of North Atlantic zonal-  
530 mean flow (section 3). However, the ETC activity response to RCP8.5 does not scale linearly  
531 with historical ETC activity across resolutions (see Supplementary information, section S3  
532 and Fig. S11). Therefore, several mechanisms governing variability in the position of the  
533 North Atlantic jets and storm track, which may be sensitive to atmospheric resolution, may  
534 explain the spatial patterns of resolution-dependence seen in this study: changes in  
535 meridional temperature gradient (Shaw et al. 2016); tropical forcing by shifts in the Northern  
536 Hemisphere Hadley circulation terminus (Tamarin-Brodsky and Kaspi 2017); positive  
537 feedback between enhanced latent heating over the north-eastern north Atlantic and increased  
538 ETC activity (Willison et al. 2013); or a strengthening of the stratospheric polar vortex  
539 (Zappa and Shepherd 2017). Fully evaluating each mechanism is beyond the scope of a single  
540 study, so we focus here on meridional temperature gradients. Haarsma et al. (2013) related  
541 projected changes in zonal wind to simulated meridional SST gradient changes and CMIP5  
542 simulations have revealed the competing effects of low- versus upper-level meridional  
543 temperature gradients in a warming climate on Northern Hemisphere jets (Barnes and  
544 Polvani 2015), a key source of uncertainty in future projections. In HadGEM3-GA3.0, the  
545 Gulf Stream SST front is more sharply resolved at N512 (Fig. S1) and the overall projected  
546 low-level meridional temperature gradient decreases under RCP8.5 due to Arctic  
547 amplification, and this decrease is greater at N512 (Fig. S12). However, a significantly

548 enhanced meridional temperature gradient, throughout the troposphere and centred at  $\sim 50^\circ\text{N}$ ,  
549 is simulated at N512, and this enhancement is most pronounced over the eastern North  
550 Atlantic (Fig. S12, lower). We interpret these differences in meridional temperature gradients  
551 under RCP8.5 across the HadGEM3-GA3.0 resolution hierarchy to be primarily responsible  
552 for the resolution sensitivity in the latitudinal position of the eddy-driven and subtropical jets,  
553 which are also more pronounced over the eastern North Atlantic (Fig. 1, Fig. 4 and Fig. 5).  
554 We found no evidence for tropical forcing of resolution-dependent zonal wind responses in  
555 HadGEM3-GA3.0. The roles of enhanced synoptic activity and diabatic storm track  
556 processes feeding back onto the large-scale circulation or by polar vortex changes are  
557 priorities for future research.

558

559 Willison et al. (2015) simulated ten initialised January-March seasons (2002-2011) using the  
560 Weather Research and Forecast model and perturbed these integrations with the temperature  
561 change simulated by five CMIP5 models (including HadGEM2) under RCP8.5, following a  
562 modelling approach with similarities to this study (see section 2.1). Willison et al. (2015)  
563 identified increased zonal wind and eddy activity under RCP8.5, which was enhanced by  
564 increasing resolution from 120 to 20 km, particularly over the north-eastern North Atlantic,  
565 consistent with our results (Fig. 7). Willison et al. (2015) used Eulerian storm track metrics to  
566 quantify enhanced cyclonic activity over the north-eastern North Atlantic simulated at 20 km  
567 resolution, consistent with our results (Fig. 7), but argued for the necessity of Lagrangian  
568 feature tracking to fully establish the resolution-dependence of ETC distributions. Our work  
569 therefore complements Willison et al. (2015) accordingly and clearly similar spatial patterns  
570 of resolution sensitivity emerged when both models were run under the same forcing scenario  
571 and span a similar range in atmospheric resolution. Set against a context of previous work  
572 showing no significant storm track response to global warming simulated at coarse

573 atmospheric resolutions (Finnis et al. 2007; Matsueda and Palmer 2011), our results provide  
574 firm evidence that high-resolution is required to avoid underestimating the magnitude of the  
575 response of North Atlantic storm track variability to climate change, with important  
576 implications for projecting hazardous weather risk across Europe.

577

578 By associating precipitation to tracked ETCs, we isolated the component of total precipitation  
579 attributable to ETCs, which exhibits a dipolar response pattern under RCP8.5: wetter (drier)  
580 across northern (southern) Europe (Fig. 9), resembling the response of total heavy and mean  
581 precipitation (Fig. 11). However, the RCP8.5 response of ensemble-mean ETC-associated  
582 precipitation exhibits little change with resolution across Europe. Rather, resolution  
583 sensitivity emerges at the sub-regional scale, with north-western European regions showing  
584 an enhanced response to RCP8.5 in the tail of area-averaged precipitation rate distributions at  
585 N512 (Fig. 10). For northern European regions, however, 25 km-resolution simulations  
586 exhibit greater (and reduced biases in) ETC-associated precipitation, indicating that  
587 simulations at CMIP5-like resolutions may underestimate the climate change response of this  
588 predominant source of European winter precipitation. At 25 km-resolution, the fidelity of  
589 simulated precipitation associated with synoptic systems is improved, but precipitation  
590 associated with fronts attending ETCs may not be adequately resolved at 25 km.  
591 Additionally, no resolution sensitivity is seen for southern Europe sub-regions, at least for the  
592 range in resolution considered in this study. We speculate that further increases in resolution  
593 to allow convection-permitting integrations are required to make more definitive statements  
594 about the role of resolution over southern Europe, a region where mesoscale convective  
595 systems are comparatively important for both mean and extreme precipitation (Tous et al.  
596 2016).

597

598 Delworth et al. (2012) simulated an enhanced precipitation increase under a CO<sub>2</sub> doubling  
599 scenario over the north-eastern North Atlantic at ~50 km resolution compared with that at  
600 ~200 km resolution, consistent with our results, but reduced drying over southern Europe,  
601 which is in contrast to our study. However, between these two atmospheric resolutions,  
602 Delworth et al. (2012) employed substantially different ocean and land surface model  
603 components, obfuscating the role of resolution and reinforcing the necessity for dedicated  
604 experiments. In our study, the overall spatial pattern of both the N512 mean and heavy  
605 precipitation responses to RCP8.5 and its resolution-dependence (Fig. 11) qualitatively  
606 resemble CMIP5 model responses forced by low tropical amplification and a strengthening of  
607 the stratospheric polar vortex (Zappa and Shepherd 2017), where the strongest precipitation  
608 responses occur over western Europe. Indeed, HadGEM3-GA3.0 simulates both moderately  
609 higher tropical Atlantic amplification and an increased strengthening of the stratospheric  
610 polar vortex at N512 compared with N96 (not shown), which suggests that this ‘storyline’  
611 offers dynamical insight into the cause of a resolution-dependent precipitation response to  
612 RCP8.5.

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## 615 **7. Conclusions and outlook**

616 This study quantifies the impact of increasing atmospheric resolution (from ~135 km in the  
617 mid-latitudes, which is typical of CMIP5 models, to ~25 km) on the responses of wintertime  
618 zonal-mean circulation, ETC activity and precipitation to RCP8.5 across the North Atlantic  
619 and Europe. Our analyses are based on an ensemble of atmosphere-only HadGEM3-GA3.0  
620 simulations that were experimentally designed for resolution sensitivity studies. We have  
621 demonstrated resolution-dependence in North Atlantic zonal-mean circulation, related to

622 differences in meridional temperature gradients, which impacts ETC activity as a function of  
623 latitude and, ultimately, downstream precipitation over Europe.

624

625 The representation of the North Atlantic eddy-driven jet in HadGEM3-GA3.0 improves when  
626 atmospheric horizontal resolution is increased from N96 to N512. Under RCP8.5, a decrease  
627 (increase) in the southern (northern) eddy-driven jet regime is projected, as well as a  
628 pronounced basin-wide poleward shift in upper-tropospheric zonal flow. These jet responses  
629 to warming are significantly enhanced by increased resolution, and related to a more sharply-  
630 resolved Gulf Stream SST front and an enhanced low-to-mid-tropospheric meridional air  
631 temperature gradient centred at  $\sim 50^\circ\text{N}$  at N512. The northeast North Atlantic is identified as  
632 a region where the increases in ETC activity and precipitation under RCP8.5 are enhanced at  
633 N512. Across southern Europe, reduced ETC activity and drying under RCP8.5 are  
634 significantly enhanced when resolution is increased. Crucially, reduced ETC track density  
635 and ETC-associated precipitation biases at N512 (compared with N96) are co-located with  
636 regions where resolution sensitivity in RCP8.5 responses are identified, exemplifying the  
637 value of resolving weather-scale processes in a global model to better capture the multi-scale  
638 processes important for European climate change projections.

639

640 To establish how systematic are these results, a multi-model study conducted under a  
641 common experimental protocol is warranted. Future research will exploit a larger ensemble  
642 of global climate model simulations, coordinated across multiple European climate modelling  
643 centres within the Horizon2020 PRIMAVERA project, which comprises the European  
644 submission to CMIP6 HighResMIP (Haarsma et al. 2016). Crucial research directions are  
645 establishing the resolution-sufficiency for capturing North Atlantic jet variability and its  
646 downstream impact on weather regime frequency and extreme event occurrence over Europe

647 as well as the role of moisture transports coincident with ETC transits, including relatively  
648 rare ETCs generated by extratropical transition of tropical cyclones. Moreover, the impact of  
649 ocean resolution on the simulated response of Atlantic Meridional Overturning Circulation to  
650 climate change and, in turn, on the response of the North Atlantic storm track is under-  
651 explored, and HighResMIP offers an opportunity to build on previous analysis of course-  
652 resolution ( $>1^\circ$ ) ocean components of GCMs (Woollings et al. 2012) with evaluations of  
653 eddy-resolving and eddy-rich ocean models. Understanding the fundamental physical drivers  
654 of the resolution-dependence of North Atlantic circulation, storm activity and precipitation,  
655 particularly their responses to climate change, as demonstrated in a global model in this  
656 study, may ultimately inform climate risk assessments and the definition of mitigation  
657 policies.  
658

659 **Author contributions**

660 AJB, RS and PLV conceived the study. AJB performed all data analyses and visualisation  
661 and wrote the manuscript. KH developed the cyclone tracking algorithm, *TRACK*, and KH  
662 and PLV wrote scripts to post-process *TRACK* output. MED, MSM, MJR, RS, JS and PLV  
663 ran the UPSCALE ensemble of simulations. AJB, RS, LES, KH and PLV discussed the  
664 results. All authors approved the final manuscript draft.

665

666

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677 reviewers, whose input much improved the final paper.

678

679

680 **Data and code availability**

681 For access to the UPSCALE simulations used in this study, see [hrcm.ceda.ac.uk/data](http://hrcm.ceda.ac.uk/data). The  
682 Met Office Unified Model (MetUM) is available for use under licence. A number of research  
683 organisations and national meteorological services use the MetUM in collaboration with the

684 Met Office to undertake basic atmospheric process research, produce forecasts, develop the  
685 MetUM code, and build and evaluate Earth system models. For further information, see  
686 [metoffice.gov.uk/research/collaboration/um-partnership](http://metoffice.gov.uk/research/collaboration/um-partnership). Version 7.7 of the source code was  
687 used in this paper. The Joint UK Land Environment Simulator (JULES) is available under  
688 licence. For further information, see [jules-lsm.github.io/access\\_req/JULES\\_access.html](http://jules-lsm.github.io/access_req/JULES_access.html).  
689 ERA-Interim data are available from [ecmwf.int](http://ecmwf.int). TRACK may be obtained from [nerc-  
690 essc.ac.uk/~kih/TRACK/Track.html](http://nerc-essc.ac.uk/~kih/TRACK/Track.html). Data analysis and visualisation scripts are available  
691 from the lead author upon reasonable request (see also [hrcm.ceda.ac.uk/contact](http://hrcm.ceda.ac.uk/contact)).  
692

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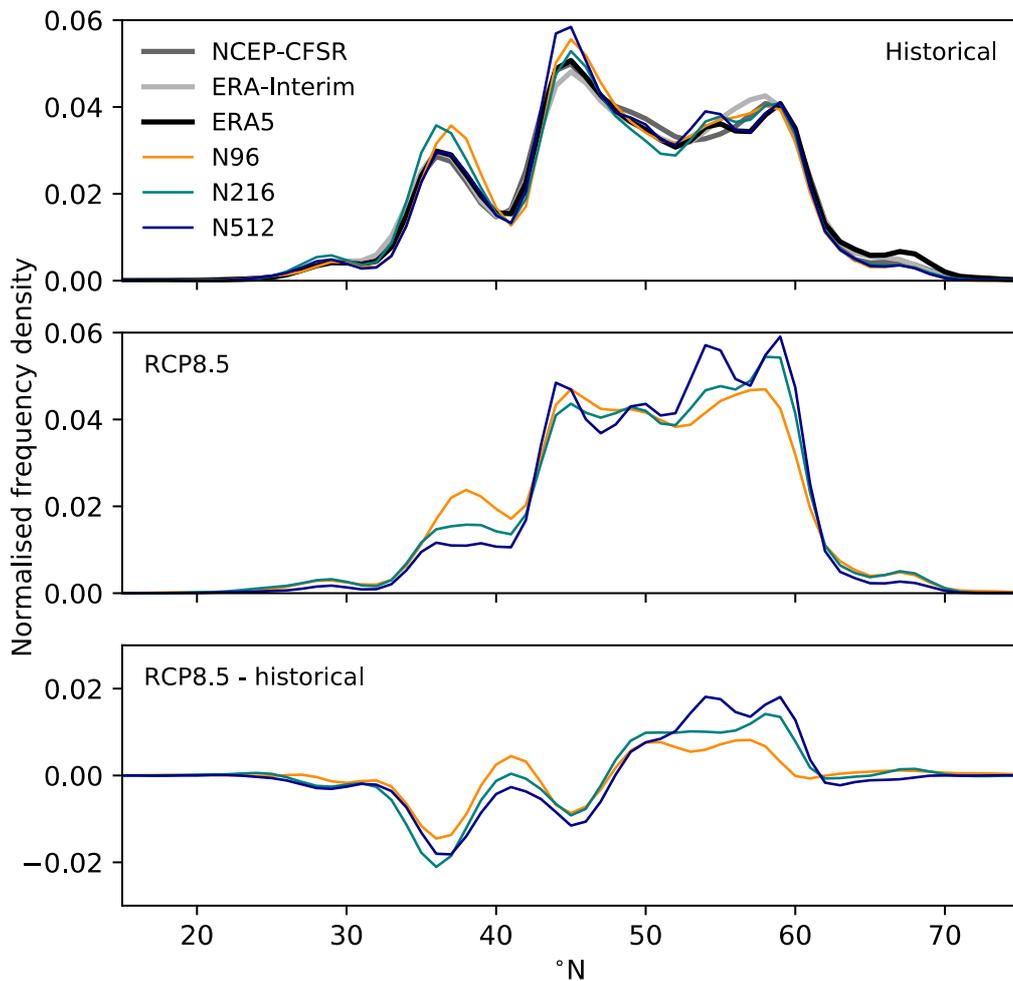
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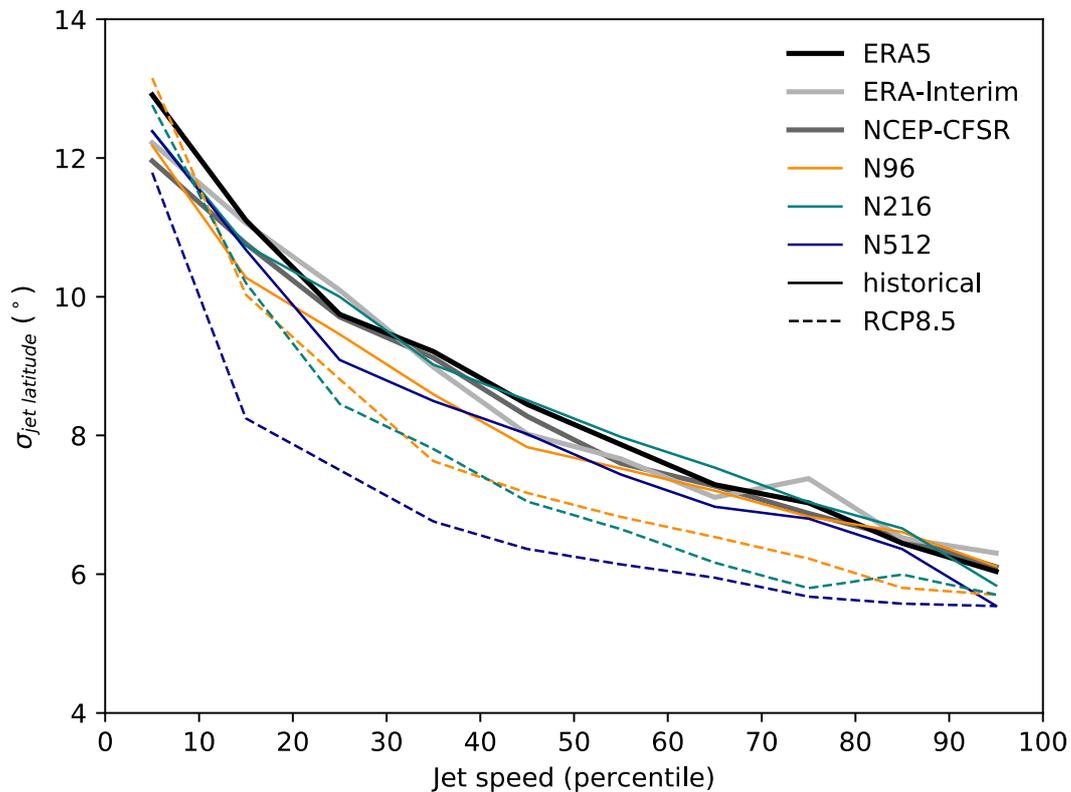
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837 **Fig. 1.** Regime behaviour of the North Atlantic eddy-driven jet stream, measured by jet  
 838 latitude, as represented in the ERA5 (black), ERA-Interim (pale grey) and NCEP-CFSR  
 839 (grey) reanalyses and simulated by HadGEM3-GA3.0 for (upper panel) historical climate,  
 840 (middle panel) under RCP8.5, and (lower panel) the difference (i.e., RCP8.5 minus historical;  
 841 lower panel). At each model resolution, N96 (orange), N216 (teal) and N512 (blue) ensemble  
 842 members were concatenated to maximise sampling. Unit is normalised frequency density and  
 843 plotted as a function of latitude. In the lower panel, frequency = 0 (horizontal black line) is  
 844 shown.

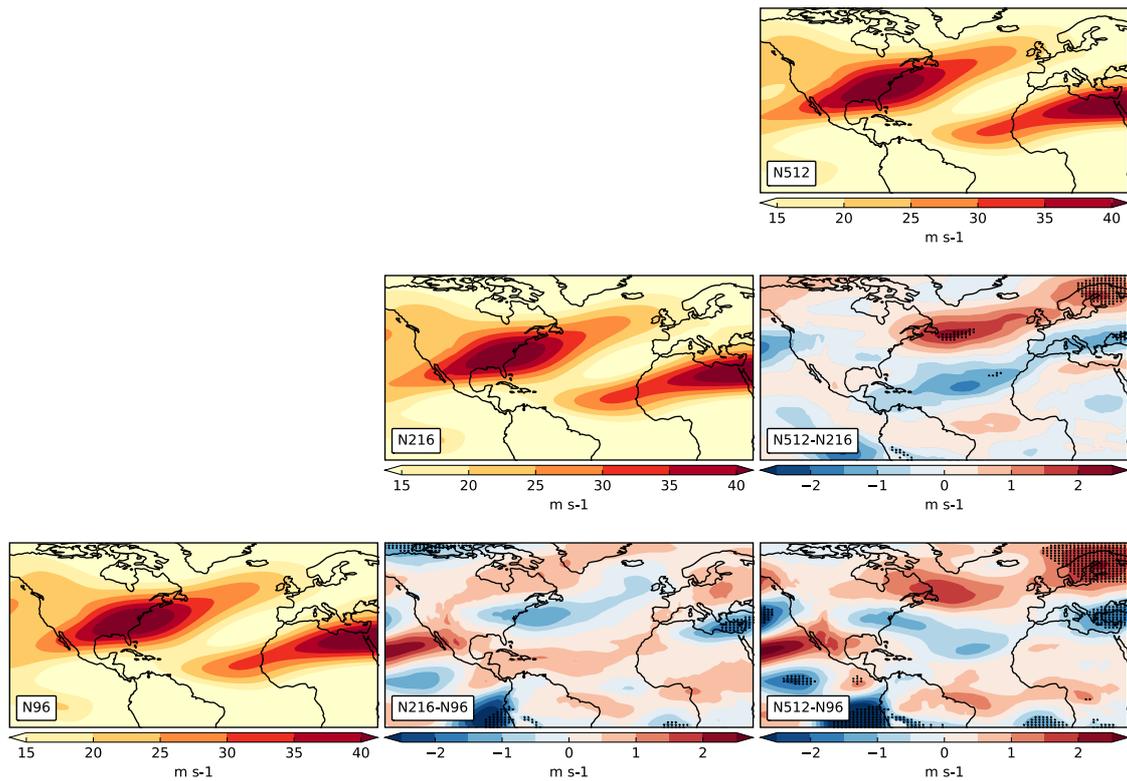
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847 **Fig. 2.** Variance in North Atlantic eddy-driven jet stream latitude ( $\sigma_{jet\ latitude}$ ) as a function of  
 848 jet speed, as represented in the ERA5 (black), ERA-Interim (pale grey) and NCEP-CFSR  
 849 (grey) reanalyses and simulated by HadGEM3-GA3.0. In this analysis, the standard deviation  
 850 of daily jet latitude is binned according to jet speed (shown as percentiles) with a bin width of  
 851 10 %, following Woollings et al. (2018). Curves for the historical climate (solid lines) and  
 852 RCP8.5 (dashed lines) integrations at N96 (orange), N216 (teal) and N512 (blue) resolutions  
 853 were constructed by concatenating ensemble members to maximise sampling.

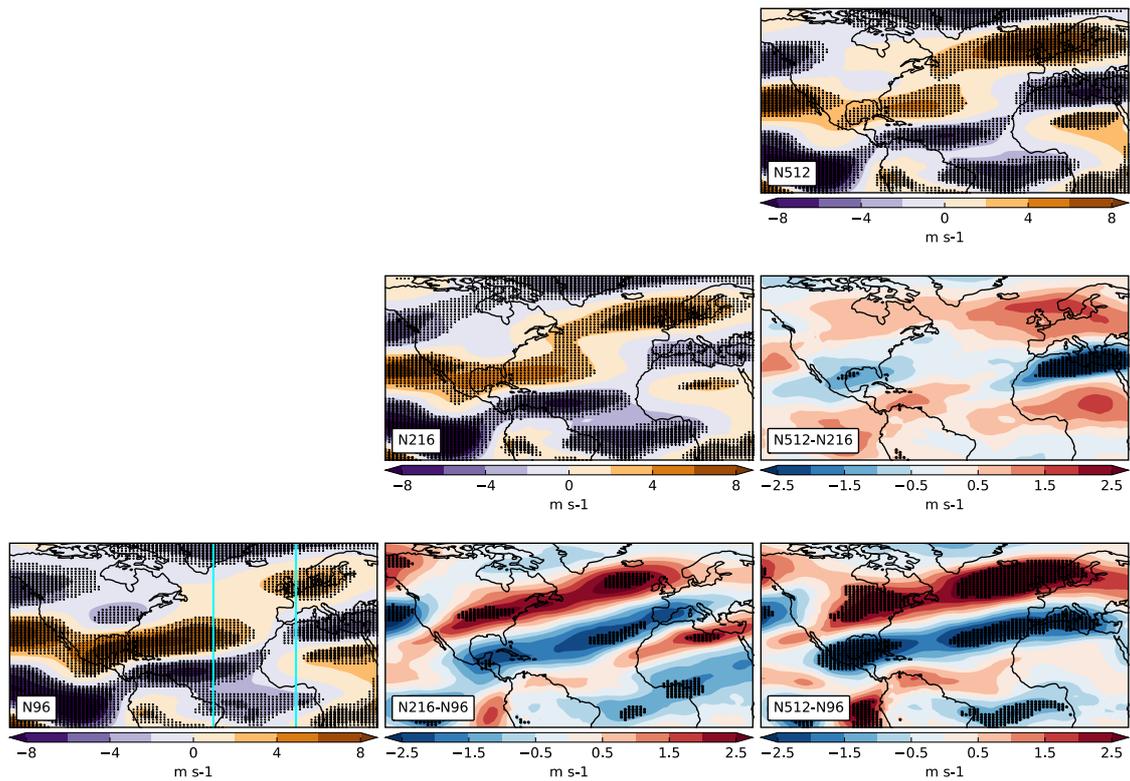
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856 **Fig. 3.** Resolution sensitivity of the ensemble-mean upper-tropospheric (250 hPa) winter  
 857 westerly zonal wind over the North Atlantic under historical SST forcing (1985-2011). N96  
 858 (lower-left), N216 (centre) and N512 (upper-right), with corresponding resolution differences  
 859 (lower-right panels). Stippling indicates statistically significant resolution differences at the  
 860 95% level. Unit is  $\text{m s}^{-1}$ .

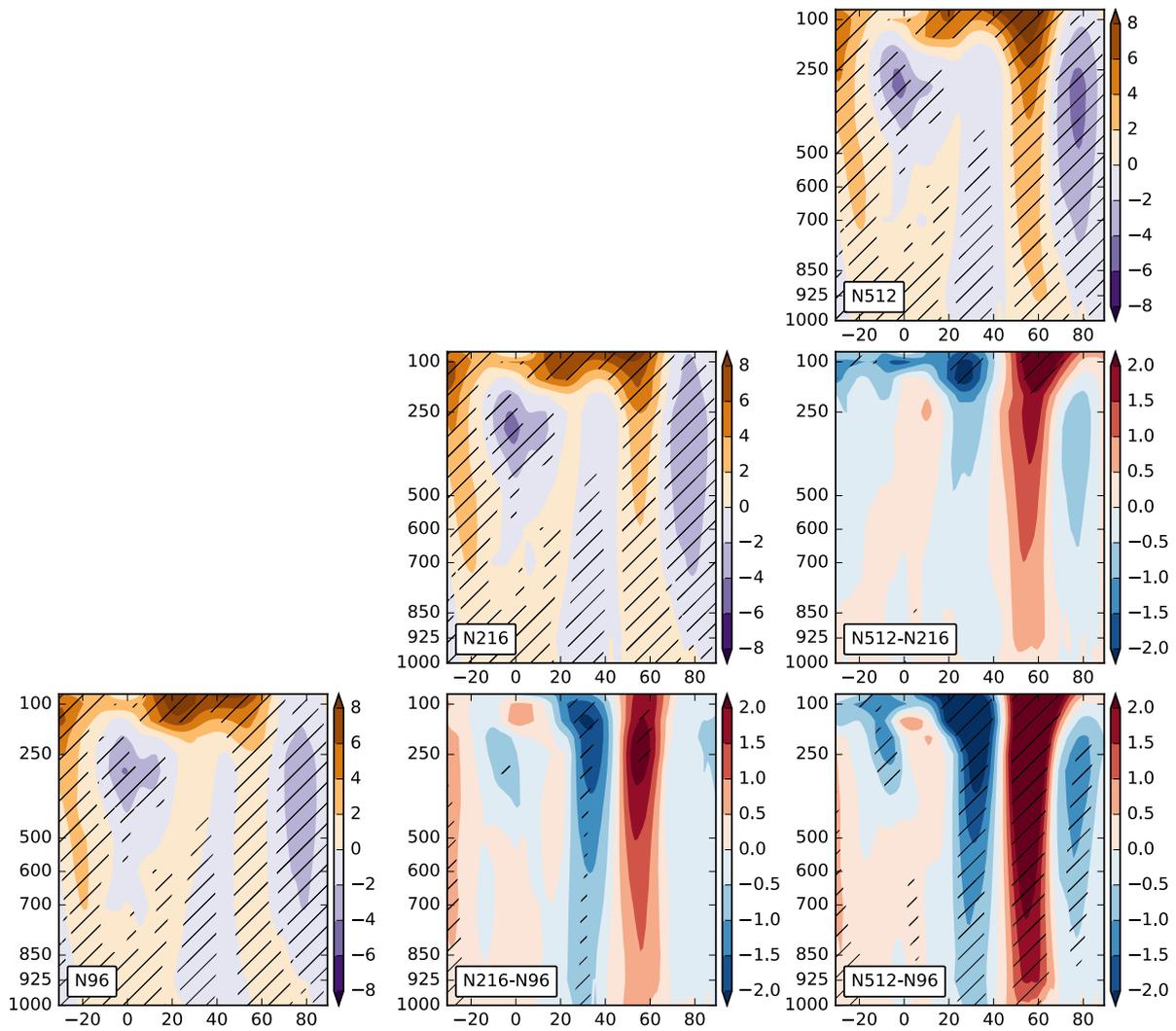
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863 **Fig. 4.** Resolution sensitivity of the ensemble-mean upper-tropospheric (250 hPa) winter  
 864 westerly zonal wind response to RCP8.5 over the North Atlantic. Panel layout as per Fig. 3.  
 865 The vertical cyan lines drawn at 40°W and 0° in the N96 panel indicate the sector averaged in  
 866 Fig. 5. Stippling indicates that the climate change response or resolution difference is  
 867 statistically significant at the 95% level. Unit is  $\text{m s}^{-1}$ .

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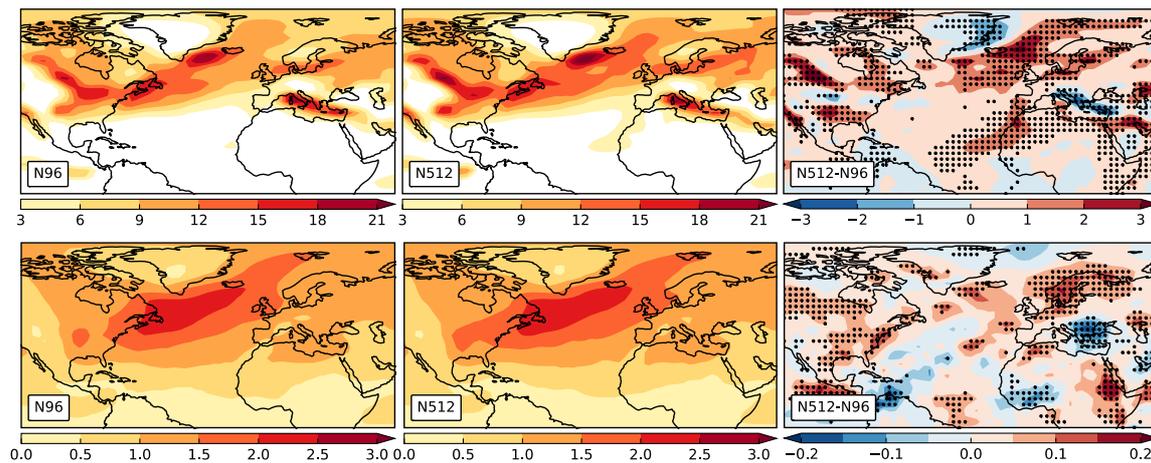


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871 **Fig. 5.** Vertical profile of the ensemble-mean winter westerly zonal wind response to  
 872 RCP8.5, averaged zonally over the eastern North Atlantic between 0° and 40°W. Panel layout  
 873 as per Fig. 3. Note that the vertical pressure axis is linear but only certain conventional  
 874 pressure levels are labelled (in hPa) for clarity. Diagonal hatching indicates that the climate  
 875 change response or resolution difference is statistically significant at the 95% level. Unit is m  
 876 s<sup>-1</sup>.

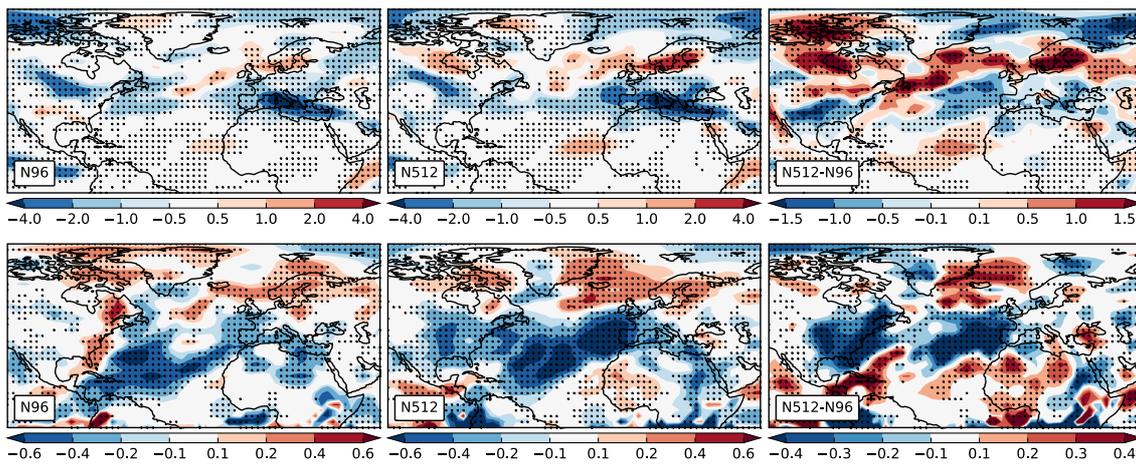
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879 **Fig. 6.** Resolution sensitivity of ensemble-mean North Atlantic winter storm track, as  
 880 measured by ETC track density (upper row) and mean ETC vorticity intensity (lower row)  
 881 for historical climate simulations (1986-2011). Shown are N96 (left), N512 (middle) and the  
 882 difference between these resolutions (right). Track density unit is cyclone transits per month  
 883 per unit area (equivalent to a cyclone-centred  $5^\circ$  spherical cap). Mean intensity unit is  
 884 vorticity scaled by  $10^5 \text{ s}^{-1}$ . Stippling indicates statistically significant resolution differences at  
 885 the 95% level.

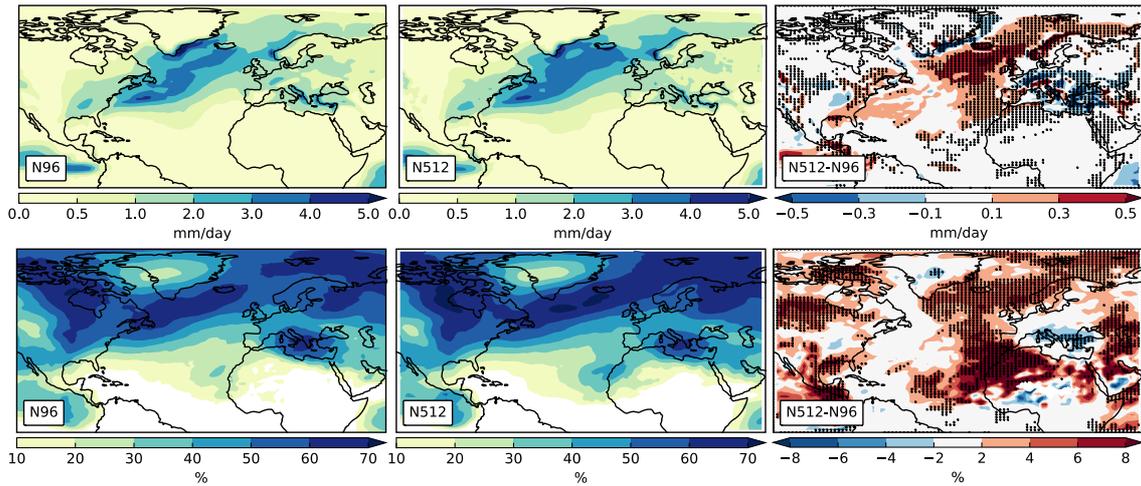
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888 **Fig. 7.** Resolution sensitivity of the ensemble-mean response of winter ETC track density  
 889 (upper row) and mean intensity (lower row) to the RCP8.5 scenario over the North Atlantic.  
 890 Panel layout as per Fig. 6. Stippling indicates that the climate change response or resolution  
 891 sensitivity is statistically significant at the 95% level. Track density unit is cyclone transits  
 892 per month per unit area (equivalent to a cyclone-centred 5° spherical cap). Mean intensity  
 893 unit is vorticity scaled by  $10^5 \text{ s}^{-1}$ .

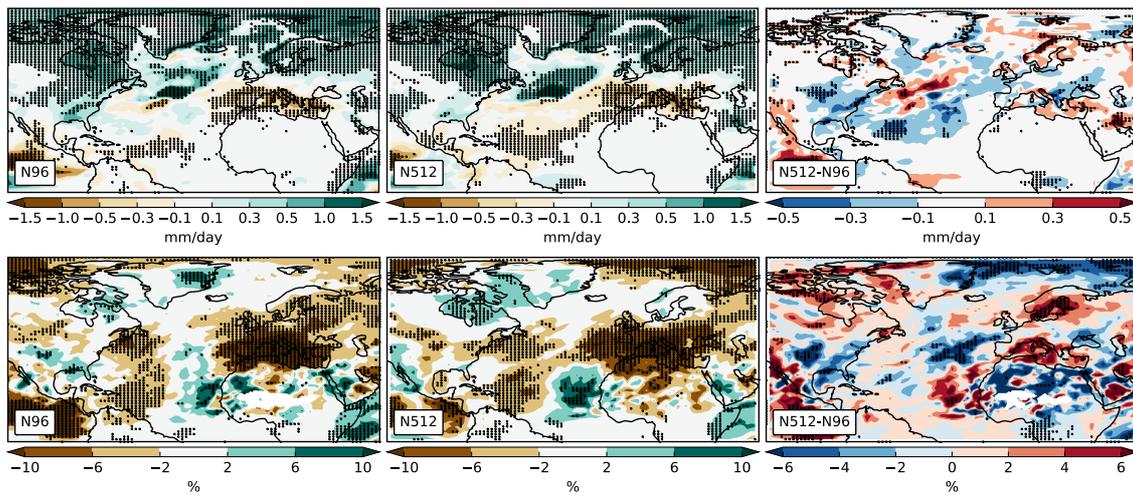
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896 **Fig. 8.** Resolution sensitivity of ensemble-mean North Atlantic winter ETC-associated  
 897 precipitation (upper row) and ETC contribution to total precipitation (lower row) for  
 898 historical climate simulations (1986-2011). Panel layout as per Fig. 6. Stippling indicates  
 899 statistically significant resolution sensitivity at the 95% level. Units are mm day<sup>-1</sup> and %,  
 900 respectively.

901



902

903 **Fig. 9.** Resolution sensitivity of the responses of ensemble-mean North Atlantic winter ETC-

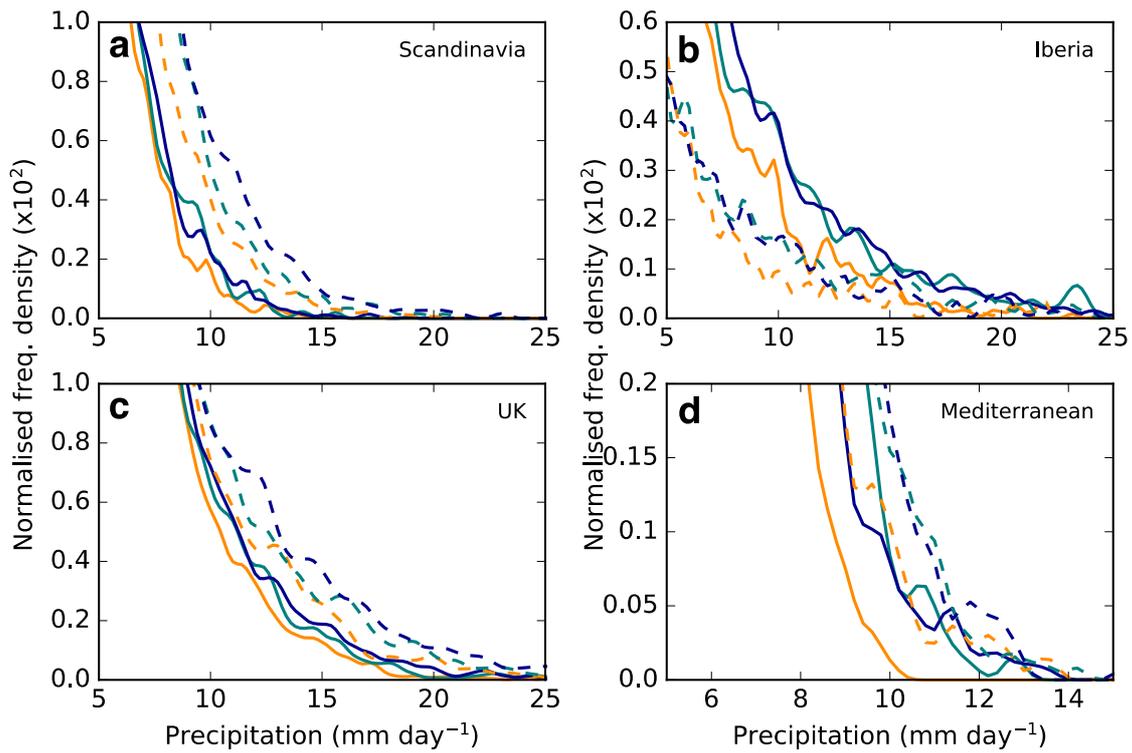
904 associated precipitation (upper row) and ETC contribution to total precipitation (lower row)

905 to RCP8.5. Panel layout as per Fig. 6. Stippling indicates that the climate change response or

906 resolution sensitivity is statistically significant at the 95% level. Units are  $\text{mm day}^{-1}$  and %,

907 respectively.

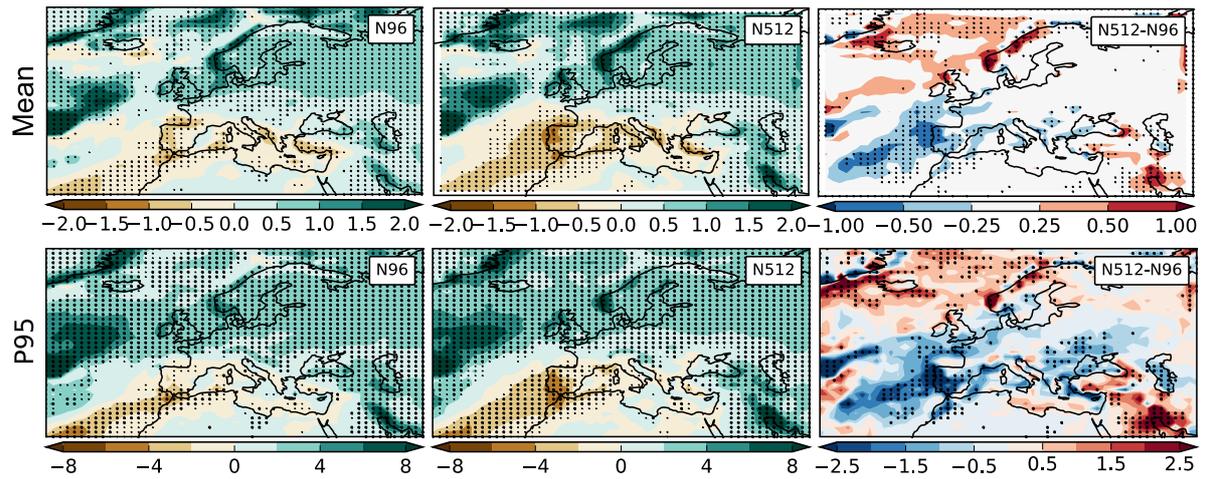
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910 **Fig. 10.** Domain-mean frequency distribution of ETC-associated precipitation over (a)  
 911 Scandinavia, (b) Iberia, (c) the UK, and (d) the Mediterranean under historical (solid lines)  
 912 and RCP8.5 forcing (dashed lines). Ensemble members were concatenated to maximise  
 913 sampling of high precipitation rates. Colours are as per Fig. 1.

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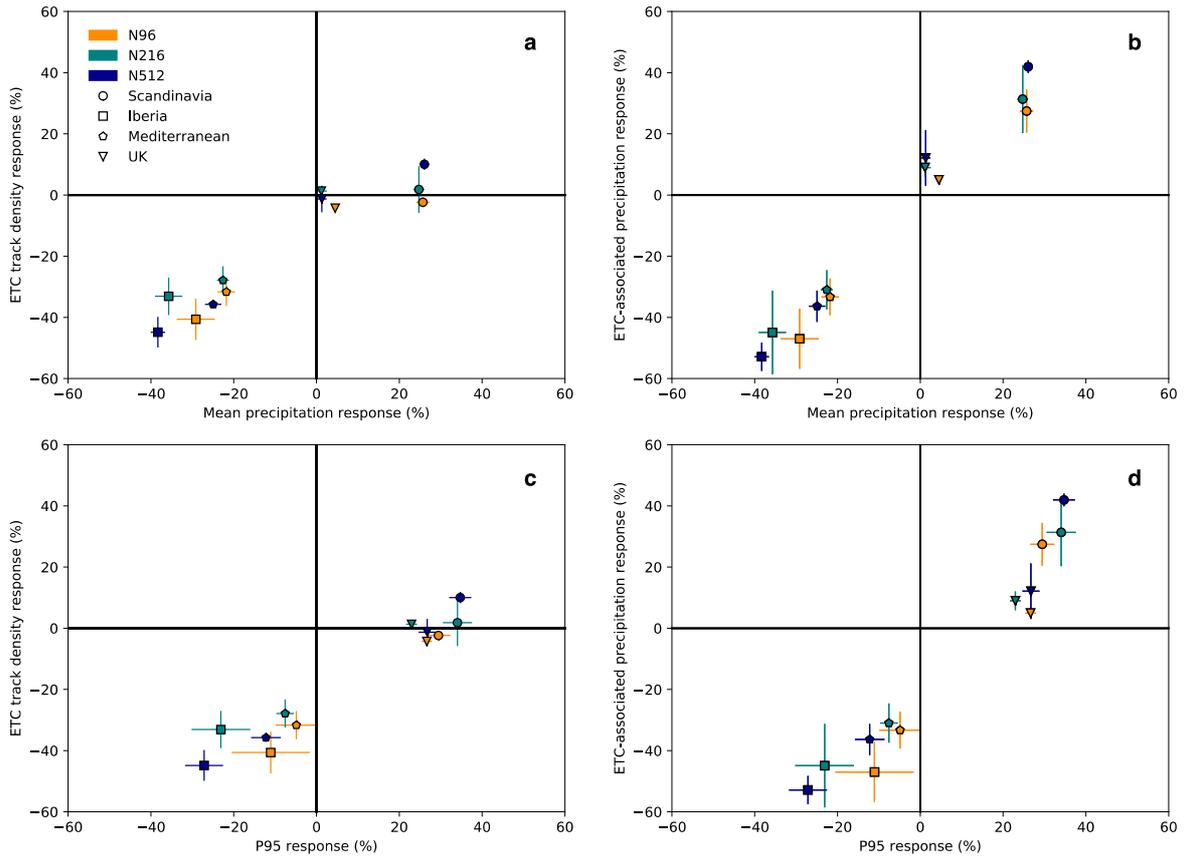
916 **Fig. 11.** Resolution sensitivity of ensemble-mean winter mean (upper row) and 95<sup>th</sup> percentile

917 (lower row) precipitation response to RCP8.5 over Europe. Panel layout as per Fig. 6.

918 Stippling indicates statistically significant climate change response or resolution sensitivity at

919 the 95% level. Unit is  $\text{mm day}^{-1}$ .

920



921

922 **Fig. 12.** Area-weighted, domain-mean percentage change of ETC track density and ETC-  
 923 associated precipitation under RCP8.5 as a function of (a,b) mean and (c,d) 95<sup>th</sup> percentile  
 924 precipitation for each HadGEM3-GA3.0 resolution. Markers indicate the ensemble mean and  
 925 error bars indicate the standard deviation of the ensemble members. The RCP8.5 response of  
 926 each individual future climate ensemble member is computed as a percentage difference from  
 927 the present-climate ensemble mean.

928