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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



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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 21st 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 5th 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 6th
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° 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° 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 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, ω , 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° 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⁻¹), 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 ω) 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 ω asymmetry (Tamarin-Brodsky and Hadas 2019).

377

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).

424

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

442

443 The role of resolution in the simulated response of ETC-associated precipitation to RCP8.5
444 emerges at smaller spatial scales and when a range of precipitation rates is considered. We
445 quantified the impact of increased resolution on area-averaged ETC-associated precipitation
446 rates over regions where statistically significant changes are projected by CMIP5 as well as
447 in our HadGEM3-GA3.0 simulations: Scandinavia, the UK, Iberia and the Mediterranean.
448 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 95th 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 CO₂ 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.

613

614

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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678

679

680 **Data and code availability**

681 For access to the UPSCALE simulations used in this study, see 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. 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.
689 ERA-Interim data are available from 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).
692

693 **References**

- 694 Barnes, E. A., and L. M. Polvani, 2015: CMIP5 Projections of Arctic Amplification, of the
695 North American/North Atlantic Circulation, and of Their Relationship. *Journal of Climate*
696 **28**, 5254-5271.
- 697 Bengtsson, L. et al., 2006: Storm Tracks and Climate Change. *Journal of Climate* **19**, 3518-
698 3543.
- 699 Brayshaw, D. J. et al., 2011: The Basic Ingredients of the North Atlantic Storm Track. Part II:
700 Sea Surface Temperatures. *Journal of the Atmospheric Sciences* **68**, 1784-1805.
- 701 Catto, J. L. et al., 2010: Can Climate Models Capture the Structure of Extratropical
702 Cyclones? *Journal of Climate* **23**, 1621-1635.
- 703 Champion, A. J. et al., 2011: Impact of increasing resolution and a warmer climate on
704 extreme weather from Northern Hemisphere extratropical cyclones. *Tellus A* **63**, 893-906.
- 705 Dacre, H. F., and S. L. Gray, 2013: Quantifying the climatological relationship between
706 extratropical cyclone intensity and atmospheric precursors. *Geophysical Research Letters* **40**,
707 2322-2327.
- 708 Dee, D. P. et al., 2011: The ERA-Interim reanalysis: configuration and performance of the
709 data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**, 553-
710 597.
- 711 Della-Marta, P. M., and J. G. Pinto, 2009: Statistical uncertainty of changes in winter storms
712 over the North Atlantic and Europe in an ensemble of transient climate simulations.
713 *Geophysical Research Letters* **36**, L14703.
- 714 Delworth, T. L. et al., 2012: Simulated Climate and Climate Change in the GFDL CM2.5
715 High-Resolution Coupled Climate Model. *Journal of Climate* **25**, 2755-2781.
- 716 Demory, M.-E. et al., 2014: The role of horizontal resolution in simulating drivers of the
717 global hydrological cycle. *Climate Dynamics* **42**, 2201-2225.
- 718 Donlon, C. J. et al., 2012: The Operational Sea Surface Temperature and Sea Ice Analysis
719 (OSTIA) system. *Remote Sensing of Environment* **116**, 140-158.
- 720 Duchon, C. E., 1979: Lanczos Filtering in One and Two Dimensions. *Journal of Applied*
721 *Meteorology* **18**, 1016-1022.
- 722 Finnis, J. et al., 2007: Response of Northern Hemisphere extratropical cyclone activity and
723 associated precipitation to climate change, as represented by the Community Climate System
724 Model. *Journal of Geophysical Research: Biogeosciences* **112**, G04S42.
- 725 Grise, K. M., and L. M. Polvani, 2014: The response of midlatitude jets to increased CO₂:
726 Distinguishing the roles of sea surface temperature and direct radiative forcing. *Geophysical*
727 *Research Letters* **41**, 6863-6871.
- 728 Haarsma, R. J. et al., 2016: High Resolution Model Intercomparison Project
729 (HighResMIP v1.0) for CMIP6. *Geoscientific Model Development* **9**, 4185-4208.

- 730 Haarsma, R. J. et al., 2013: Anthropogenic changes of the thermal and zonal flow structure
731 over Western Europe and Eastern North Atlantic in CMIP3 and CMIP5 models. *Climate*
732 *Dynamics* **41**, 2577-2588.
- 733 Hawcroft, M. et al., 2018: Significantly increased extreme precipitation expected in Europe
734 and North America from extratropical cyclones. *Environmental Research Letters* **13**, 124006.
- 735 Hawcroft, M. K. et al., 2012: How much Northern Hemisphere precipitation is associated
736 with extratropical cyclones? *Geophysical Research Letters* **39**, L24809.
- 737 Hawcroft, M. K. et al., 2016: Can climate models represent the precipitation associated with
738 extratropical cyclones? *Climate Dynamics* **47**, 679-695.
- 739 Hodges, K. I., 1995: Feature Tracking on the Unit Sphere. *Monthly Weather Review* **123**,
740 3458-3465.
- 741 Hodges, K. I., 1999: Adaptive Constraints for Feature Tracking. *Monthly Weather Review*
742 **127**, 1362-1373.
- 743 Hoskins, B. J., 1983: Dynamical processes in the atmosphere and the use of models.
744 *Quarterly Journal of the Royal Meteorological Society* **109**, 1-21.
- 745 Hoskins, B. J., and K. I. Hodges, 2002: New Perspectives on the Northern Hemisphere
746 Winter Storm Tracks. *Journal of the Atmospheric Sciences* **59**, 1041-1061.
- 747 Hoskins, B. J. et al., 1983: The Shape, Propagation and Mean-Flow Interaction of Large-
748 Scale Weather Systems. *Journal of the Atmospheric Sciences* **40**, 1595-1612.
- 749 Huntingford, C. et al., 2014: Potential influences on the United Kingdom's floods of winter
750 2013/14. *Nature Climate Change* **4**, 769.
- 751 Iqbal, W. et al., 2018: Analysis of the variability of the North Atlantic eddy-driven jet stream
752 in CMIP5. *Climate Dynamics* **51**, 235-247.
- 753 Kaspi, Y., and T. Schneider, 2013: The Role of Stationary Eddies in Shaping Midlatitude
754 Storm Tracks. *Journal of the Atmospheric Sciences* **70**, 2596-2613.
- 755 Madonna, E. et al., 2017: The link between eddy-driven jet variability and weather regimes in
756 the North Atlantic-European sector. *Quarterly Journal of the Royal Meteorological Society*
757 **143**, 2960-2972.
- 758 Masato, G. et al., 2016: A regime analysis of Atlantic winter jet variability applied to
759 evaluate HadGEM3-GC2. *Quarterly Journal of the Royal Meteorological Society* **142**, 3162-
760 3170.
- 761 Matsueda, M., and T. N. Palmer, 2011: Accuracy of climate change predictions using high
762 resolution simulations as surrogates of truth. *Geophysical Research Letters* **38**.
- 763 Mizielinski, M. S. et al., 2014: High-resolution global climate modelling: the UPSCALE
764 project, a large-simulation campaign. *Geoscientific Model Development* **7**, 1629-1640.

- 765 O'Reilly, C. H. et al., 2017: The Gulf Stream influence on wintertime North Atlantic jet
766 variability. *Quarterly Journal of the Royal Meteorological Society* **143**, 173-183.
- 767 Pfahl, S. et al., 2017: Understanding the regional pattern of projected future changes in
768 extreme precipitation. *Nature Climate Change* **7**, 423.
- 769 Pfahl, S., and H. Wernli, 2012: Quantifying the Relevance of Cyclones for Precipitation
770 Extremes. *Journal of Climate* **25**, 6770-6780.
- 771 Pinto, J. G. et al., 2009: Factors contributing to the development of extreme North Atlantic
772 cyclones and their relationship with the NAO. *Climate Dynamics* **32**, 711-737.
- 773 Prein, A. F. et al., 2016: Precipitation in the EURO-CORDEX 11° and 44° simulations: high
774 resolution, high benefits? *Climate Dynamics* **46**, 383-412.
- 775 Roberts, M. J. et al., 2018: The benefits of global high-resolution for climate simulation:
776 process-understanding and the enabling of stakeholder decisions at the regional scale.
777 *Bulletin of the American Meteorological Society*.
- 778 Saha, S. et al., 2010: The NCEP Climate Forecast System Reanalysis. *Bulletin of the*
779 *American Meteorological Society* **91**, 1015-1058.
- 780 Schiemann, R. et al., 2018: Mean and extreme precipitation over European river basins better
781 simulated in a 25km AGCM. *Hydrology and Earth System Sciences* **22**, 3933-3950.
- 782 Schneider, T., 2006: The General Circulation of the Atmosphere. *Annual Review of Earth*
783 *and Planetary Sciences* **34**, 655-688.
- 784 Shaw, T. A. et al., 2016: Storm track processes and the opposing influences of climate
785 change. *Nature Geoscience* **9**, 656-664.
- 786 Shepherd, T. G., 2014: Atmospheric circulation as a source of uncertainty in climate change
787 projections. *Nature Geoscience* **7**, 703-708.
- 788 Small, R. J. et al., 2019: Atmosphere surface storm track response to resolved ocean
789 mesoscale in two sets of global climate model experiments. *Climate Dynamics* **52**, 2067-
790 2089.
- 791 Tamarin-Brodsky, T., and O. Hadas, 2019: The Asymmetry of Vertical Velocity in Current
792 and Future Climate. *Geophysical Research Letters* **46**, 374-382.
- 793 Tamarin-Brodsky, T., and Y. Kaspi, 2017: Enhanced poleward propagation of storms under
794 climate change. *Nature Geoscience* **10**, 908-913.
- 795 Tous, M. et al., 2016: Projected changes in medicanes in the HadGEM3 N512 high-resolution
796 global climate model. *Climate Dynamics* **47**, 1913-1924.
- 797 van Haren, R. et al., 2015: Resolution Dependence of European Precipitation in a State-of-
798 the-Art Atmospheric General Circulation Model. *Journal of Climate* **28**, 5134-5149.
- 799 Vidale, P. L. et al., 2007: European summer climate variability in a heterogeneous multi-
800 model ensemble. *Climatic Change* **81**, 209-232.

801 Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the Geopotential Height Field
802 during the Northern Hemisphere Winter. *Monthly Weather Review* **109**, 784-812.

803 Walters, D. N. et al., 2011: The Met Office Unified Model Global Atmosphere 3.0/3.1 and
804 JULES Global Land 3.0/3.1 configurations. *Geoscientific Model Development* **4**, 919-941.

805 Willison, J. et al., 2013: The Importance of Resolving Mesoscale Latent Heating in the North
806 Atlantic Storm Track. *Journal of the Atmospheric Sciences* **70**, 2234-2250.

807 Willison, J. et al., 2015: North Atlantic Storm-Track Sensitivity to Warming Increases with
808 Model Resolution. *Journal of Climate* **28**, 4513-4524.

809 Woollings, T., 2010: Dynamical influences on European climate: an uncertain future.
810 *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering*
811 *Sciences* **368**, 3733.

812 Woollings, T. et al., 2018: Daily to Decadal Modulation of Jet Variability. *Journal of Climate*
813 **31**, 1297-1314.

814 Woollings, T. et al., 2012: Response of the North Atlantic storm track to climate change
815 shaped by ocean–atmosphere coupling. *Nature Geoscience* **5**, 313.

816 Woollings, T. et al., 2010: Variability of the North Atlantic eddy-driven jet stream. *Quarterly*
817 *Journal of the Royal Meteorological Society* **136**, 856-868.

818 Zappa, G. et al., 2015: Extratropical cyclones and the projected decline of winter
819 Mediterranean precipitation in the CMIP5 models. *Climate Dynamics* **45**, 1727-1738.

820 Zappa, G. et al., 2013a: The Ability of CMIP5 Models to Simulate North Atlantic
821 Extratropical Cyclones. *Journal of Climate* **26**, 5379-5396.

822 Zappa, G. et al., 2013b: A Multimodel Assessment of Future Projections of North Atlantic
823 and European Extratropical Cyclones in the CMIP5 Climate Models. *Journal of Climate* **26**,
824 5846-5862.

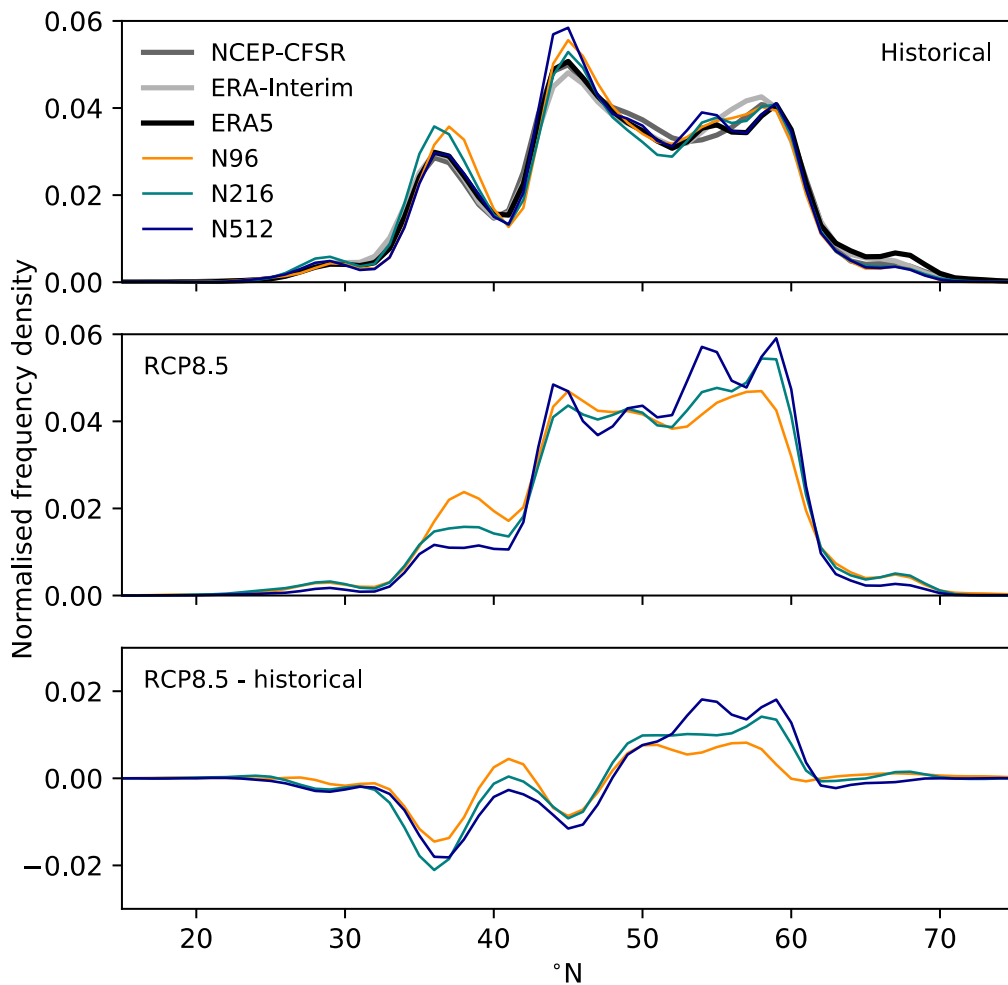
825 Zappa, G., and T. G. Shepherd, 2017: Storylines of Atmospheric Circulation Change for
826 European Regional Climate Impact Assessment. *Journal of Climate* **30**, 6561-6577.

827 Zhang, L. et al., 2016: Added value of high resolution models in simulating global
828 precipitation characteristics. *Atmospheric Science Letters* **17**, 646-657.

829 Zveryaev, I. I., 2004: Seasonality in precipitation variability over Europe. *Journal of*
830 *Geophysical Research: Atmospheres* **109**, D05103.

831 Zveryaev, I. I., 2006: Seasonally varying modes in long-term variability of European
832 precipitation during the 20th century. *Journal of Geophysical Research: Atmospheres* **111**,
833 D21116.
834

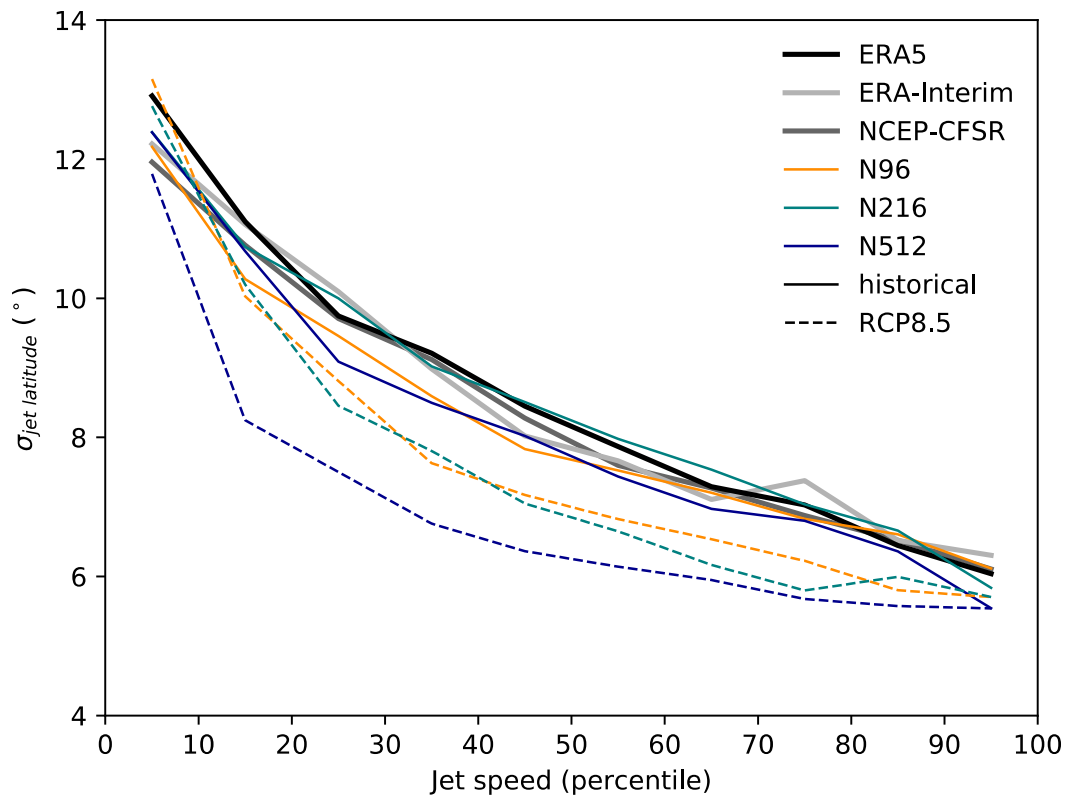
835 **Figures**



836

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.

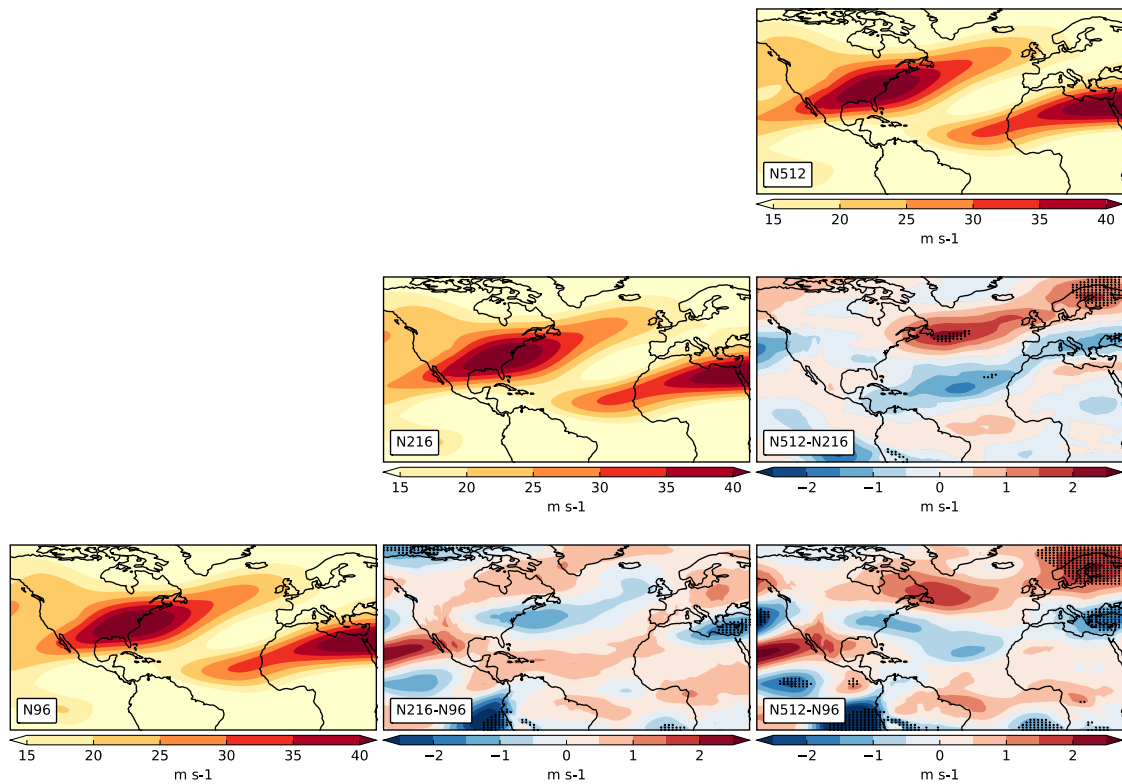
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847 **Fig. 2.** Variance in North Atlantic eddy-driven jet stream latitude ($\sigma_{jet\ latitude}$) as a function of
 848 jet speed, as represented in the ERA5 (black), ERA-Interim (pale grey) and NCEP-CFSR
 849 (grey) reanalyses and simulated by 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.

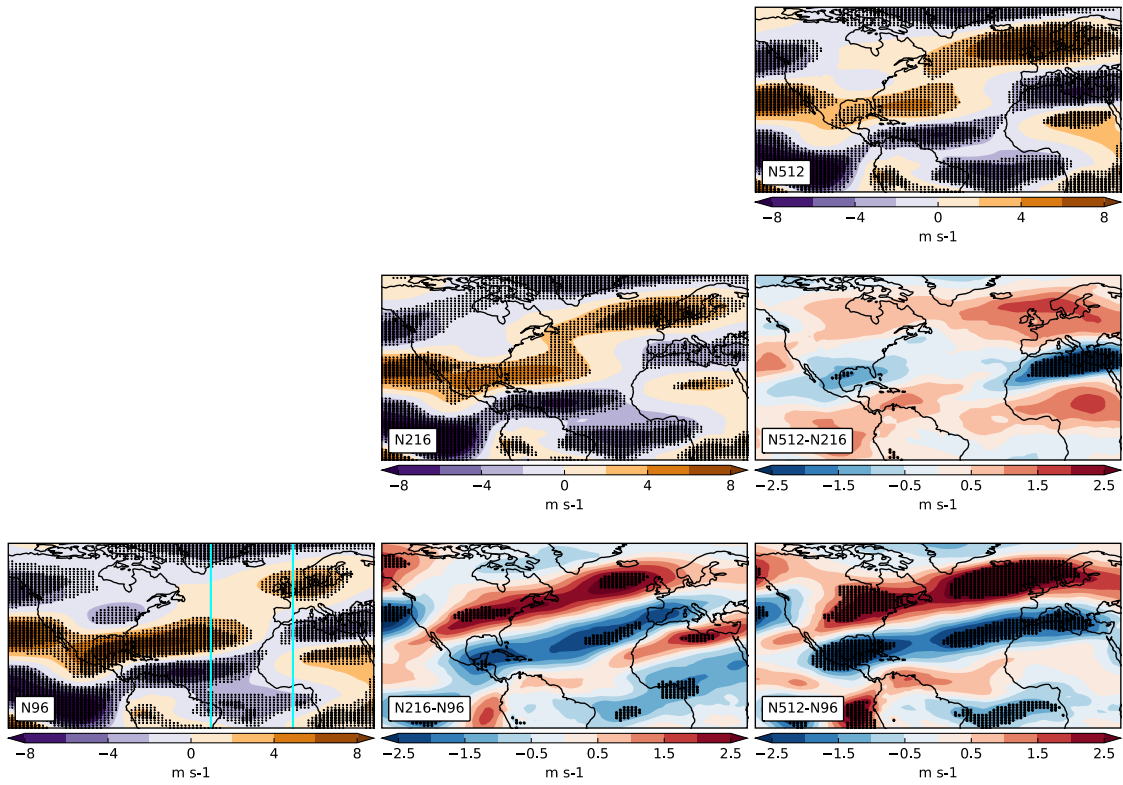
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856 **Fig. 3.** Resolution sensitivity of the ensemble-mean upper-tropospheric (250 hPa) winter
 857 westerly zonal wind over the North Atlantic under historical SST forcing (1985-2011). N96
 858 (lower-left), N216 (centre) and N512 (upper-right),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

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862

863 **Fig. 4.** Resolution sensitivity of the ensemble-mean upper-tropospheric (250 hPa) winter

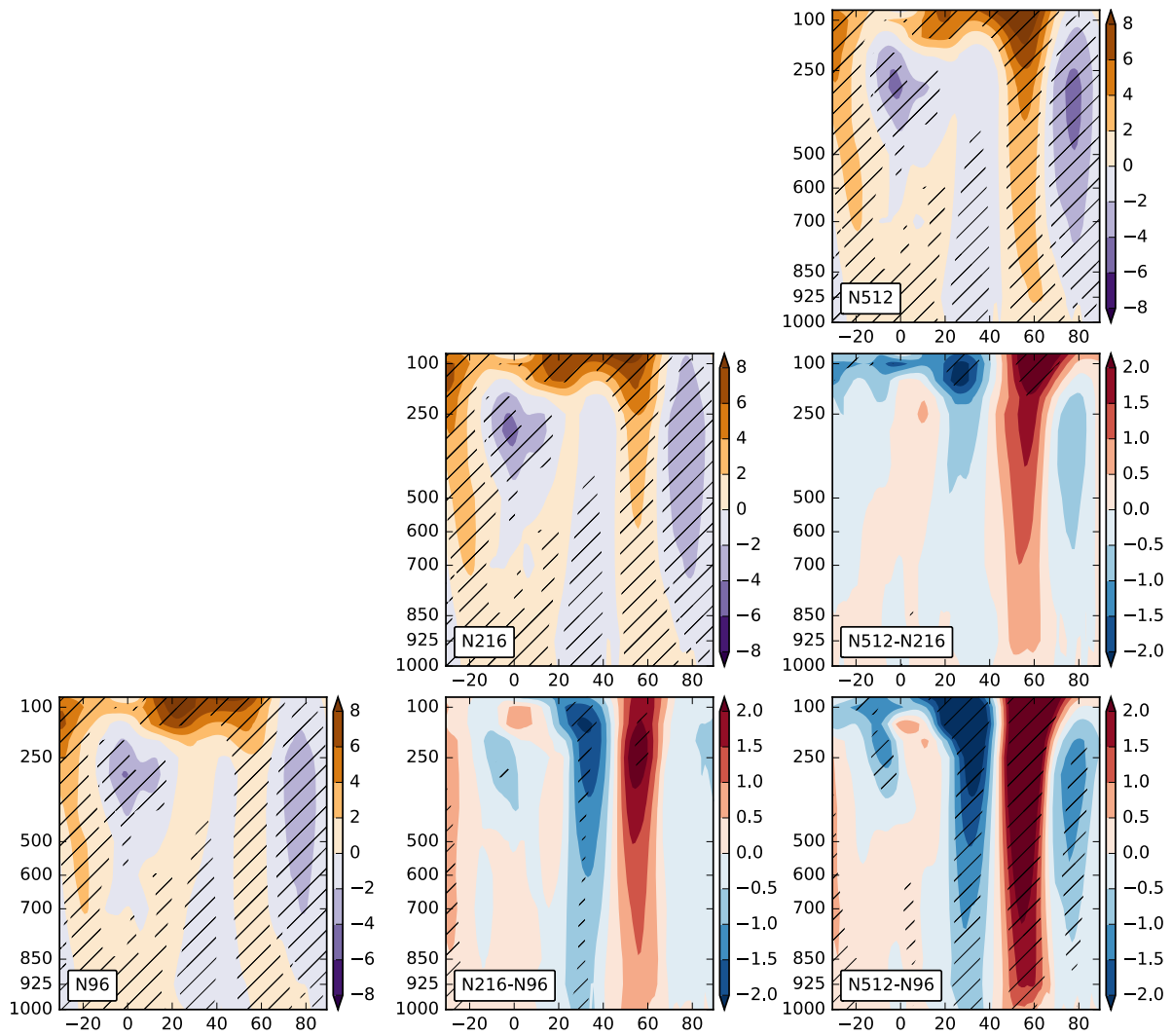
864 westerly zonal wind response to RCP8.5 over the North Atlantic. Panel layout as per Fig. 3.

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 m s^{-1} .

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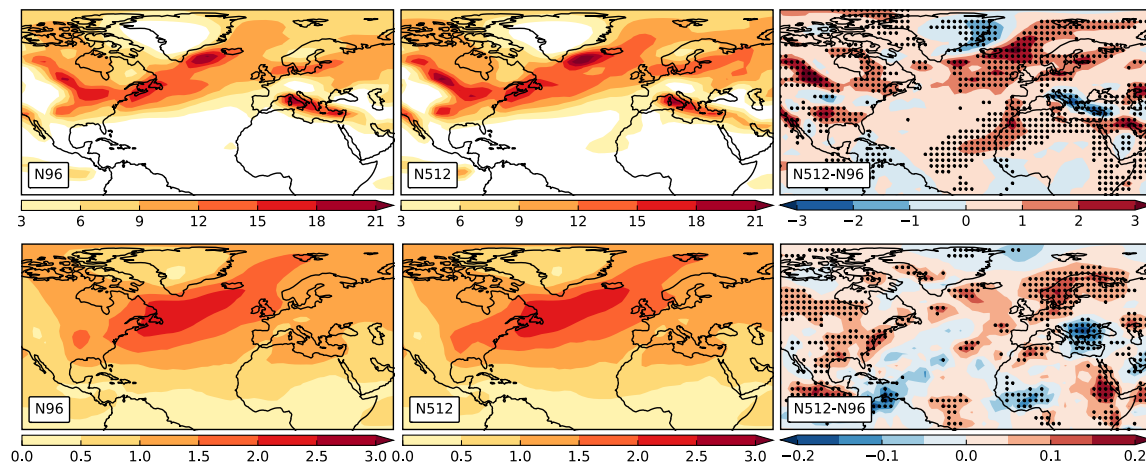


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870

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⁻¹.

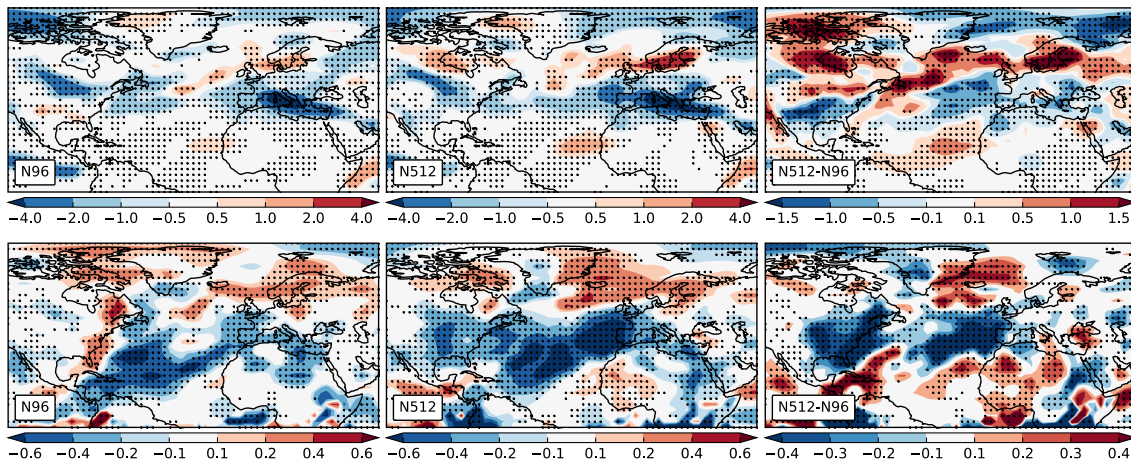
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879 **Fig. 6.** Resolution sensitivity of ensemble-mean North Atlantic winter storm track, as
 880 measured by ETC track density (upper row) and mean ETC vorticity intensity (lower row)
 881 for historical climate simulations (1986-2011). Shown are 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° spherical cap). Mean intensity unit is
 884 vorticity scaled by 10^5 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.

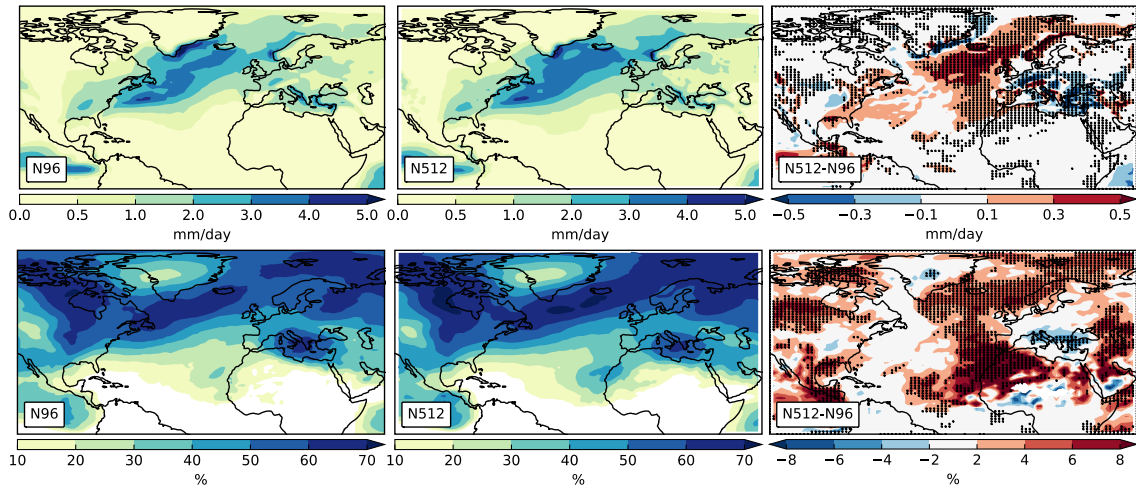
890 Panel layout as per Fig. 6. Stippling indicates that the climate change response or resolution

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 s^{-1} .

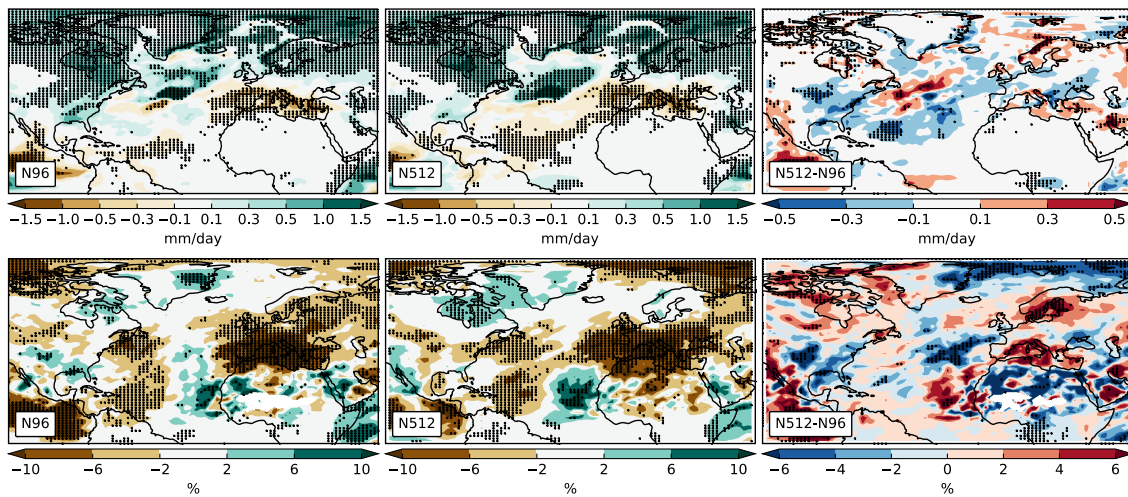
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896 **Fig. 8.** Resolution sensitivity of ensemble-mean North Atlantic winter ETC-associated
 897 precipitation (upper row) and ETC contribution to total precipitation (lower row) for
 898 historical climate simulations (1986-2011). Panel layout as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

901



902

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

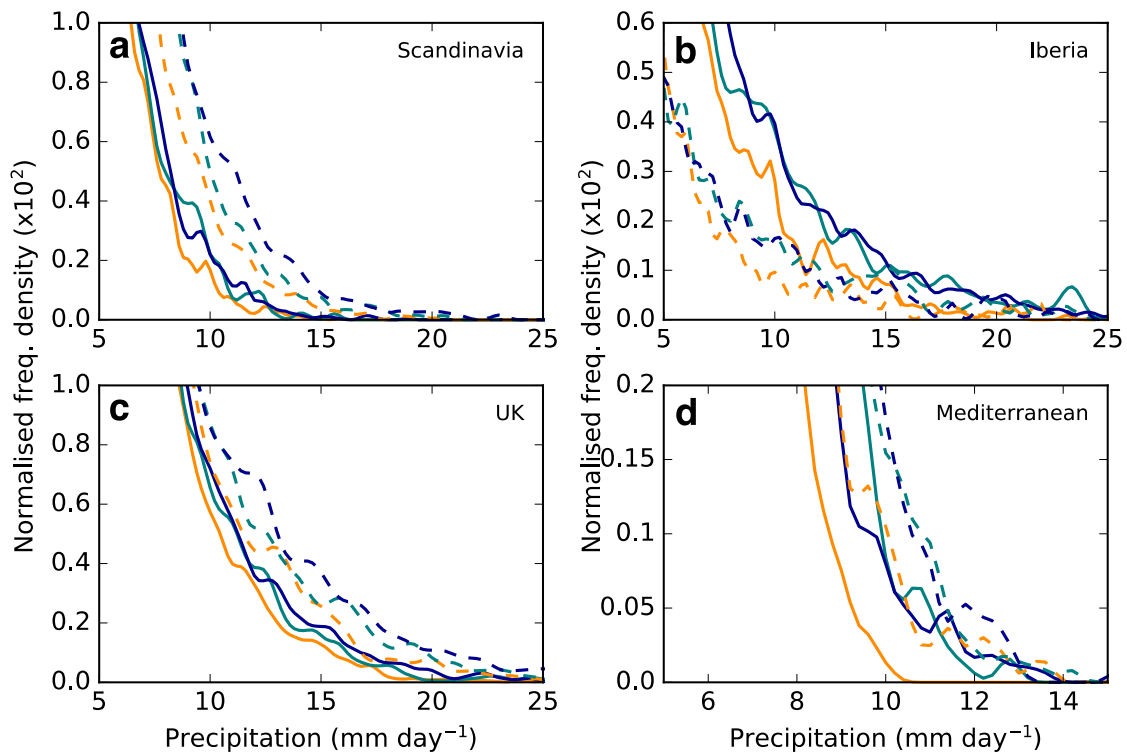
904 associated precipitation (upper row) and ETC contribution to total precipitation (lower row)

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 mm day^{-1} and %,

907 respectively.

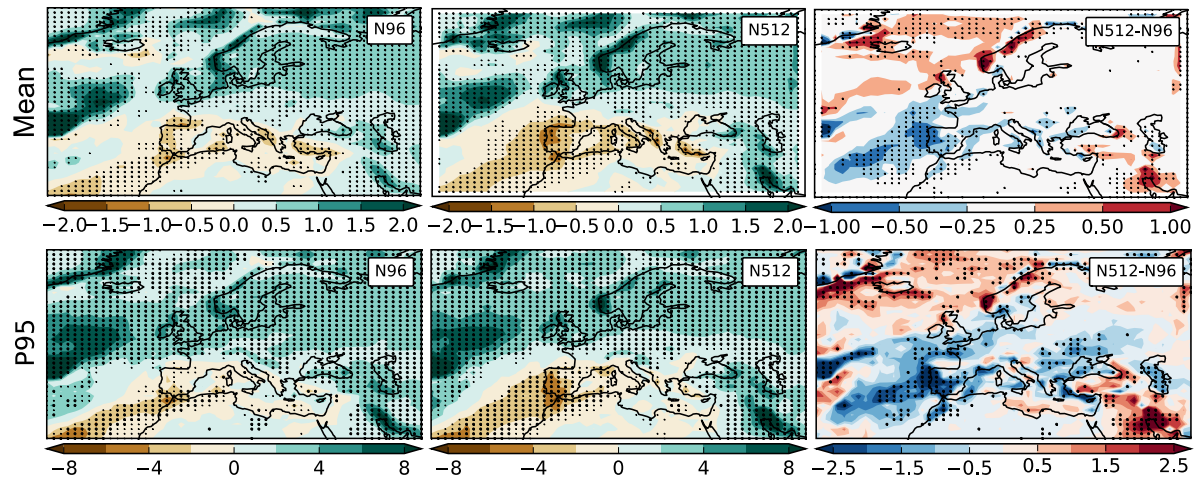
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910 **Fig. 10.** Domain-mean frequency distribution of ETC-associated precipitation over (a)
 911 Scandinavia, (b) Iberia, (c) the UK, and (d) the Mediterranean under historical (solid lines)
 912 and RCP8.5 forcing (dashed lines). Ensemble members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

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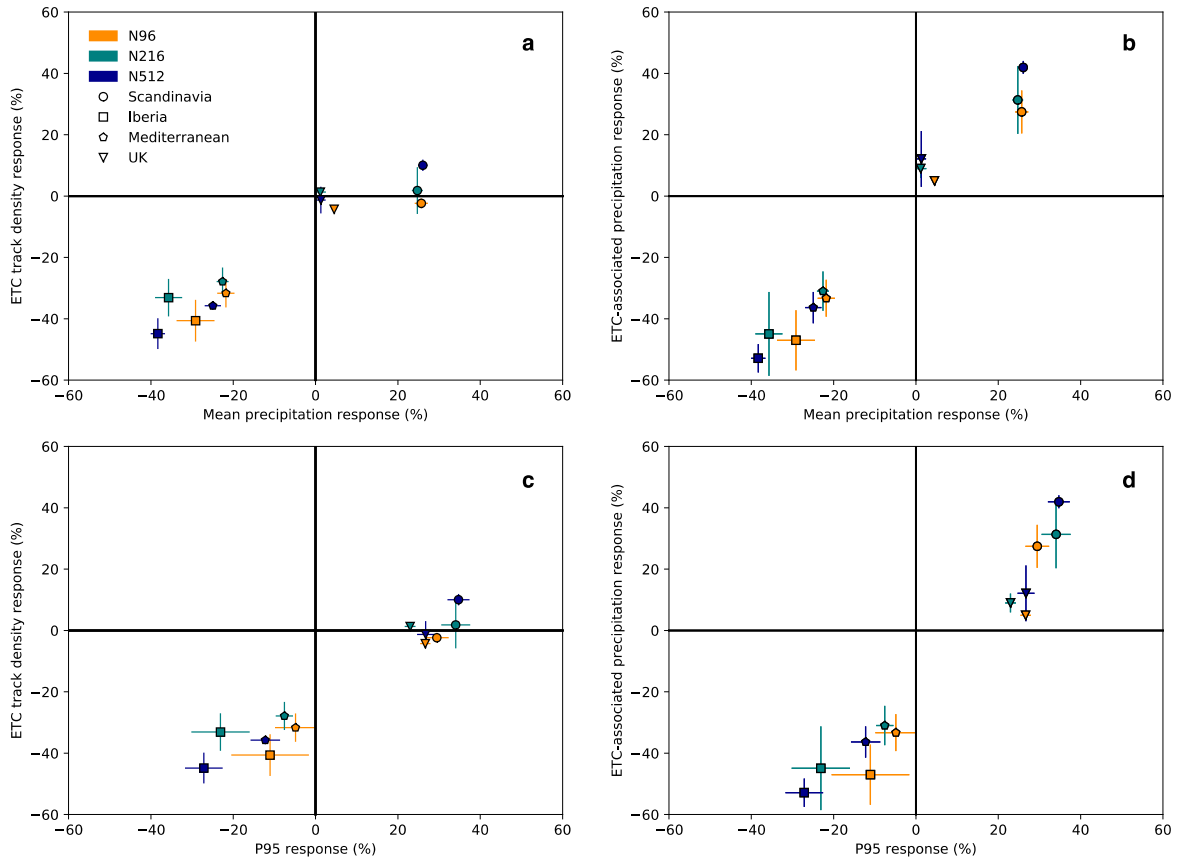
916 **Fig. 11.** Resolution sensitivity of ensemble-mean winter mean (upper row) and 95th percentile

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 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) 95th 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