

Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling

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1 Response of the North Atlantic storm track to
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8 A poleward shift of the mid-latitude storm tracks in response to an-
9 thropogenic greenhouse-gas forcing has been diagnosed in climate model
10 simulations^{1;2}. Explanations of this effect have focused on atmospheric
11 dynamics^{3;4;5;6;7}. However, in contrast to storm tracks in other regions,
12 the North Atlantic storm track responds by strengthening and extend-
13 ing further east, in particular on its southern flank⁸. These adjustments
14 are associated with an intensification and extension of the eddy-driven
15 jet towards western Europe⁹ and are expected to have considerable so-
16 cietal impacts related to a rise storminess in Europe^{10;11;12}. Here we
17 apply a regression analysis to an ensemble of coupled climate model
18 simulations to show that the coupling between ocean and atmosphere
19 shapes the distinct storm track response to greenhouse-gas forcing in
20 the North Atlantic region. In the ensemble of simulations we anal-
21 yse, at least half of the difference between the storm track responses
22 of different models is associated with uncertainties in ocean circulation
23 changes. We compare the fully coupled simulations with both the asso-
24 ciated slab model simulations and an ocean-forced experiment with one
25 climate model to establish causality. We conclude that uncertainties in
26 the response of the North Atlantic storm track to anthropogenic emis-
27 sions could be reduced through tighter constraints on the future ocean
28 circulation.

29 We focus on the role of the Meridional Overturning Circulation (MOC) which
30 transports heat northwards in the Atlantic Ocean. There is evidence from mod-
31 elling studies that the MOC has an influence on both the mean state^{13;14;15} and
32 variability¹⁶ of the storm track. The MOC is projected to weaken in response to
33 greenhouse-gas forcing¹ and over the northern North Atlantic this is expected to
34 offset some of the greenhouse-induced warming in sea surface temperature (SST).

35 The meridional gradient in SST is therefore projected to increase in the mid-
36 latitude North Atlantic, implying an increase in the baroclinic instability from
37 which the storm track draws its energy. Some studies have speculated that the
38 storm track and MOC/SST responses might be related^{17;18;19;20} but this has never
39 been investigated specifically. Here we show that the MOC is an important factor
40 influencing both the mean storm track response of climate models and the spread
41 between different models (using the CMIP3 models; see methods for more details).

42 We begin by comparing the MOC reduction in each model with the surface
43 temperature response to the forcing. To do this we calculate the temperature
44 response pattern (2060-99 - 1960-99) for each model and regress this set of patterns
45 on a vector comprising the MOC reduction in the same models between the same
46 two periods. The result is given in Figure 1a, showing that a larger MOC reduction
47 is associated with a greater cooling in the North Atlantic, which locally offsets the
48 greenhouse warming. This is consistent with the role of the MOC in transporting
49 heat northward into this region. A dimensional version of this regression analysis
50 applied to the region (20-60°W, 45-70°N) gives a temperature change of 0.31 K
51 for a 1 Sv weakening of the MOC, consistent with previous analyses^{21;22}, with a
52 corresponding correlation of 0.67.

53 Figure 1c shows the regression of the storm track response onto the MOC
54 response (see Methods). This shows a clear and significant signal, with models
55 featuring a strong MOC response also exhibiting a particular strengthening and
56 eastward extension of the storm track towards Europe. The regression of 850 hPa
57 zonal wind responses onto the MOC responses is shown in Figure 1b, indicat-
58 ing a strengthening and eastward extension of the low-level westerlies over and
59 downstream of the main storm track region, consistent with the mean flow forc-
60 ing expected from a strengthening of the storm track. If the regression is instead
61 performed on the global mean temperature response of the models there are no

62 significant regressions for either of the atmospheric fields (not shown). This shows
63 that while the Atlantic storm track response is related to the weakening of the
64 MOC, it has no dependence on the climate sensitivity of the models.

65 In comparing the storm track response to the MOC response the set of models
66 is reduced significantly due to data availability. To demonstrate that a similar
67 relation is likely seen across all the models we show a similar analysis in Figure 1d-
68 e using only the atmospheric fields. We take the leading Empirical Orthogonal
69 Function (EOF) of the set of surface temperature response patterns as a proxy
70 for the MOC response in the full set of climate models. In this application, the
71 EOFs are the patterns which explain most of the spread between the 22 individual
72 model response patterns, and the principal components give the relative projection
73 of each model response pattern onto the corresponding EOF. The leading EOF over
74 this North Atlantic region (Figure 1d) is very similar to the surface temperature
75 regression onto the MOC response, which implies that the MOC plays a leading
76 role in the spread in North Atlantic temperature response. The regressions of zonal
77 wind and storm track activity onto the associated principal component are shown
78 in Figure 1e-f. The storm track response in particular is also very similar to its
79 counterpart in the MOC analysis, suggesting that the MOC-storm track relation
80 carries over to the full set of models. The wind patterns show some difference
81 in the mid-Atlantic but are again quite similar over Europe where the pattern in
82 Figure 1e is most significant.

83 To show that these relationships are consistent with the influence of the MOC
84 on the storm track we show in Figure 1g-i the results of a freshwater hosing ex-
85 periment with the HadCM3 climate model. In this experiment the MOC was
86 artificially shut down by continuously adding fresh water to the North Atlantic²³.
87 The responses shown here comprise the differences between twenty year equilib-
88 rium periods in the hosing and control runs¹³ and have been linearly scaled so that

89 the patterns correspond to the same MOC change as in panels a-c (3.5Sv). The
90 response to MOC shutdown is very similar to the regressions among the CMIP3
91 models, with surface cooling in the northern North Atlantic and a strengthening
92 and extension of the storm track and zonal wind downstream into Europe. This
93 quantitative comparison suggests that the MOC changes seen in the CMIP3 mod-
94 els are able to cause storm track changes at least as large as those seen. Some
95 differences from the regression patterns are evident, in particular in the tempera-
96 ture changes north of Scandinavia, where the presence of sea-ice suggests that the
97 response would not scale linearly, and in the zonal wind over the western North
98 Atlantic.

99 To illustrate the scatter in the relationship, Figure 2a compares the MOC
100 response with the storm track response averaged over the main storm track region,
101 where there is also a strong and significant relation with the MOC response in
102 Figure 1. There is one outlying model with a very strong MOC decrease, but
103 regardless of whether or not this model is included in the analysis the regression
104 accounts for at least half of the spread in the storm track responses between the
105 models. Figure 2a also shows that the storm track responses are generally as
106 large as the internal decadal variability, and that for models with a strong MOC
107 response the storm track response is large enough to be of the same magnitude as
108 the interannual variability. In fact for some of the individual models this signal-to-
109 noise ratio is close to or greater than one (not shown). The MOC therefore appears
110 to be a strong source of uncertainty in climate projections of Atlantic storm track
111 change.

112 This regression analysis can also be used to infer the role of the MOC reduction
113 in the ensemble mean storm track response to forcing. Figure 2b shows the diag-
114 nosed ensemble mean storm track response and Figure 2c shows an estimate of the
115 same quantity, calculated by applying the pointwise regression fits of Figure 1c to

116 the ensemble mean MOC response. The MOC-derived estimate is very similar in
117 character to the diagnosed response, and the residual pattern (Figure 2d) shows
118 that they differ only in a southward shift of the storm track which is evident in
119 the diagnosed response but not in the MOC-derived estimate.

120 Atmospheric changes such as the storm track and zonal wind responses seen
121 here are likely to influence the ocean circulation in various ways^{24;25}. To show that
122 the ocean is not simply responding to the atmospheric changes we now analyse the
123 slab model versions contained in the CMIP3 archive. These models do not repre-
124 sent changes in ocean dynamics and heat transports (see methods), so differences
125 in the ensemble mean responses of slab models and AOGCMs indicate that the
126 AOGCM mean response is influenced by the ocean. The pronounced minimum in
127 surface warming in the North Atlantic in the AOGCMs (Figure 3a) is not seen in
128 the corresponding slab models (Figure 3d, with the difference field in Figure 3g).
129 This confirms that this feature arises due to the changes in ocean circulation and
130 heat transport, which is generally assumed but has not been demonstrated be-
131 fore in this way to our knowledge. However, the zonal wind responses are almost
132 identical in the slab models and AOGCMs (Figure 3b, e, h). This suggests that
133 changing ocean heat transport has little influence on this part of the mean zonal
134 wind response of the AOGCMs.

135 In contrast, the storm track response is different in the AOGCMs and slab mod-
136 els (Figure 3c, f, i). Interestingly, the response in the slab models is a strengthening
137 of the storm track, so that even in the absence of ocean circulation changes the
138 North Atlantic storm track does not shift poleward in response to forcing. The
139 addition of a dynamic coupled ocean then acts to shift the storm track southward
140 in the response pattern. This is consistent with the enhanced meridional SST
141 gradient at latitudes south of the British Isles, corresponding to an increase in
142 baroclinic instability for storm development, and a decreased meridional gradient

143 at latitudes to the north. The slab model comparison therefore confirms that the
144 changes in ocean circulation have some impact on the storm track. Surprisingly,
145 the storm track and low-level zonal wind responses appear to be decoupled to some
146 extent in the model responses. This is a general feature of the mean response of
147 the AOGCMs, where the zonal winds shift to the north and storm track shifts to
148 the south. Further investigation is clearly required on the relation between the
149 storm track, the eddy-driven jet and the baroclinic zone in a changing climate.

150 The results presented here show that there is a strong relation between the
151 MOC and storm track responses in the AOGCMs. The response of the atmo-
152 spheric mean circulation and storm tracks will influence both gyre and overturning
153 circulations through changes in wind stress forcing and surface fluxes. Analysis
154 of the slab model versions shows that the changes in ocean circulation in turn
155 influence the storm track response, and comparison with the hosing simulation
156 provides further evidence of causality from the MOC in particular. In this way
157 the ocean and atmosphere circulations are responding to the forcing as a coupled
158 system.

159 There is an interesting contrast between the slab model and AOGCM results.
160 Figure 2 shows that the aspect of the mean storm track change which cannot be
161 explained as a linear response to the mean MOC change is the particular strength-
162 ening of the storm track on its southern flank. Correspondingly, the mean effect
163 of including a dynamical ocean model is precisely to shift the storm track south in
164 the response pattern (Figure 3). These storm track differences are consistent with
165 the differences in SST patterns, which are focused in the western North Atlantic
166 in Figure 1a but extend across the basin in Figure 3g. This implies that the MOC
167 alone is not sufficient to explain all of the coupling introduced with a dynamical
168 ocean model, and other processes such as changes in the wind-driven circulation
169 may play a role^{26;27}.

170 This paper shows that future storm track uncertainty could be reduced if pro-
171 jections of MOC behaviour can be better constrained, either through improvements
172 in climate modelling or ocean observation. For example, climate models with a
173 relatively strong MOC in their control simulations tend to predict a larger than
174 average reduction in the MOC. The correlation between these quantities is 0.46
175 for the models in Figure 2 but has been found to be larger in other model en-
176 sembles^{21;28}. Observational estimates of MOC strength could therefore provide an
177 effective means of constraining future storm track projections.

178

179 **Methods**

180

181 In this paper we analyse the ensemble of climate model simulations performed
182 for the third Coupled Model Intercomparison Project (CMIP3). Up to 22 coupled
183 atmosphere–ocean general circulation models (AOGCMs) have been used, depend-
184 ing on the data availability for the specific diagnostics required, and these are
185 described in the Fourth Assessment Report of the Intergovernmental Panel on
186 Climate Change²⁹. The forcing scenarios 20C3M and SRESA1B are used to char-
187 acterise the end of the 20th and 21st centuries respectively.

188 Following previous work⁸, the storm track is described using the standard
189 deviation of 2-6 day bandpass filtered sea level pressure (SLP; hPa), for which the
190 necessary data is available for many of the models for the periods 1960-99 and 2080-
191 99. Monthly mean fields of surface air temperature (K) and zonal wind (m s^{-1})
192 have also been used, in this case over the longer 21st century period of 2060-99
193 since the data is available. The surface air temperature describes changes in sea-
194 ice as well as SST, which may play a role in the ocean-atmosphere interaction. In
195 all cases, the response to anthropogenic forcing is defined as the DJF mean of the
196 future period minus the DJF mean of the control period. The MOC is described

197 by the maximum value of the meridional streamfunction ($Sv \equiv 10^6 m^3 s^{-1}$) at 45N
198 in the Atlantic Ocean, although similar results are obtained if the MOC is instead
199 defined by the maximum value wherever it occurs. All results are derived using
200 wintertime (DJF) atmospheric data but annual mean MOC values.

201 Figure 2a includes values of the models' internal variability in the period 1960-
202 99. For each model the interannual variability was calculated as the standard
203 deviation of the individual winter means and the boxplot summarises these 14 val-
204 ues. For the decadal variability one value was obtained by combining the decadal
205 means from all 14 models (after removal of each model's climatology) and taking
206 the standard deviation of this set of 56 decadal anomalies.

207 The slab models used comprise an atmospheric model, as in an AOGCM, cou-
208 pled to a single-layer ocean model, with prescribed seasonally varying fields of
209 ocean heat convergence ($W m^{-2}$), which takes the place of a dynamically evolving
210 ocean. Comparison of the AOGCM and slab model responses reveals the impor-
211 tance of changes in ocean heat transports in shaping the storm track responses.
212 The slab simulations are equilibrium experiments with pre-industrial (year 1860,
213 with 280 ppm CO₂) and doubled carbon dioxide concentrations.

214 The HadCM3 hosing simulations were performed by Vellinga and Wu²³ and we
215 analyse the same twenty year periods as in Brayshaw et al.¹³. Between these two
216 periods the maximum MOC at 45N in the Atlantic decreases from 21.6Sv to 0.9Sv.

217

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220

221 **Author Contributions**

222 TW led the analysis and writing of the paper, JMG analysed the ocean data, JGP
223 and MR analysed the storm track data and DJB analysed the HadCM3 data. All

224 authors contributed to writing the paper.

225

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227

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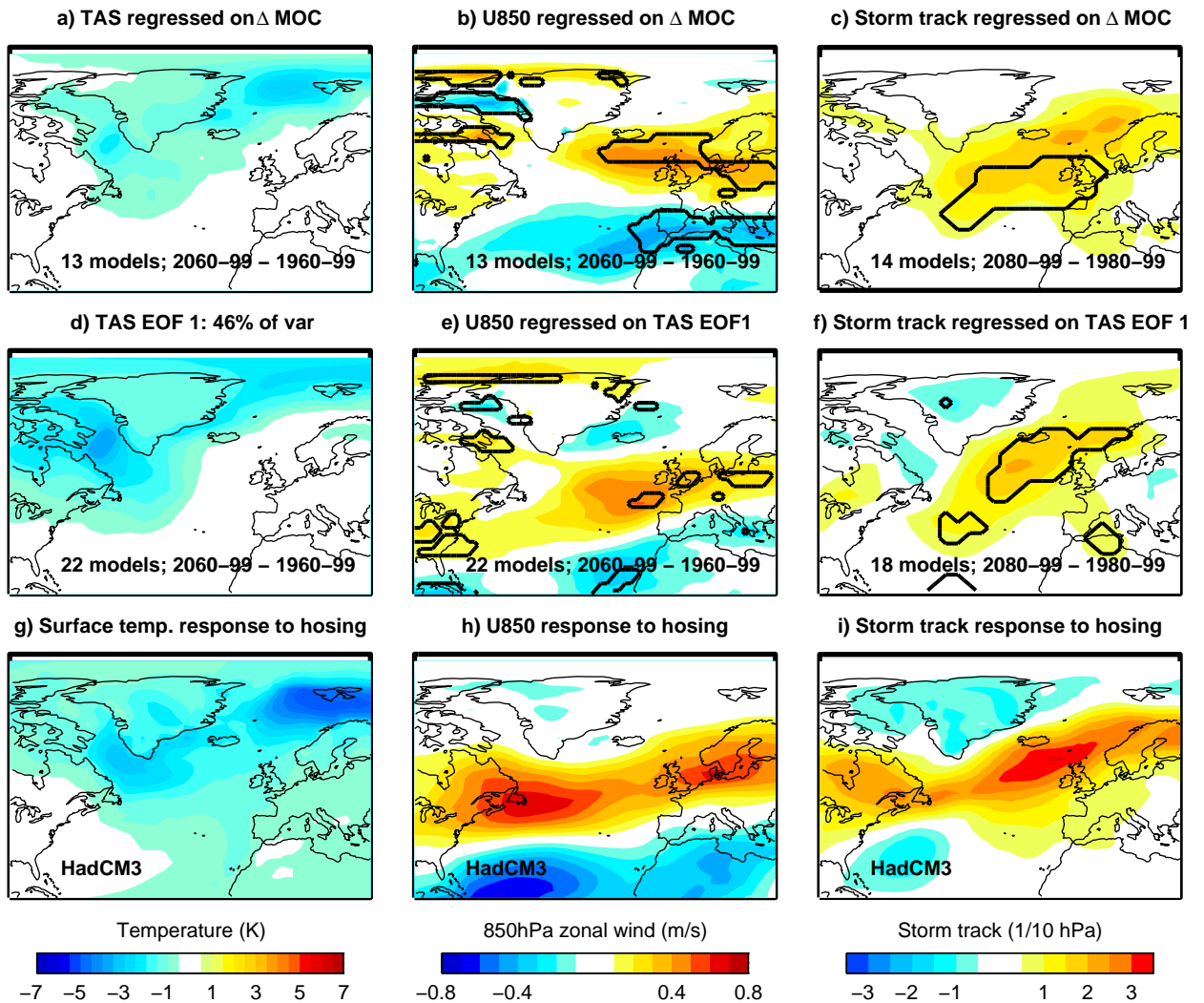


Figure 1: Maps of regression slopes quantifying ocean-atmosphere relationships in the wintertime responses of the AOGCMs to anthropogenic forcing. In each panel, at each point, a linear regression is done across the set of models. Panels a-c show the responses in surface temperature (TAS), 850 hPa zonal wind (U850) and storm tracks (standard deviation of 2-6 day filtered SLP) regressed onto the MOC reduction in the models. Panels d-f show the same quantities regressed onto the leading EOF of the surface temperature response. In each case the regressions are performed over the longest period and largest set of models permitted by the data availability, as indicated. The independent variable in each case has been normalised so that each panel shows the pattern associated with one standard deviation of the spread between the models. Black contours in the zonal wind and storm track panels show regions where the patterns are inconsistent with random sampling at the 95% level, as estimated using a Monte Carlo shuffling of the models. Panels g-i show the responses in the same fields in the HadCM3 freshwater hosing experiment for comparison.

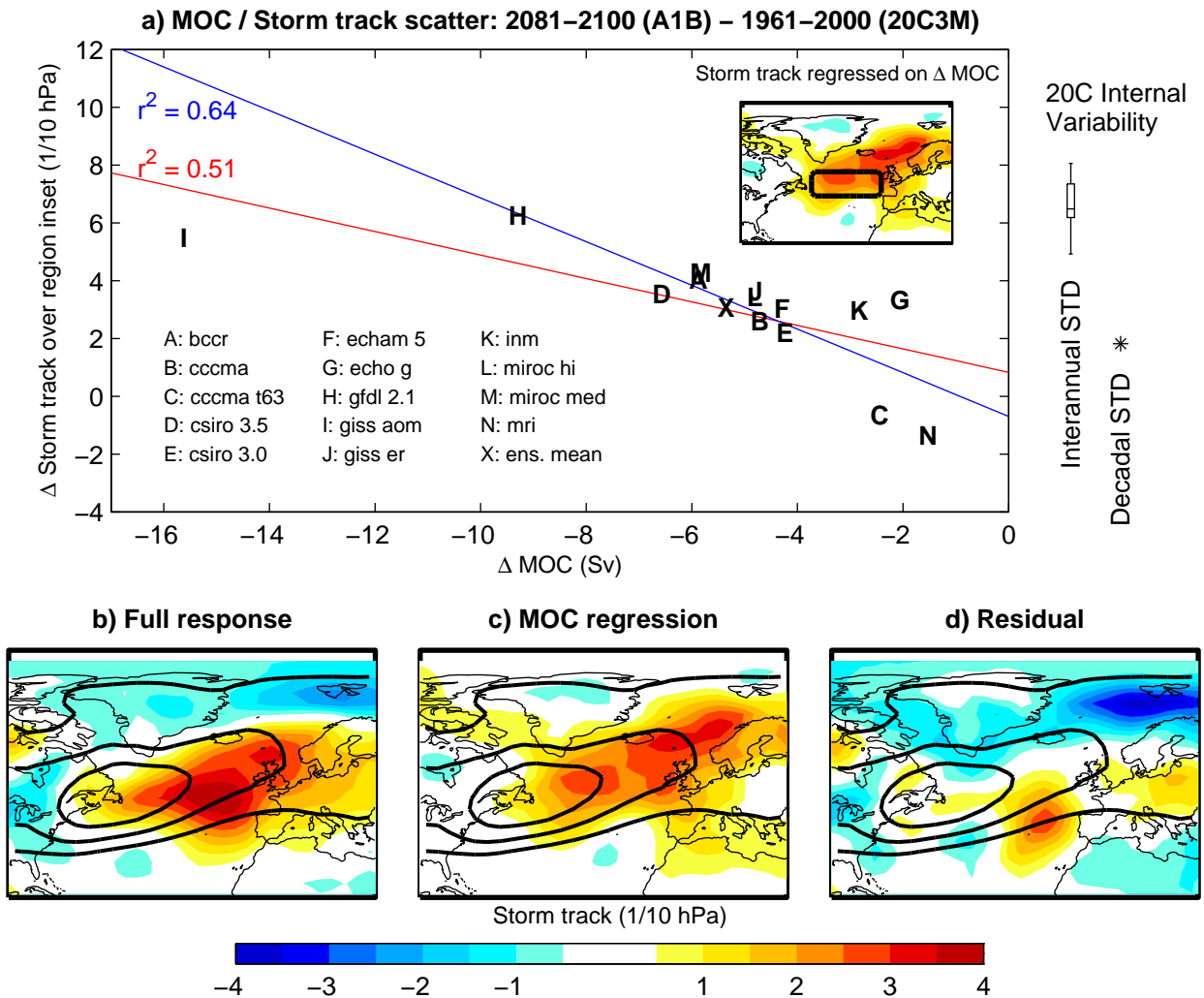


Figure 2: Quantifying the role of the MOC in the mean and model spread of the storm track response. a) Scatterplot of the storm track response area-averaged over the region shown inset ($45\text{--}55^\circ\text{N}$, $10\text{--}50^\circ\text{W}$) against the MOC response in the AOGCMs. Regression lines are shown both including (red) and excluding (blue) the outlier model I. For comparison, the magnitude of internal variability of the same region in the control ensemble is summarised with respect to the same y axis (see methods). b) The ensemble mean diagnosed storm track response of this subset of 14 models. c) The response estimated using the ensemble mean MOC response. d) The residual b-c. Contour lines in b-d show the storm track in the control ensemble at 3, 4 and 5 hPa.

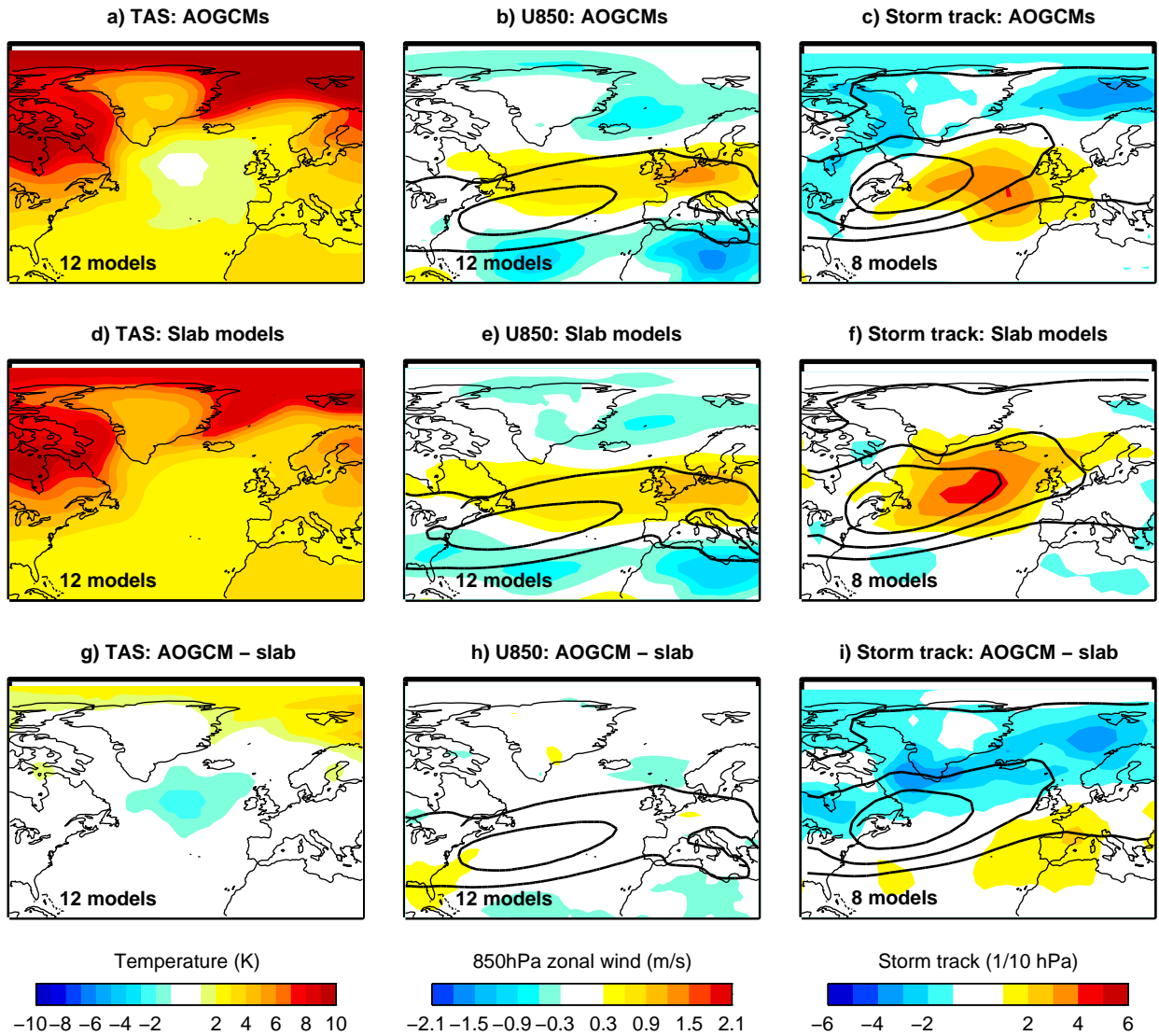


Figure 3: Comparison of the mean responses of the surface temperature (TAS), 850 hPa zonal wind (U850) and the storm tracks in the AOGCMs and slab models. In all cases the responses have been scaled by the global mean surface temperature response so that the magnitude of warming is comparable despite the differences among models in forcing, transient climate response and equilibrium climate sensitivity. Solid contours mark control period ensemble mean values (5 and 10 m s^{-1} for the zonal winds and 3 , 4 and 5 hPa for the storm tracks).