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1 **A limited role for unforced internal variability in 20th century warming.**

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ABSTRACT

23 The early 20th century warming (EW; 1910-1945) and the mid-20th century
24 cooling (MC; 1950-1980) have been linked to both, internal variability of the
25 climate system and changes in external radiative forcing. The degree to which
26 either of the two factors contributed to EW and MC, or both, is still debated.
27 Using a two-box impulse response model, we demonstrate that multidecadal
28 ocean variability was unlikely to be the driver of observed changes in global
29 mean surface temperature (GMST) after 1850 A.D. Instead, virtually all (97-
30 98%) of the global low-frequency variability (> 30 years) can be explained
31 by external forcing. We find similarly high percentages of explained vari-
32 ance for inter-hemispheric and land-ocean temperature evolution. Three key
33 aspects are identified which underpin the conclusion of this new study: inho-
34 mogeneous anthropogenic aerosol forcing (AER), biases in the instrumental
35 sea surface temperature (SST) datasets, and inadequate representation of the
36 response to varying forcing factors. Once the spatially heterogeneous nature
37 of AER is accounted for, the MC period is reconcilable with external drivers.
38 SST biases and imprecise forcing responses explain the putative disagreement
39 between models and observations during the EW period. As a consequence,
40 Atlantic Multidecadal Variability (AMV) is found to be primarily controlled
41 by external forcing too. Future attribution studies should account for these im-
42 portant factors when discriminating between externally-forced and internally-
43 generated influences on climate. We argue that AMV must not be used as a
44 regressor and suggest a revised AMV index instead (North Atlantic Variability
45 Index; NAVI). Our associated best estimate for the transient climate response
46 (TCR) is 1.57 K (± 0.70 at the 5-95% confidence level).

47 **1. Introduction**

48 The global temperature evolution over the instrumental period is conventionally attributed to the
49 combination of external forcing and internal variability (Stott et al. 2000; Bindoff et al. 2013; Flato
50 et al. 2013). Virtually all of the warming since 1950 is attributed to human influences (Stocker
51 et al. 2013; Jones et al. 2013, 2016; Ribes et al. 2017). Yet due to the loosely constrained nature
52 of magnitude and evolution of AER, there continues to be a fierce debate about the cause of
53 multidecadal GMST fluctuations present in the instrumental record (Shiogama et al. 2006; Booth
54 et al. 2012; Zhang et al. 2013; Thompson et al. 2015). Most prominently, the origin of the EW
55 and MC periods, thought to be linked with North Atlantic (NA) ocean variability and commonly
56 expressed in terms of AMV (Delworth and Mann 2000; Knight et al. 2005, 2006), is still hotly
57 contested because of the difficulties to disentangle the contributions from internal and external
58 drivers at different timescales (Brönnimann 2009; Mann et al. 2014; Zhang et al. 2016; Clement
59 et al. 2016; Vecchi et al. 2017; Sutton et al. 2017; Hegerl et al. 2018).

60 Conventionally, the AMV has predominantly been attributed to internal ocean variability, which
61 in turn has been linked to changes in the Atlantic Meridional Overturning Circulation (AMOC)
62 as a deep ocean driving mechanism on multidecadal timescales (Zhang and Wang 2013; Yeager
63 and Robson 2017). While stochastic atmospheric flux forcing is thought to influence SSTs on
64 shorter timescales (Roberts et al. 2013; Ducheze et al. 2016; Josey et al. 2019), associated with
65 changes in the North Atlantic Oscillation (NAO) index (Hurrell and Deser 2009), the prevailing
66 view regarding NA SST changes on longer timescales is that large internal variations are superim-
67 posed on the anthropogenic warming trend. However, in recent years, external forcing has been
68 shown to contribute to multidecadal swings in the AMV region (Otterå et al. 2010; Murphy et al.
69 2017; Bellucci et al. 2017), suggesting a reduced role for internal ocean dynamics. Changes in

70 AER (Booth et al. 2012; Bellomo et al. 2018) as well as periods of strong volcanic activity (Iwi
71 et al. 2012; Knudsen et al. 2014; Pausata et al. 2015; Swingedouw et al. 2017) have been linked
72 to these changes. Also, it has been demonstrated that AMV-like SST pattern can be reproduced in
73 slab-ocean experiments (Clement et al. 2015, 2016; Bellomo et al. 2018). Hence internally gen-
74 erated low-frequency GMST variations are increasingly thought to play only a smaller role, with
75 Pacific ocean variability to be more recognised as a pacemaker for global temperature (Schurer
76 et al. 2015; Dong and McPhaden 2017).

77 While there is no debate about the existence of aerosol-related dimming and brightening (Wild
78 et al. 2007; Wild 2009) due to a huge array of supporting data from observations (Boers et al.
79 2017; Dumitrescu et al. 2017; Manara et al. 2017) and modelling (Shindell et al. 2013; Wilcox
80 et al. 2013; Rotstayn et al. 2015; Dallafior et al. 2016; Chung and Soden 2017), its impact on the
81 AMV is less certain. Many studies do not (Huss et al. 2010; Chylek et al. 2014) or insufficiently
82 (Ting et al. 2009; Zhang et al. 2013) incorporate or acknowledge AER, which potentially leads to
83 misattribution of cause (Zhang et al. 2016; O'Reilly et al. 2016) and effect (Chylek et al. 2009;
84 Wyatt et al. 2012; Tung and Zhou 2013; Pasini et al. 2016; Levine et al. 2018). Arguments for
85 the presence of an internally-generated AMV based on ostensible pseudo-oscillatory behaviour in
86 instrumental, proxy, or model data are unconvincing (Singh et al. 2018), and it is noted that such
87 behaviour can arise from statistical artefacts alone (Vincze and János 2011; Cane et al. 2017).
88 Regression-based methods are thereby particularly susceptible to conflating internal variability
89 with forced responses because of strong covariance between the predictors (Mann et al. 2014;
90 Stolpe et al. 2017), yet studies that use the AMV as regressor or explanatory factor continue to
91 be published despite the lack of an unequivocal physical underpinning (Lewis and Curry 2018;
92 Rypdal 2018; Shen et al. 2018; Zhang et al. 2018; Folland et al. 2018).

93 We argue that any attribution exercise that does not sufficiently account for the spatio-temporal
94 AER changes will invariably produce unreliable and erroneous results. Incorporating now better
95 quantifiable biases in the instrumental SST record, we demonstrate that a carefully designed anal-
96 ysis (that avoids overfitting) yields a surprisingly high level of agreement between our model and
97 observations without the need to infer additional unexplained internal variability. We endeavour
98 to highlight the pitfalls associated with attributing and identify the shortcomings in representing
99 the externally forced temperature responses.

100 Since attempts to estimate the magnitude of internal variability by means simple climate models
101 are plagued from dissatisfying low correlations with observations (Aldrin et al. 2012; Skeie et al.
102 2014), here we use a refined two-box impulse response model framework which accounts for fast
103 and slow responses to forcing perturbations in the climate system. To constrain the complexity of
104 the model, we introduce a novel TCR adjustment factor for different forcing agents that is gov-
105 erned by robust physical factors. Apart from Northern Hemisphere (NHem) and GMST (Global),
106 we also analyse Southern Hemisphere (SHem), land surface air temperature (Land) and SSTs
107 (Ocean), expanding on previous GMST-only analyses (Mann et al. 2014; Dong and McPhaden
108 2017) to better understand the impact of radiative forcing changes on surface temperatures. We
109 recommend all impulse response or energy balance model studies use land, ocean, and hemi-
110 spheric temperature records with our dedicated set of model parameters as separate benchmark
111 tests to robustly evaluate model performance.

112 **2. Radiative forcing and observational data**

113 We use the latest well-mixed greenhouse gas (WMGHG) radiative forcing (Etminan et al. 2016;
114 Meinshausen et al. 2017) and the gridded aerosol community emission dataset (CEDS) (Hoesly
115 et al. 2017), including sulphur dioxide (SO₂), ammonia (NH₃), black carbon (BC), and organic

116 carbon (OC). For solar forcing, we use sunspot numbers from the Greenwich Royal Observatory
117 (Wilson and Hathaway 2006), scaled to solar forcing according to Dewitte and Nevens (2016).
118 Stratospheric aerosol optical depth (AOD) data from explosive volcanic eruptions (Crowley et al.
119 2008; Crowley and Unterman 2013) are scaled to match NASA-GISS volcanic forcing data (Sato
120 et al. 1993), and updated to include recent smaller eruptions (Vernier et al. 2011; Solomon et al.
121 2011; Arfeuille et al. 2014; Schmidt et al. 2018). Fig. 1a shows our revised forcing estimates.

122 The global direct radiative forcing for each aerosol component (SO₂, NH₃, BC, OC) is derived
123 by scaling the current emissions to the AR5-forcing estimate for 2011 (Myhre et al. 2013; Stocker
124 et al. 2013). Using BC emissions over North America, we account for enhanced Arctic warming
125 during the first half of the 20th century (Johannessen et al. 2004; McConnell et al. 2007; Mc-
126 Connell and Edwards 2008; Suo et al. 2013) (orange shading in Fig. 1b). The indirect forcing
127 of -0.45W/m^2 is mostly a function of SO₂ (90%; 10% for OC). While considerable uncertainty
128 regarding aerosol-cloud effects exist (Carslaw et al. 2013; Regayre et al. 2014; Nazarenko et al.
129 2017; Lohmann 2017), the best estimate for indirect AER in AR5 has not been fundamentally
130 challenged since. Together with the direct effects, we obtain a total AER of $\sim -0.55\text{W/m}^2$ in ac-
131 cordance with AR5 (Fig. 1b), which is set to -0.75W/m^2 *pseudo-effective* global aerosol radiative
132 forcing (ERF) in our response model framework (Fig. 1b, c). The total ERF estimate is guided
133 by a recent review by Forest (2018), which is slightly lower than the best estimate for ERF of
134 -0.9W/m^2 published in AR5. We note that other recent research has also suggested that AER ERF
135 might be lower (Stevens 2015; Myhre et al. 2017), essentially reflecting arguments for stronger BC
136 warming effects (Bond et al. 2013; Myhre and Samset 2015) and less cooling due to noticeable
137 SO₂ reductions in China since 2006 (Smith et al. 2011; Klimont et al. 2013).

138 We use Berkeley Earth Land/Ocean (BE) (Rohde et al. 2012), HadCRUT4-Cowtan/Way
139 (Cru4CW) (Cowtan and Way 2014; Cowtan et al. 2015), HadISST2 (Titchner and Rayner 2014;

140 Kennedy et al. 2017) and OSTIA (Donlon et al. 2012) as observational data. We note that there
141 are indications that the land datasets may still underestimate warming in northern areas (Wang
142 et al. 2017; Way et al. 2017). Since Cru4CW uses HadSST3 data (Kennedy et al. 2011) over
143 oceans, we developed an additional composite product with Cru4CW over land and HadISST2
144 (1850-1985; preliminary release available only until 2010) and OSTIA data (1986-now; calibra-
145 tion period 1986-2005) over ocean to reflect the full range of available SST products (hereinafter
146 referred to as HadOST). To obtain land and ocean proxies, ocean points that are covered with sea
147 ice are treated as land points. The sea ice extent to generate the ice mask is taken from HadISST2
148 and OSTIA. The same mask is applied to Cru4CW and BE.

149 Due to continuous problems in currently available SST datasets, mainly manifest as warm bias
150 as a result of changing SST sampling methods (from bucket to engine-room intake measurements)
151 during World War II, associated with changing fleet composition (Karl et al. 2015; Hansen et al.
152 2016; Kent et al. 2017), Cowtan et al. (2017) have recently proposed a novel method to address
153 the WWII bias using island and coastal weather stations only. Inspired by the idea, we replicate
154 their analysis with a slightly simplified methodology. We use a mask where grid boxes over land
155 (adjacent to ocean) and over ocean (along coastlines) are selected, including islands. The global
156 average of all such subsampled ocean grid boxes establishes our new SST proxy. The two coastal
157 time series are scaled to match the 1980-2016 global SST trend (see Cowtan et al. (2017) for
158 details on the scaling method) as it is deemed the most reliable period in the marine instrumental
159 record (Rahmstorf et al. 2017).

160 The results are shown in Fig. 1d for HadOST and BE and in Fig. 1e for ERSSTv4 and GHCNv3
161 as used in GISTEMP (Hansen et al. 2010). The scaling factors are provided in the figure legend.
162 In both cases, the two coastal records (derived from HadISST2 and ERSSTv4) show excellent
163 agreement during the calibration period. As expected, the land scaling factor is lower in agreement

164 with amplified warming trends over land. The land and ocean proxies agree after 1920 and show
165 only minor deviations before 1920 (Fig. 1d). The HadOST proxies (land and ocean), suggest that
166 HadISST2 is reliable with marginal biases between 1880-1940. We find much less agreement
167 between GHCNv3 and ERSSTv4 before 1980. Our analysis further suggests that ERSSTv4 has
168 a substantial cold bias between 1900-80 as well as a spurious warm bias during WWII (Fig. 1e).
169 While by no means perfect, this straight-forward analysis is at least indicative that SSTs in general
170 and ERSST in particular (versions 4 and 5 are almost identical throughout the period of coverage)
171 are still impacted by substantial unresolved inhomogeneities. In our main analysis we discard
172 GISTEMP and apply the following correction factors to HadOST, Cru4CW and BE during four of
173 the WWII years (1942-45): NHem = -0.04°C , Global = -0.08°C , SHem = -0.12°C and Ocean =
174 -0.18°C . The remaining years in the time series remain unchanged. We discuss the implications in
175 section 4.

176 Finally, we use historical climate simulations from the Coupled Model Intercomparison Project
177 (CMIP5) (Taylor et al. 2012) and an ensemble of the UK MetOffice HadCM3 model (Euro500)
178 (Schurer et al. 2014) to estimate warming ratios and multidecadal internal variability.

179 **3. Impulse response model and uncertainty**

180 Following the method introduced in earlier work (Otto et al. 2015; Haustein et al. 2017),
181 (vaguely similar to the analysis presented in Lean and Rind (2008) and Lean (2018)) we employ
182 a two-box impulse response model framework that accounts for fast and slow temperature (T)
183 changes in response to external forcing factors (*comp*: WMGHGs, anthropogenic aerosols (AER)
184 and volcanic eruptions (VOL)). The fast component can be associated with the ocean mixed layer
185 response whereas the slow component approximates the response of the deep ocean (Li and Jarvis
186 2009):

$$\frac{dT_j}{dt} = \frac{q_j \cdot F - T_j}{d_j}; T_{comp} = \sum_{j=1}^2 T_j \quad (1)$$

$$TCR_{comp} = F_{2xCO_2} \cdot \left(q_1 \cdot \left(1 - \frac{d_1}{70} \left(1 - e^{-\frac{70}{d_1}} \right) \right) \right) + q_2 \cdot \left(1 - \frac{d_2}{70} \left(1 - e^{-\frac{70}{d_2}} \right) \right) \quad (2)$$

$$ECS = F_{2xCO_2} \cdot (q_1 + q_2) \quad (3)$$

187 More details can be found in Millar et al. (2017). The forcing due to doubling of CO₂ (F_{2xCO_2}) is
 188 3.71 W/m². The factor q_j (integrated contribution for response j) can be determined using Equa-
 189 tion (2) and (3) with a defined set of values for TCR and ECS. Our chosen TCR range encompasses
 190 values from 1.1-2.1K, with an associated ECS range of 2.0-4.0K, in line with IPCC AR5 estimates
 191 (Stocker et al. 2013). As TCR/ECS-ratios derived from observational data are plagued by a vari-
 192 ety of shortcomings (Armour 2017; Proistosescu and Huybers 2017; Marvel et al. 2018), we apply
 193 the CMIP5 mean of ~ 0.53 as our central TCR/ECS-ratio estimate, supported, for example, by a
 194 reasonably good match of measured and simulated ocean heat uptake (Cheng et al. 2016). The
 195 associated adjustment factors for NHem, SHem, Land and Ocean as well as for AER and VOL
 196 forcing are introduced below.

197 The slow response time (d_2) is taken from Geoffroy et al. (2013a) (320 years), which included
 198 deep ocean feedbacks in contrast to accompanying work (Geoffroy et al. 2013b). Given that
 199 the fast response time (d_1) of 4 years suggested in the same study (Geoffroy et al. 2013a) relies
 200 on estimates from GCM simulations, we follow the approach presented in Rypdal (2012) and
 201 double d_1 to 8 years, which is in line with coefficients presented in Boucher and Reddy (2008)
 202 based on idealised simulations undertaken with the HadCM3 model. It is argued that observed

203 temperatures show a prolonged/delayed response due to mediating effects intrinsic to our climate
204 system (Emile-Geay et al. 2008; Santer et al. 2014; McGregor et al. 2015) which may be less well
205 represented in many GCMs (Le 2017). These estimates of d_1 and d_2 yield the highest correlation
206 with observations.

207 As far as the response to AER is concerned, Shindell (2014) and Marvel et al. (2016) have
208 highlighted the importance of different hemispheric treatment of the heterogeneous aerosol load.
209 The conceptual idea is to have an enhanced TCR for AER due to its preponderance over land
210 as a result of the skewed spatial distribution of aerosols. Differential heat capacities over land
211 and ocean (and therefore implicitly the hemispheres) lead to considerably different response times
212 over land and ocean, associated with inhomogeneous hemispheric warming rates that are medi-
213 ated by cross-equatorial energy transports (Loeb et al. 2016; Stephens et al. 2016) for all forcing
214 agents. Having said that, aerosols are transported over vast distances (Uno et al. 2009; Schulz et al.
215 2012), affecting oceans directly (due to albedo effect) and indirectly as well (due to cloud effects,
216 particularly over formerly pristine areas), despite very low direct emissions over oceans mainly
217 from ship exhaust (Kunkel et al. 2013; Shindell et al. 2013). Therefore, Ocean aerosol emissions
218 are not a suitable proxy for the associated ocean temperature response. To remedy the problem,
219 the inter-hemispheric exchange of aerosol-induced temperature responses has to be accounted for
220 appropriately using coupling factors (introduced below).

221 The differential warming requires dedicated TCR calibration factors for the WMGHG, VOL
222 and AER induced temperature responses. To obtain a plausible and robust set of such calibration
223 factors, we use observed Transient Warming Ratios (TWR) between NHem and SHem as well as
224 Land and Ocean. In Fig. 2, the temperature responses to total anthropogenic (a, b), WMGHG (c,
225 d), AER (e, f) and VOL (g, h) are shown. Decadally averaged warming ratios are provided above

226 or under each graph. All data are low-pass filtered with a smoothing radius of 5 years. The TWR
227 is obtained during the 30 year period of strongest transient warming.

228 Given that TWRs for WMGHG, AER and VOL can only be inferred from GCMs, we apply a
229 scaling factor which represents the difference between observed and all-forcing TWRs. Assuming
230 that the observed TWR (red shaded area in Fig. 2a, b) is our target ratio, the responses in HadCM3
231 are scaled accordingly. HadCM3 is used because it provides a small ensemble of simulations
232 (mainly drawn from the Euro500 experiment) which is consistent across the experiments. The
233 TWR in the historical HadCM3 ensemble is 1.7, compared to 2.8 in HadOST (Fig. 2a). Hence a
234 scaling factor of ~ 1.6 is applied to the TWR deduced from the WMGHG and AER ensemble of the
235 same model in order to correct for the underestimated TWR in the historical HadCM3 simulations.
236 The resulting inferred TWR (hereinafter referred to as TWRD; D = diagnosed), which is then used
237 in the response model, is provided in the boxes at the bottom of Fig. 2.

238 Since the bulk of the VOL response takes place on the fast timescale (1-10 years) and thus differ
239 from WMGHG related responses (Ding et al. 2014), we refrain from scaling and use the TWR
240 from HadCM3 directly (consistent with above-mentioned findings in Boucher and Reddy (2008)
241 regarding HadCM3's fast response time). Note that the VOL responses in Fig. 2g, h are shown
242 for the full 1500-1999 period in contrast to the shorter 1850-1999 (1850-2017) period for all other
243 scenarios.

244 In addition, since we do not know the resulting warming ratios in the response model a priori
245 when we impose the inferred TWRD, we compare them with the posteriori TWRs (hereinafter
246 referred to as TWRE; E = estimated) in order to validate our approach. We find that, for example,
247 the TWRD for WMGHGs (TCR of 2.65K over Land and 1.11K over Ocean) of ~ 2.4 results in a
248 TWRE of ~ 2.2 (see Fig. 2d). We therefore argue that our method is reasonably well constrained
249 to provide a robust answer.

250 All TCR calibration factors based on the deduced TWRDs (and shown at the bottom of Fig. 2)
 251 are summarised in the upper box in Fig. 3. We would like to point out that these calibration factors
 252 modulate the TCR/ECS ratio and are used for the full range of TCR and ECS values, respectively,
 253 not only the best estimate. The latter is provided at the top of Fig. 3 as well, together with the TCR
 254 for AER effective forcing which is $\sim 40\%$ higher (best estimate = $2.2K$) than that of WMGHGs
 255 (best estimate = $1.6K$), consistent with findings in Rotstayn et al. (2015) and in pursuit to reflect
 256 the higher aerosols load over land.

257 To estimate the TCR calibration factor for AER, hemispheric and land-ocean coupling factors
 258 need to be determined. They reflect the above-mentioned fact that inter-hemispheric energy ex-
 259 changes in response to the heterogeneous distribution of AER need to be balanced. Conveniently,
 260 the coupling factors are an emergent property and as such a function of the hemispheric area
 261 weighting factors, which are strictly interlinked and hence constrained as follows (example for
 262 WMGHGs):

$$\begin{aligned}
 T_{GHG}^{Global} &= 0.5 \cdot T_{GHG}^{NHem} + 0.5 \cdot T_{GHG}^{SHem} \\
 &= 0.32 \cdot T_{GHG}^{Land} + 0.68 \cdot T_{GHG}^{Ocean}
 \end{aligned}
 \tag{4}$$

263 Note that the Land fraction is marginally $>30\%$ because areas covered with sea ice are treated
 264 as land throughout the analysis. Apart from the area-weighted constraint, the coupling factors
 265 are also dependent on the emission ratio, i.e. the ratio between the hemispheric (and land/ocean)
 266 and the total global aerosol emission strength, which in turn determines the appropriate fractional
 267 contribution to match the inferred AER-TWRD (see Appendix A for more details). The resulting
 268 coupling factors are 3.9 (ratio of 1.47 and 0.38, which corresponds to 85% NHem and 15% SHem
 269 AER contribution for NHem AER and vice versa for SHem AER) and 2.1 (ratio of 1.46 and 0.7,

270 which corresponds to 70% Land and 30% Ocean AER contribution for Land AER and vice versa
271 for Ocean AER). These factors are also provided in the bottom box of Fig. 3, together with all
272 other parameters used in the response model. Global temperature trends for the 1978-2017 period
273 in HadOST (a), CMIP5 (b) and HadCM3 (c) are also shown in Fig. 3. The spatial distribution
274 of the trend highlights why observed and modelled TWR do not agree, which is primarily caused
275 by delayed southern ocean warming (Armour et al. 2016), and partly by an accelerated Arctic
276 amplification (Serreze and Barry 2011). Both physical processes are not satisfactorily reproduced
277 in most GCMs.

278 Lastly, as apparent from the discrepancy between the AER factor provided at the bottom of Fig. 2
279 (3.5 and 2.4 for NHem/SHem and Land/Ocean, resp) and that shown in the top box of Fig. 3 (5.1
280 and 2.9 for NHem/SHem and Land/Ocean, resp), we increased the inferred AER-TWRD slightly.
281 While the adjustment of the AER-TWRD does not change our conclusions (see Fig. S1 and S2 for
282 the same result without AER-TWRD tuning), it does lead to better agreement between HadOST
283 and the response model during the period of strongest AER cooling between 1960-80. Given
284 that the HadCM3 AER ensemble is not a strict AER-only simulation rather than the difference
285 between the *allforcing* and a non-aerosol ensemble of HadCM3, the results likely do not reflect
286 the full extent of the aerosol-induced TWR. Therefore we think it is a defensible decision and well
287 within the realm of the uncertainty of our AER-TWR estimate. The resulting AER timeseries is
288 shown in Fig. 1c.

289 For the uncertainty analysis, response model, radiative forcing and internal variability uncer-
290 tainty is considered. Apart from the TCR (1.1...2.1K) and ECS (2.0...4.0K) range, we also include
291 a range of fast response times (3...13 years) in our response model uncertainty estimate. For the
292 forcing, 200 total radiative forcing realisations are used (Forster et al. 2013) and converted into
293 response model temperature equivalents to estimate the associated error range. The resulting σ

294 (32-68th percentiles) of the fractional uncertainties is shown in Fig. 4a (response model error
295 in green and radiative forcing error in blue). If we assume that potential internally generated,
296 low-frequency variability adds linearly to the externally forced response, we need an estimate of
297 (modelled) unforced multidecadal variability. As introduced in Haustein et al. (2017), we use
298 equidistant intervals of selected CMIP5 pre-industrial control simulations that do not drift (Knut-
299 son et al. 2013) and possess a similar range of unforced variability as our response model based
300 estimate of the residual observational variability. In Fig. 4b, the low-pass filtered residuals for Ha-
301 dOST, Cru4CW and BE between 1850-2017 and low-pass filtered sample intervals of 168 years
302 from selected CMIP5 models are shown together with their standard deviation (σ). The obtained
303 5-95th percentiles of their internal variability span $\pm 0.17^\circ\text{C}$ ($\bar{\sigma}=0.1^\circ\text{C}$ and $\bar{\sigma}^2=0.01^\circ\text{C}^2$) as shown
304 in Fig. 4a in grey.

305 We note that there is additional parameter uncertainty, which is not fully included here as it
306 is difficult to objectively constrain the upper and lower bounds of the respective parameters. In
307 order to rectify this problem, in Fig. S3, we have plotted the response model results for a set
308 of reasonable model parameters, including aerosol sensitivity, TWRs, coupling strength, TCR
309 efficiency, varying SOL and VOL forcing, as well as high and low AER ERF (dashed line for -0.5
310 and -1.0 W/m^2). The resulting uncertainty is small compared to the total uncertainty, which is
311 dominated by the forcing uncertainty. Hence we conclude that the our results are insensitive to the
312 parameter choices, even if our observationally constrained estimates were biased.

313 **4. Model performance and evolution**

314 In Fig. 5, the response model results for Land (a; brown), NHem (b; red) and Global (c; green),
315 Ocean (d; purple) and SHem (e; blue) are shown. The central *allforcing* temperature response es-
316 timate is shown as the bold line in the lower graph in each panel, while thin lines indicate slightly

317 higher/lower alternative TCR estimates as indicated at the right hand side (1.2...2.0K). The 5-
318 95th percentiles and the inter-quantile (25-75th) uncertainties are added as shaded grey contours.
319 The low-pass filtered (30 year smoothing radius) instrumental data from HadOST (dark green),
320 Cru4CW (yellow) and BE (black) are shown for comparison, including the WWII correction in-
321 troduced in section 2. Before filtering, the influence of ENSO (Deser et al. 2012) is removed from
322 the observational timeseries in order to minimise short-term noise (Stuecker et al. 2015), following
323 the multiple regression approach of Foster and Rahmstorf (2011).

324 Conversely, in the upper graphs in Fig. 5a - 5e we have added ENSO variability to the response
325 model results by scaling the multivariate ENSO index (MEI) (Wolter and Timlin 1998) for each do-
326 main and applying the lag coefficient obtained from the multiple regression. Other than the WWII
327 bias correction, the observational data in the upper graphs show the annual mean temperatures. On
328 the top left in each panel, the explained variance (R^2) for non-ENSO corrected, model-adjusted
329 (MEI), and observation-adjusted correlations between model and the observational datasets are
330 shown. The correlations are based on the low-pass filtered timeseries (30 year smoothing radius).
331 To avoid problems due to autocorrelation, the associated non-filtered R^2 between Global HadOST
332 and model-adjusted (MEI) timeseries is 0.935 (not shown; 0.92 for Cru4CW and 0.912 for BE).
333 We would like to highlight that our R^2 for HadOST exceeds the explained variance found in Ryp-
334 dal (2018) and Folland et al. (2018), without the need to invoke any contribution of the contentious
335 AMV.

336 We find excellent agreement between our response model and observations in all three time-
337 series. NHem and Land are well reproduced over the entire duration of the instrumental period,
338 including the EW and the MC periods (Fig. 5a, 5b). SHem and Ocean are similarly well re-
339 produced, with notable deviations before and after WWII when compared with Cru4CW or BE
340 (Fig. 5d, 5e). Using HadOST, the SHem and Ocean model results can be almost entirely reconciled

341 with observations (Fig. 5d). HadOST and Ocean only start to diverge before 1900. But overall,
342 the Global results (Fig. 5c) leave little room (of the order of $\sim 0.1^{\circ}\text{C}$) for unforced low-frequency
343 temperature variations.

344 Before we investigate other notable excursions in light of the role of unforced Pacific and At-
345 lantic ocean variability, in Fig. 6 the evolution of the response model for all five domains is shown.
346 The top graph in each panel shows the response model result using WMGHG and aerosol forc-
347 ing based on IPCC AR5 (Meinshausen et al. 2011), extrapolated to 2017, volcanic forcing from
348 NASA-GISS (Sato et al. 1993) updated to 2017 and a fast response time of 4 years. As such, it
349 corresponds to the results published in Haustein et al. (2017). The middle graph in each panel is
350 using our slightly modified VOL and solar forcing and a fast response time of 8 years. All what
351 is otherwise different compared to our final response model result as shown in the lower graph
352 in each panel is AER. The results based on the new CEDS AER show significant improvements
353 in each domain, resolving most of the discrepancies associated with the EW and MC period. As
354 far as EW is concerned, the improved response model performance is partly linked with the SST
355 bias correction during WWII which is only applied in the lower graph in Fig. 6. Accordingly,
356 the warming spike particularly over Ocean (Fig. 6d) and SHem (Fig. 6e) disappears, leading to a
357 visibly better agreement between model and observations.

358 With the current AER lowered by $>10\%$ (Fig. 1a), here we briefly explore the implications for
359 TCR, including a cautionary remark regarding the lack of robustness when estimating ECS. In
360 Fig. 5, the TCR range from 1.2-2.0K is indicated with our best estimate using a TCR of 1.6K
361 (bold lines). Based on linear regression between HadOST and the Global response model re-
362 sult, our most precise TCR estimate is 1.57K with an associated inter-decile uncertainty range of
363 0.87-2.27K (10-90th percentiles). This is in good agreement with other recent work (Richardson
364 et al. 2016), despite the lower AER estimate. While others have suggested that TCR might be

365 time-dependent (Gregory et al. 2015), our results do not provide evidence for a change over the
366 instrumental period.

367 With the TCR/ECS-ratio held constant, ECS is tied to TCR by construction in our analysis
368 (3.0K with an associated inter-decile uncertainty range of 1.7-4.3K). Nonetheless, it is instructive
369 to investigate the impact of different ECS values upon the model results when the TCR/ECS ratio
370 is permitted to vary. As shown in the lower graphs of Fig. 6 where we have added the response
371 model result for the low-end (2.0K) and high-end (4.0K) ECS range, neither of the two estimates
372 provides sufficient guidance as to which ECS value is more likely to be correct. The small range
373 of possible outcomes severely hampers a robust ECS estimation. We therefore agree with others
374 (Armour 2017; Proistosescu and Huybers 2017; Marvel et al. 2018) who found that ECS cannot
375 reliably be inferred from historical observations alone, and recommend caution as ECS is easily
376 conflated with the Effective Climate Sensitivity, the latter of which is likely to be lower (Knutti
377 et al. 2017; Andrews and Webb 2018). Hence such attempts (Aldrin et al. 2012; Otto et al. 2013;
378 Skeie et al. 2014; Lewis and Curry 2015; Mauritsen and Pincus 2017; Lewis and Curry 2018)
379 should be viewed with extreme skepticism.

380 **5. Role of unforced Pacific ocean variability**

381 Returning to Fig. 5, here we assess a few noteworthy remaining excursions that are arguably
382 related to unforced internal variability. To facilitate quantifying those excursions, in Fig. 7 the
383 residuals between the HadOST and response model temperature timeseries are plotted for the five
384 domains. In Fig. 7b, the low-pass filtered MEI evolution is provided (black line). Cru4CW and
385 BE are shown in Fig. 7e for completeness.

386 We note that MEI shows signs of multidecadal variability, which is linked to the Pacific Decadal
387 Variability (PDV) index (Newman et al. 2016; Henley 2017). Whether or not the unique behaviour

388 of the North Pacific variability (Williams et al. 2017; Kohyama and Hartmann 2017) and the
389 associated observed strengthening of the Walker circulation (L’Heureux et al. 2013; McGregor
390 et al. 2014; de Boissésou et al. 2014; Ma and Zhou 2016; Kajtar et al. 2017) are unforced or partly
391 caused by changes in WMGHG (DiNezio et al. 2012; Xiang et al. 2014; Cai et al. 2015), AER
392 (Dong et al. 2014; Takahashi and Watanabe 2016), or VOL (Emile-Geay et al. 2008; Le 2017) is a
393 matter of intense debate and beyond the scope of this paper. However, the residuals as well as the
394 explained variabilities provided in Fig. 5 suggest that low-frequency ENSO variability has little
395 bearing on the outcome of our response model results. Merely the timing of the modern warming
396 is slightly better aligned with observations when MEI rather than NINO3.4 (Trenberth 1997) is
397 used (not shown), which is indicative of a minor role for additional decadal PDV impacts indeed.

398 Modelled Land (Fig. 7d) shows only a few peaks that are not explained by ENSO (e.g. 1884,
399 1913, 1939, 1949, 1980, 1991, 2010). Such excursions should be expected given the large standard
400 deviation over land due to the stochastic nature of continental interannual variability (Mahlstein
401 et al. 2012). There are a few years between 1950-60 which appear to be cooler than the response
402 model suggests, but since no such deviation shows up over Ocean (see Fig. 7f), it might be related
403 to European aerosol emissions (Persad and Caldeira 2018).

404 The positive residual after 2000 (also visible in the NHem residual in Fig. 7a) is perhaps more
405 interesting as it relates to the infamously dubbed ”hiatus” period in the wake of the strong El
406 Niño in 1997/98. While primarily caused by a clustering of La Niña events around 2010 (Kosaka
407 and Xie 2013; England et al. 2014; Schurer et al. 2015; Dong and McPhaden 2017), upon closer
408 inspection another feature stands out. There has been a succession of anomalously cold years
409 between 2010-2013, which is exclusively linked with boreal winter. More precise, this period
410 is linked with extremely cold Eurasian winters (Cohen et al. 2012) which may or may not have
411 been assisted by forced atmospheric circulation changes in response to declining sea ice (Tang

412 et al. 2013; Cohen et al. 2014; Overland 2016; Francis 2017; Hay et al. 2018). But other than
413 that, SHem (Fig. 7c) and Ocean (Fig. 7f) residuals are inconspicuously smooth and only diverge
414 before 1900 as outlined above already. Overall, our results support previous work that has shown
415 that using updated external radiative forcing (Huber and Knutti 2014; Schmidt et al. 2014) and
416 accounting for ENSO-related variability explains the so-called "hiatus". We refer to Medhaug et al.
417 (2017) for a comprehensive review of the unprecedented flurry of publications on the subject. That
418 said, despite being less sensitive to small changes near the endpoints compared to higher degree
419 polynomial fits, we caution that the lowess smoother is still susceptible to overestimating trend
420 changes at the beginning and end of the time series.

421 With explained variabilities $\sim 98\%$ for HadOST for the Land (Fig. 5a), NHem (Fig. 5b) and
422 Global (Fig. 5c) response model results, we conclude that almost all low-frequency variability
423 is explained by external forcing factors independent of ENSO. The Ocean (Fig. 5d) and SHem
424 (Fig. 5e) results reveal similar explanatory skill with explained variabilities between 93-95%. In-
425 terestingly, BE shows lower correlation factors than Cru4CW over Ocean (even more so over
426 SHem), despite their common use of HadSST3. Thus, differences in data processing alone can
427 explain much of the discrepancies. The fact that HadOST not only fares considerably better in
428 terms of correlation, but also performs best regarding the coastal proxy analysis (Fig. 1d), justifies
429 its inclusion in our analysis. However, more work needs to be done to reconcile the differences
430 between the available SST products and to reduce associated biases (Davis et al. 2019). In Ap-
431 pendix B, we briefly analyse the spatio-temporal characteristics of those products with regard to
432 decadal means.

433 **6. Role of unforced Atlantic ocean variability**

434 While the accurate reproduction of the EW and MC period in our response model framework
435 does not require multidecadal temperature variability to attribute to the ostensible AMV, we do not
436 dispute the existence of internal variability associated with AMOC variations. Therefore here we
437 aim at quantifying the AMOC's role in setting NHem temperatures and its relation to the AMV. In
438 order to facilitate the assessment, we would like to propose a more adequate, straight-forward and
439 intuitive definition of the AMV index itself. Rather than using the standard definition (Delworth
440 and Mann 2000) or an improved definition thereof (van Oldenborgh et al. 2009), we define the
441 AMV as average SST at 25-60°N and 7-75°W (red box in Fig. 8d) minus NHem temperature. The
442 resulting revised timeseries is shown in Fig. 7a (bold black line).

443 The revised AMV index (which we more appropriately propose to be named *North Atlantic Vari-*
444 *ability Index* or NAVI) is essentially reflecting and reliably mirroring the long-term AMOC decline
445 in response to anthropogenic warming. The unprecedented dip around 2015 is associated with the
446 continued advection of very cold air of Arctic origin over the Canadian archipelago region during
447 the winters of 2014/15 and 2015/16. Atmospheric forcing has been recognised to drive short-term
448 AMOC variability (Roberts et al. 2013; Duchez et al. 2016) as opposed to gradual changes in sea
449 ice cover (Sévellec et al. 2017), temperature, salinity and pressure gradients that eventually cause
450 the slower long-term AMOC changes that are indeed already detectable Rahmstorf et al. (2015)
451 and concomitant with the well-known Atlantic Warming Hole (AWH) (Menary and Wood 2018).
452 Arguably, asymmetric land-ocean warming is a more mundane explanation for the colder NA re-
453 gion relative to NHem, as it is physically consistent with a transient warming scenario, but the
454 slow pace of the NAVI decline suggests a contributing role for AMOC.

455 In order to qualitatively explore the role of longer-term effects associated with low-frequency
456 modes of variability, we have conducted a simple correlation analysis. In Fig. 8, we have plotted
457 the spatial map of correlation coefficients between Global and NHem timeseries obtained from the
458 response model versus global observations (HadOST). The correlation between the older, slightly
459 more advanced AMV index (van Oldenborgh et al. 2009) and HadOST is provided as well (Fig. 8d,
460 g, k). We notice that the AWH in the subpolar NA region appears uncorrelated with the forcing
461 timeseries (Fig. 8a, b, e), regardless whether we use the Global or NHem timeseries. Another
462 noteworthy feature is the accompanying anti-correlation between the AMV index and most world
463 regions.

464 Since we are not aware of a robust mechanism that would cause multidecadal AWH variability
465 as opposed to a steady decline, in the following we test three potential reasons for why the AWH
466 region may or may not follow externally forced changes: (1) A long-term warming trend differ-
467 ence, (2) a different spectrum of high-frequency SST variability, or (3) true internal low-frequency
468 variability. To investigate whether (3) is a viable explanation, we applied running means from 5-20
469 years (Fig. 8e, h, m; middle panel), we linearly detrended model and observations (Fig. 8c), or we
470 did both (Fig. 8f, j, n; rhs panel).

471 What we find is that the AWH is robust against temporal averaging as far as non-detrended
472 data are concerned. In contrast, if detrended data are used, the temporal averaging aligns the
473 NAVI/AWH region with the NHem forcing response in terms of correlation, maintaining its
474 (forced) multidecadal low-frequency variability. In fact, detrending alone considerably reduces
475 the unique behaviour of the AWH region already (Fig. 8c). What we infer from this is that the
476 secular warming trend (1) is responsible for the specific characteristic of the AMV region. The
477 root cause of this cooling trend is well known and one of the key features in GCM projections
478 (Rahmstorf et al. 2015; Menary and Wood 2018). The high-frequency variability over the wider

479 NA region is higher than on global average, but comparable in magnitude to the western North
480 Pacific (equally high supply of baroclinicity) or Eurasia (Fig. 8b).

481 After a decade, not much multi-annual stochastic variability is left (Fig. 8e). Together with
482 the Indian ocean, the wider NA region shows high correlations with the NHem model after trend
483 removal in both (Fig. 8f), suggesting substantial dependencies on externally forced low-frequency
484 variability. It is a different story over land (and much of the Pacific), where the signal-to-noise
485 ratio is lower on decadal scales due to limited radiative constraints on winter temperatures (Cohen
486 et al. 2012; Knutson et al. 2013; Deser et al. 2017). The positive correlation between the 20 year
487 low-pass filtered, detrended AMV and the Arctic (Fig. 8k) is physically very plausible as amplified
488 Arctic warming relies on heat transport via the NA region, governed by the NAO index and the
489 associated strength of the AMOC. However, it is the forced long-term warming trend that is the
490 driver as evident from Figs. 8m and 8n.

491 Since no noticeable low-frequency signal can be detected over the key AWH region (Fig. 8n),
492 we conclude that it is unlikely that internal variability on timescales > 5 years plays an important
493 role in the North Atlantic. There is room for 1-5 year unforced feedbacks, but apart from the
494 cooling due to the long-term decline in AMOC strength (Fig. 8m), high- and low-frequency AMV
495 pattern appear to be externally forced according to our response model results. This is in line with
496 an empirical model study that uses multiple regression to attribute forcing contributions globally
497 (Suckling et al. 2017), and also supported by other studies that show that subpolar NA variability
498 is largely driven by AMOC changes, with little evidence for a strong AMV-AMOC link (Marini
499 and Frankignoul 2014; Frankignoul et al. 2017).

500 In conclusion, combined with the recent downward trend in the new NAVI index, our analysis
501 strongly suggests that the impact of internally generated NA ocean dynamics on Global, NHem
502 and Land temperatures is rather limited. Remaining AMOC related to low-frequency variability

503 (Zhang 2017) may have regional implications, but a strong influence beyond that is unlikely. The
504 results are supported by another simple exercise in which NA SSTs are weighted by the surface
505 area of the AMV/NAVI region, divided by the NHem surface area. This way, the fractional fin-
506 gerprint of the AMV on NHem temperatures can be inferred. The peak contribution would be
507 $<0.03^{\circ}\text{C}$, assuming all NA SST variability is of internal origin, which we have shown not to be a
508 very plausible conjecture. Helped by a more advanced (yet still debatable) regression analysis, we
509 note that Folland et al. (2018) also found almost no AMV contribution to global temperature.

510 **7. Conclusions**

511 With explained variabilities of observed global temperatures of up to 98% (30 year smooth) or
512 $\sim 93\%$ (with ENSO variability), respectively, our impulse response model performs exceptionally
513 well. We are able to match the historical temperature evolution since at least 1850 in general, and
514 succeed in reproducing both the EW and the MC period with high precision in particular, with-
515 out the need to invoke unexplained internal multidecadal temperature variability as an additional
516 driver.

517 Three key aspects are crucial for an appropriate attribution of the temperature response to ex-
518 ternal radiative forcing perturbations. (1) Careful treatment of the spatially heterogeneous AER
519 forcing as its temporal evolution has major repercussions for both the EW and the MC period. (2)
520 Removal of the WWII warm bias in the current generation of SST datasets as there is now solid
521 evidence that 1942-1945 period is biased warm to differing degrees, causing a spurious warming
522 trend at the end of the EW period. (3) Calibration of the fast response time in order to account for
523 the mediating effects of ENSO as far as the response to volcanic eruptions is concerned.

524 While others (Mann et al. 2014; Folland et al. 2018) have found similarly good agreement as
525 far as the GMST evolution is concerned, our analysis demonstrates that it is possible to reproduce

526 the temperature evolution separately for NHem, SHem, Land and Ocean with equal precision. We
527 achieve this by introducing a set of suitable TCR calibration factors that are informed by observed
528 (HadOST) and modelled (HadCM3) TWRs and traceable throughout the analysis. Apart from
529 minor fine-tuning related to the deduced TWR for AER, every response model parameter used in
530 our study is backed up by independent analysis and/or based on well-established research. The
531 use of updated aerosol emission and volcanic forcing data as well as the application of a longer
532 fast response time (complemented by a hemispherically more uniform fast VOL response) are
533 otherwise the only changes that we made compared to previous iterations within the response
534 model framework. Owing to the introduced analytical constraints, which are designed to avoid
535 model tuning, our results warrant robustness against overfitting.

536 With the introduction of HadOST, which includes a coastal temperature analysis inspired by
537 Cowtan et al. (2017) that appears least biased with regard to the incorporated HadISST2 and OS-
538 TIA SSTs, we add another option to the existing batch of GMST datasets. We recommend to use
539 it more widely as it resolves some of the discrepancies present in HadSST3 before 1940. Despite
540 a smaller warm bias during WWII in HadISST2 compared to HadSST3, we still have to impose
541 a correction factor (-0.08°C for GMST) to reconcile it with the coastal hybrid temperature time-
542 series. As a result, almost all of the EW warming could ultimately explained by external forcing
543 changes, which - if confirmed by future research - may call the current partition of attributable EW
544 causes, as recently reviewed in Hegerl et al. (2018), in considerable doubt.

545 In our assessment of potential contributions from Atlantic and Pacific multidecadal variability,
546 we demonstrate that with the exception of prolonged periods of El Niño or La Niña preponderance,
547 there is little room for internal unforced ocean variability beyond subdecadal timescales, which is
548 particularly true for the NA region. This finding is buttressed by our demonstration that despite
549 high co-variability, cause (VOL and AER) and effect (AMV) are clearly distinguishable. That

550 does not mean AMV cannot have internal mechanisms (Zhang 2017), rather only that the signal
551 cannot be detected in Global or NHem (nor is necessary to explain their temporal evolution).
552 Hence the traditional AMV index must not be used as predictor or explanatory variable, as it may
553 lead to demonstrably incorrect or flawed attribution results (Hetzinger et al. 2008; Chylek et al.
554 2009; Huss et al. 2010; Wyatt et al. 2012; Tung and Zhou 2013; Chylek et al. 2014; Pasini et al.
555 2016; Hodgkins and Wilson 2017; Yan et al. 2017; Shen et al. 2018; Zhang et al. 2018). We
556 suggest a revised AMV index formulation (NAVI) which avoids such pitfalls as it better mirrors
557 the long-term AMOC decline as suggested, for example, in (Rahmstorf et al. 2015).

558 On that note, we also caution against confusing atmospherically driven short-term variability
559 (noise) with changes due to anthropogenic or natural external forcing factors (signal). As demon-
560 strated in the supplementary analysis, anomalous atmospheric NHem winter circulation features
561 explain most of the short-term AMOC variability, acting as the control knob on multi-monthly
562 timescales. Longer timescales are conceivable: (1) Via changing wind stress related to anoma-
563 lous NAO phasing, which in turn affects the subpolar horizontal gyre circulation (Piecuch et al.
564 2017). (2) Via atmospheric teleconnections associated with ENSO such as the PNA-NAO rela-
565 tionship (Pinto et al. 2011), which in turn links to the emerging paradigm of the Pacific basin as
566 pacemaker for global temperature (Guan and Nigam 2009; Kosaka and Xie 2013; England et al.
567 2014; Schurer et al. 2015; Dong and McPhaden 2017; Frankignoul et al. 2017). (3) Via *ocean*
568 *memory* effects, which may favour the reoccurrence of certain large-scale weather patterns in the
569 Euro-Atlantic region during successive boreal winter seasons via air-sea coupling (Scaife et al.
570 2014). But generally, progress in understanding Atlantic decadal climate variability has been slow
571 (Yeager and Robson 2017). Taken together, our analysis underscores that despite the complexities
572 of the climate system, changes to the mean state are dominated by radiative forcings on longer
573 timescales and ENSO-related variability on shorter timescales.

574 By virtue of these findings, we are confident that our associated best TCR estimate of 1.57
575 (± 0.70) K is robust, despite a substantial error range due to the large forcing uncertainty. We
576 strongly advise against the use of ECS estimates based on the instrumental record alone with-
577 out considering further evidence (from paleo-archives or GCMs), as they cannot be reliably con-
578 strained with data of such a short time interval.

579 In a future analysis, we aim to quantify another important response model feature which also
580 contributes to an improved representation of the EW period. In a nutshell, it can be demonstrated
581 that failure to initialise the response model (or GCMs for that matter) before a series of strong
582 volcanic eruptions will very likely bias the beginning of the simulated EW period warm, leading
583 to an artificially low warming trend in models.

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Calculation of coupling factors

As outlined in Section 3, inter-hemispheric energy exchanges in response to the heterogeneous distribution of AER need to be balanced by virtue of so-called coupling factors. As shown in Fig. 3, for AER there is a notable discrepancy between the TCR scaling factors (2.5/1.9 for NHem/SHem and 2.7/1.95 for Land/Ocean) and the diagnosed AER-TWR (5.1 for NHem/SHem and 2.9 for Land/Ocean). A discrepancy that does not appear for WMGHG and VOL (for instance: $TWRD_{WMGHG} = 2.23/0.97 = 2.3$). This is where the coupling factor comes into play. Since the TCR scaling only works under the assumption that the NHem aerosol response is governed by NHem aerosol emissions (and vice versa for SHem; same problem for Land and Ocean), we have to find a way to accommodate the additional temperature response from SHem emissions in case of the NHem response.

We have applied two-stage methodology: (1) We derive the emission ratio, i.e. the ratio between the hemispheric (and land/ocean) and the total global aerosol emission strength. It is a function of the fractional contribution of each hemisphere (or land/ocean) and could vary between 95% to 5%, up until 50% to 50%. (2) We determine the optimal fractional contribution or coupling strength. For this to work, we balance the ratio of the TCR scaling factors (e.g. 2.5 for NHem and 1.9 for SHem) and the TWRD (e.g. 5.1 for NHem/SHem). Since the effective forcing of the SHem emissions will be lower (due to the lower TCR scaling factor), a secondary scaling factor has to be applied to NHem and SHem emission strength. This factor is only be equal for one particular set of coupling strengths. For NHem/SHem, the fractional contributions are 85% and 15%, associated with a NHem emission ratio (fractional NHem emission divided by Global emissions) of 1.58 and a SHem emission ratio (fractional SHem emission divided by Global emissions) of 0.42. The

620 additional secondary scaling factor is 0.93. Hence the NHem/SHem emission ratio is reduced to
621 1.47 and 0.38. Their ratio defines the coupling factor, which is 3.9 accordingly ($=1.47/0.38$).

622 Applying the same method for Land/Ocean, the fractional contributions are 70% and 30%, asso-
623 ciated with a Land emission ratio (fractional Land emission divided by Global emissions) of 1.35
624 and an Ocean emission ratio (fractional Ocean emission divided by Global emissions) of 0.65. The
625 secondary scaling factor is 1.08, which is explained by the fact that the Ocean sensitivity is lower,
626 but instead covers a much larger area fraction compared to Land (area fractions are equal in case
627 of NHem/SHem). Hence the Land/Ocean emission is increased to 1.46 and 0.70. The associated
628 ratio to determine the coupling factor is 2.1 (see lower box in Fig. 3 and fine-print below it).

629 APPENDIX B

630 **Decadal temperature evolution**

631 As highlighted in the main text, SST observations are still afflicted with considerable uncertain-
632 ties. Having investigated time series of field means, here we provide the spatiotemporal context
633 and discuss potential causes for some of the discrepancies noted above. In Fig. B1, the GMST
634 dataset used in this study are plotted as decadal average from 1850-1859 to 2010-2017 (BE,
635 Cru4CW, HadOST), accompanied by GISTEMP during 1880-1889 to 2010-2017. In addition,
636 the 20th Century reanalysis (20C Rean) (Hirahara et al. 2014), the ensemble mean of a subset of
637 CMIP5 simulations are plotted, together with NorESM1-M (Bentsen et al. 2013) which is found
638 to represent the temperature evolution since 1850 very well compared to observations. We also
639 added the recently proposed Hybrid SSTs (Cowtan et al. 2017). The decade 1940-1949 is high-
640 lighted by the red box. Note that HadOST and Cru4CW use the same infilled HadCRUT4 (Morice
641 et al. 2012) data over land. We also note that both, Cru4CW and BE have shown to carry a small

642 negative trend bias in recent years (Hausfather et al. 2017). If that is not enough, it has also been
643 suggested that the Arctic region might still be biased cold (Wang et al. 2017; Way et al. 2017).

644 As noted above, the 1880-1935 period is too cold in HadSST3 (Cru4CW) compared to
645 HadISST2 (HadOST), most pronounced during 1890-1920. Looking at those three decades, at
646 least the first two show a noteworthy feature near Cape Cauldron off the southern tip of South
647 Africa, presumably associated with the Agulhas and Brazil currents. The otherwise distinct cold
648 SST anomalies in the turbulent exit region where the Agulhas current leaks into the South Atlantic
649 ocean (compare HadOST) turns into a vast area of cold SST anomalies that essentially covers
650 most of the South Atlantic. Given the poor observational coverage and the intrinsic shortcomings
651 of any infilling technique (Kriging in case of Cru4CW), it is likely that the cold South Atlantic
652 SST anomalies in Cru4CW, BE and GISTEMP are exaggerated to varying degrees.

653 Since the only bias in HadOST with regard to our response model results was found during the
654 1850-1879 period, mainly caused by warmer NH SST conditions, it is interesting to ask whether
655 the warm SST anomaly in the North Pacific in HadOST is real given it does not show up in other
656 observational datasets. While such a pattern is consistent with a prolonged PDV negative phase,
657 the amplitude of the anomaly appears very strong, especially during the 1860s. The pattern re-
658 occurs during the 1950-80 period, but background SSTs are less cold than during the 1850-79
659 period. This is arguably a feature which deserves to be investigated in more detail, particularly in
660 light of recent work by Huang et al. (2018).

661 Regarding the WWII period, even though we have plotted decadal averages, what stands out
662 is the sudden warming of all ocean basins in ERSST during the 1940s (and to a much lesser
663 extent HadSST3 and HadOST). As evident from Fig. 5a, Land did not notably warm during the
664 same period, which strongly suggests an artifactual feature, related to biases due to the previously
665 explained change in fleet composition during WWII. The final feature we would like to mention

666 concerns the cold bias during 1950-80 in ERSST. While the general NHem ocean cooling due
667 to increased anthropogenic SO₂ emissions is visible in all observations (and CMIP5 simulations,
668 irrespective of some temporal misalignments), ERSST seems to exaggerate the cooling slightly
669 given that the spatial pattern of the SST anomalies are indistinguishable from other datasets. We
670 speculate that this might be a general theme in ERSST given that it draws heavily from maritime
671 nighttime measurements in contrast to other products. We note that ERSSTv5 (Huang et al. 2017)
672 has not changed notably compared to ERSSTv4.

673 As we cannot provide robust conclusions with regard to causes for the mismatch between dif-
674 ferent observational dataset at this point, we would like to close by encouraging the research
675 community to address the oftentimes under-appreciated problems in more depth. Insights from
676 energy balance models such as presented in this study can guide such efforts. With clever new
677 strategies to combine the various information available, we are confident that the remaining gaps
678 in our understanding will be eliminated and instrumental data brought into better agreement.

679 **References**

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LIST OF FIGURES

1190 **Fig. 1.** Global radiative forcing components used in our study (a), decomposition of the four AER
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 1192 and non-effective AER (c). Scaled coastal HadOST (blue) and coastal BE anomalies (red)
 1193 in comparison with 60N-60S HadOST (black) in (d) and the same for coastal ERSSTv4,
 1194 coastal GISTEMP and 60N-60S ERSSTv4 in (e). 59

1195 **Fig. 2.** Transient Warming Ratios (TWR) to estimate the TCR adjustment factors for WMGHGs,
 1196 AER and VOL for NHem/SHem (lhs) and Land/Ocean (rhs). *Allforcing* warming contri-
 1197 butions in CMIP5, HadCM3, HadOST and the response model (a, b). WMGHG only (c,
 1198 d), AER only (e, f) and VOL only (g, h) contributions in HadCM3 and the response model.
 1199 Modelled VOL (negative) temperature response is shifted by +10 and +25 years merely for
 1200 better readability. The timeline of volcanic eruptions (scaled radiative forcing) is shown in
 1201 black (g, h). All data are low-pass filtered to remove interannual variability. The boxes at
 1202 the bottom show the inferred (diagnosed) warming ratios (TWRD) for WMGHG and AER
 1203 using the product of the ratios of observed (red) and modelled (orange) *allforcing* TWRs (a,
 1204 b), multiplied by the modelled TWRs (orange) for WMGHG (c, d) and AER (e, f). The es-
 1205 timated warming ratios (TWRE) refer to the simulated response model TWR using TWRD.
 1206 Both values are given in light purple. Only the 30 year period of strongest differential warm-
 1207 ing is used for the central TWR estimates. VOL TWR is only a function of the fast response.
 1208 61

1209 **Fig. 3.** Summary panel for all the necessary response model parameter, including their justification.
 1210 Global, hemispheric and Land/Ocean TCR scaling factors for WMGHGs, anthropogenic
 1211 aerosols (AER) and volcanic eruptions (VOL) based on the findings shown in Fig. 1 (top
 1212 box). Forcing response time estimates and sensitivities used in this analysis are provided,
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1216 **Fig. 4.** Fractional variance (square of the model error) for impulse response model uncertainty
 1217 (green), total radiative forcing uncertainty (blue) and internal variability uncertainty (grey)
 1218 in (a). The 1σ (32-68th percentiles) range is shown. We note that internal variability is
 1219 no response model uncertainty in a strict sense as it is added post-hoc (i.e. onto the cal-
 1220 culated temperature). The peaks in the response model uncertainty coincide with volcanic
 1221 eruptions (e.g. Tambora in 1816) eruption. The Internal variability from selected CMIP5
 1222 piControl runs is contrasted with the unforced residuals from the GMST datasets used in this
 1223 study (b). Observed and modelled timeseries are low-pass filtered with a 30 year smoothing
 1224 radius. The standard error is provided in brackets. 63

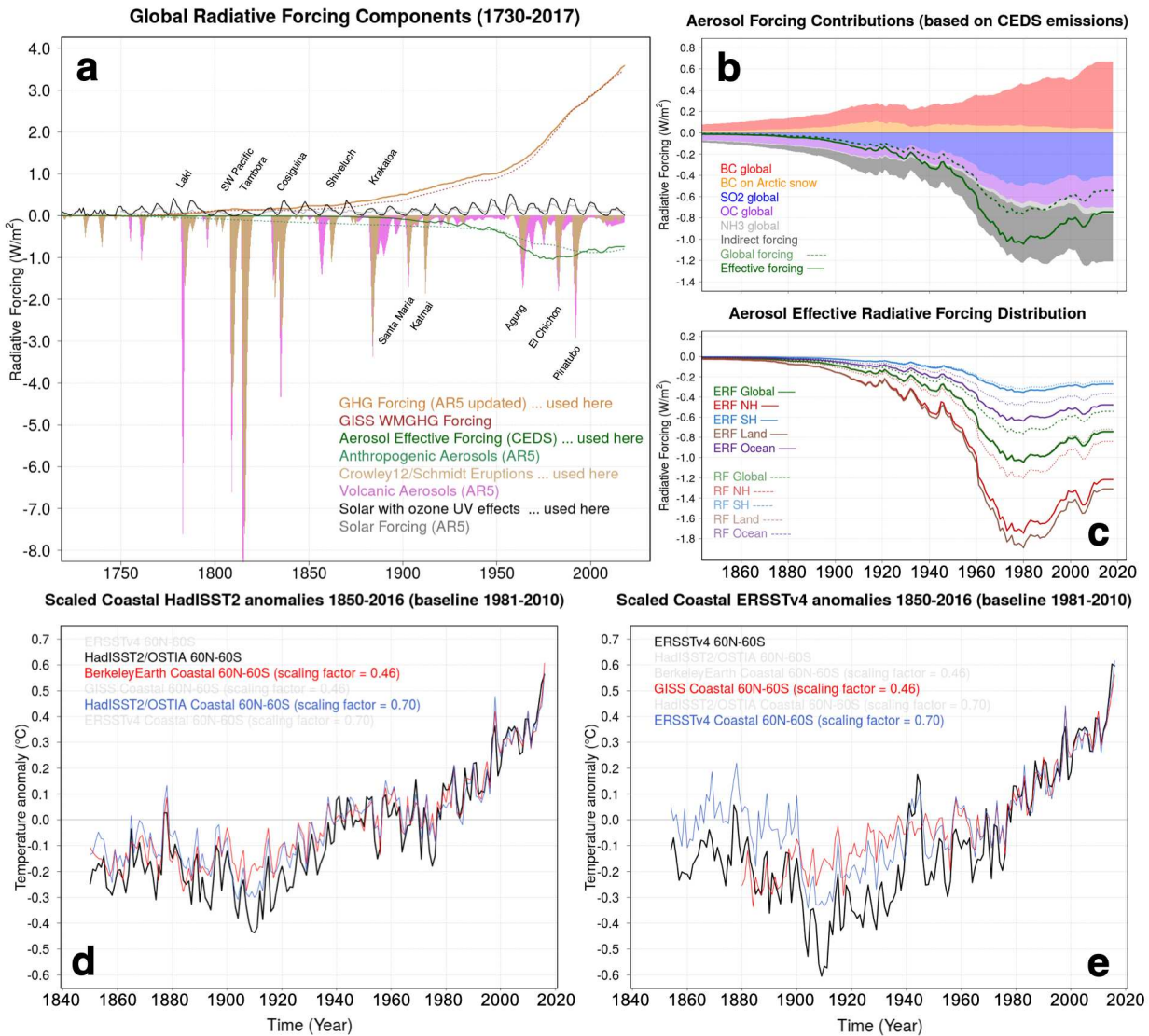
1225 **Fig. 5.** Illustration of the ENSO influence on our results. In the upper graph in each panel, the ob-
 1226 servations are plotted against the response after adding MEI variability to the time series.
 1227 The lower graph shows the raw impulse response model results against the ENSO-corrected
 1228 suite of observational data. Land (including sea ice grid points) is shown on the upper left
 1229 (brown), NHem on the lower left (red), GMST on the upper right (green), Ocean (excluding
 1230 sea ice grid points) in the centre right (purple), and SHem on the lower right (blue). Ob-
 1231 servations from the HadOST composite (pale grey), Cru4CW (yellow), and BE (black) are
 1232 shown. Explained variances (R^2) are given for non-ENSO corrected, model-adjusted (MEI),
 1233 and observation-adjusted (MEI) (Foster and Rahmstorf 2011) low-pass-filtered correlations.
 1234 The WWII correction factors are applied to both instrumental temperature timeseries in each
 1235 panel (except Land). TCR values associated with alternative response model results are pro-
 1236 vided on the right of each panel (1.2-2.0K). 65

1237 **Fig. 6.** Evolution of the response model from forcing and response times as applied in Haustein
 1238 et al. (2017) (H17), with AER as used in CMIP5 (old AER) and the current version using
 1239 CEDS AER (new AER). Note that the WWII bias correction is only applied in case of new
 1240 AER in order to illustrate the impact (no change in Land only). The results are shown for
 1241 Land (a), NHem (b), Global (c), Ocean (d) and SHem (e). The two dashed lines in the
 1242 lower graph of each panel indicate the variability of the result as a function of the ECS
 1243 value applied in the response model. The default value of 3.0K corresponds with our central
 1244 estimate. 67

1245 **Fig. 7.** Unforced residual observed variability. Impulse Response Model (IRM) minus HadOST for
 1246 NHem (a), Global (b), SHem (c), Land (d), and Ocean (f). HadOST Global as in (b) is
 1247 compared to CruCW4 and BE Global in (e). A 30 year lowess smooth is added in each plot.
 1248 The revised AMV index is shown in (a). The Multivariate ENSO Index is added in (b). Note
 1249 that the rhs y-axis labels for AMV (a) and MEI (b) are different. 68

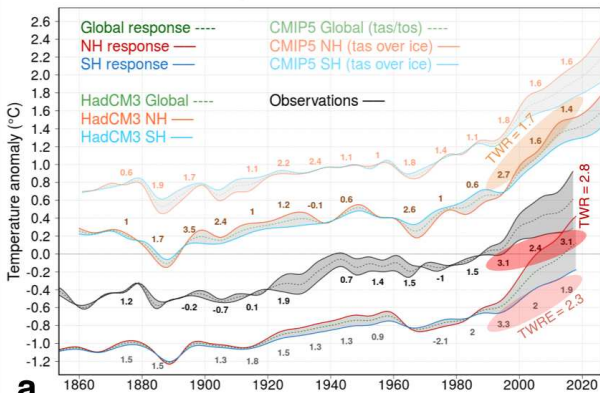
1250 **Fig. 8.** Spatial map of correlation coefficients (R) over time between 1850-2016. Positive correla-
 1251 tions in red and negative correlations in black. Annual means are used. (a) Time series of the
 1252 global response model vs HadOST composite. (b) As (a) but with MEI noise added to the
 1253 global response model time series. (c) Timeseries of the NHem response model vs HadOST.
 1254 (d) The improved AMV index (van Oldenborgh et al. 2009) vs HadOST. The AMV/NAVI
 1255 region is highlighted with a red box. (e) As (c), but with 5 year running means applied
 1256 to both NHem and HadOST. (f) Combination of (c) and (e) where both regressors are de-
 1257 trended and low-pass filtered with a 5 year running mean. (g) As (d), but with both AMV
 1258 and HadOST being detrended. (h) As (e) but with 10 year running mean. (j) as (f) but with
 1259 10 year running mean. (k) As (d), but with both AMV and HadOST being detrended and
 1260 low-pass filtered with a 20 year running mean. (m) As (e) but with 20 year running mean.
 1261 (n) As (f) but with 20 year running mean. SHem area is shown in semi-transparent colours
 1262 to highlight the NHem region of interest. 69

1263 **Fig. B1.** Decadal GMST anomalies for the 20th century Reanalysis, all observational data used in
 1264 this study including the new Hybrid SST dataset (Cowtan et al. 2017), CMIP5 subset and
 1265 the NorESM1-M global circulation model. Decade from 1850-59 (top) to 2010-17 (bottom)
 1266 are shown in each row. All anomalies are given relative to the 1901-2000 baseline period.
 1267 The 1940-49 decade that is affected by the WWII warm bias is highlighted by the red box. 71



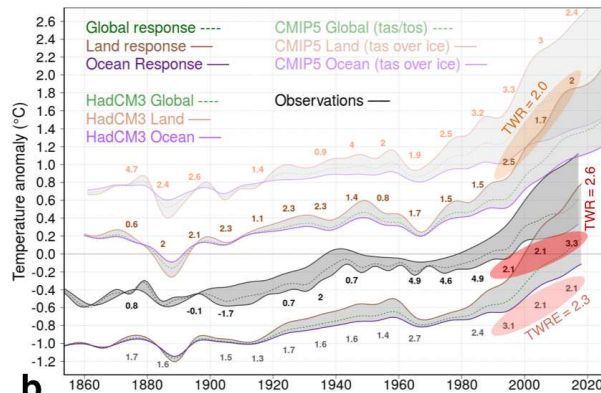
1268 FIG. 1. Global radiative forcing components used in our study (a), decomposition of the four AER components
 1269 including indirect aerosol effects (b), and spatial decomposition of the effective and non-effective AER (c).
 1270 Scaled coastal HadOST (blue) and coastal BE anomalies (red) in comparison with 60N-60S HadOST (black) in
 1271 (d) and the same for coastal ERSSTv4, coastal GISTEMP and 60N-60S ERSSTv4 in (e).

Hemispheric warming contributions: Model vs Observation



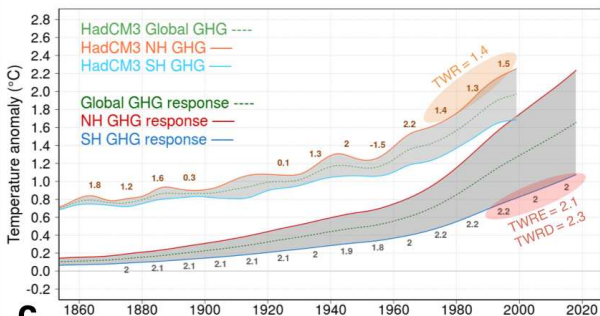
a

Land/Ocean warming contributions: Model vs Observation



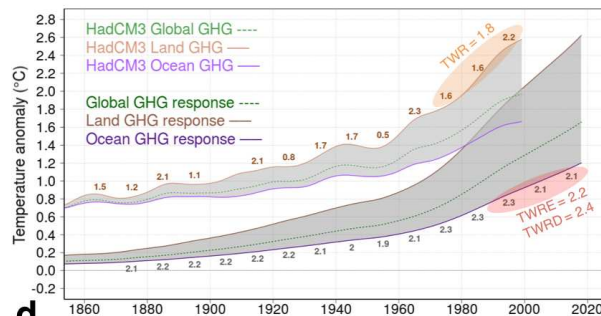
b

GreenhouseGas-Only Forcing: Hemispheric Response Ratio



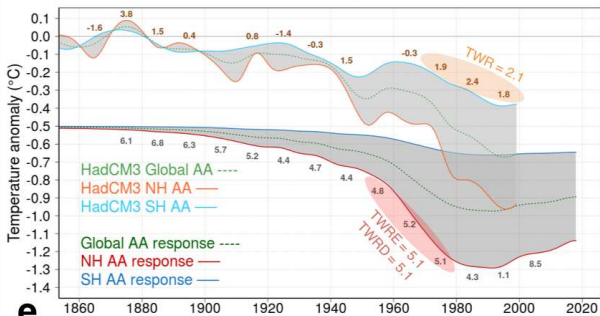
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GreenhouseGas-Only Forcing: Land/Ocean Response Ratio



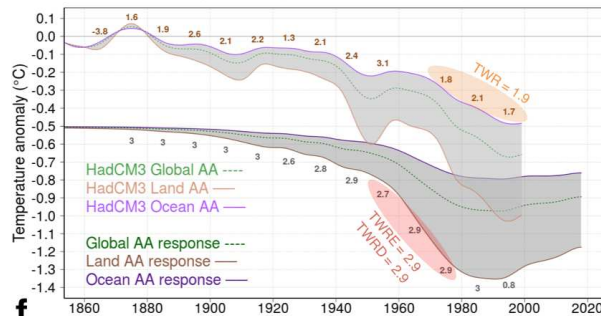
d

Aerosol-Only Forcing: Hemispheric Response Ratio



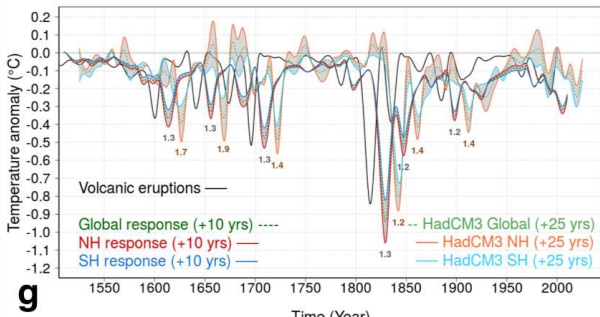
e

Aerosol-Only Forcing: Land/Ocean Response Ratio



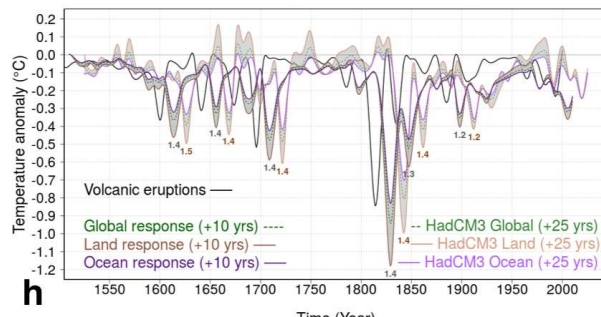
f

Volcanic-Only Forcing: Hemispheric Response Ratio



g

Volcanic-Only Forcing: Land/Ocean Response Ratio



h

TWR = Transient Warming Ratio
TWRE = Estimated Model TWR
TWRD = Diagnosed Model TWR

GHG-Only: NHem/SHem = $1.4 \times (2.8 / 1.7) = 2.3$
AER-Only: NHem/SHem = $2.1 \times (2.8 / 1.7) = 3.5^*$
VOL-Only: NHem/SHem (fast) = $1.3 \times 1.0 = 1.3$

Land/Ocean = $1.8 \times (2.6 / 2.0) = 2.4$
Land/Ocean = $1.9 \times (2.6 / 2.0) = 2.4^{**}$
Land/Ocean (fast) = $1.4 \times 1.0 = 1.4$

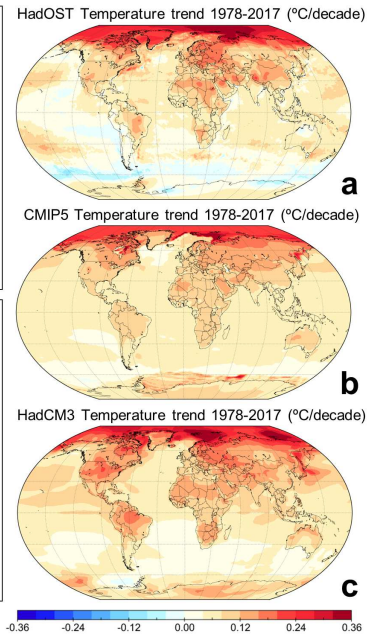
1272 FIG. 2. Transient Warming Ratios (TWR) to estimate the TCR adjustment factors for WMGHGs, AER
1273 and VOL for NHem/SHem (lhs) and Land/Ocean (rhs). *Allforcing* warming contributions in CMIP5, HadCM3,
1274 HadOST and the response model (a, b). WMGHG only (c, d), AER only (e, f) and VOL only (g, h) contributions
1275 in HadCM3 and the response model. Modelled VOL (negative) temperature response is shifted by +10 and +25
1276 years merely for better readability. The timeline of volcanic eruptions (scaled radiative forcing) is shown in
1277 black (g, h). All data are low-pass filtered to remove interannual variability. The boxes at the bottom show the
1278 inferred (diagnosed) warming ratios (TWRD) for WMGHG and AER using the product of the ratios of observed
1279 (red) and modelled (orange) *allforcing* TWRs (a, b), multiplied by the modelled TWRs (orange) for WMGHG
1280 (c, d) and AER (e, f). The estimated warming ratios (TWRE) refer to the simulated response model TWR using
1281 TWRD. Both values are given in light purple. Only the 30 year period of strongest differential warming is used
1282 for the central TWR estimates. VOL TWR is only a function of the fast response.

Global TCR	GHG: updated AR5 1.6 K... <i>example using best estimate</i>
	AER: CEDS emissions 2.2 K = $TCR_{GHG} \times \text{AER ERF/AER RF}$
	VOL: Crowley/Schmidt 1.6 K = TCR_{GHG}^2
NHem/SHem* TCR	GHG: 2.23/0.97 K ... TWRD = 2.3 ... HadCM3 GHG warming ratio
	AER: 2.50/1.90 K ... TWRD = 5.1 ... HadCM3 AER est. warming ratio
	VOL: 1.80/1.40 K ... TWRD = 1.3 ... HadCM3 VOL fast warming ratio
Land/Ocean** TCR	GHG: 2.65/1.11 K ... TWRD = 2.4 ... HadCM3 GHG warming ratio
	AER: 2.70/1.95 K ... TWRD = 2.9 ... HadCM3 AER est. warming ratio
	VOL: 2.00/1.40 K ... TWRD = 1.4 ... HadCM3 VOL fast warming ratio

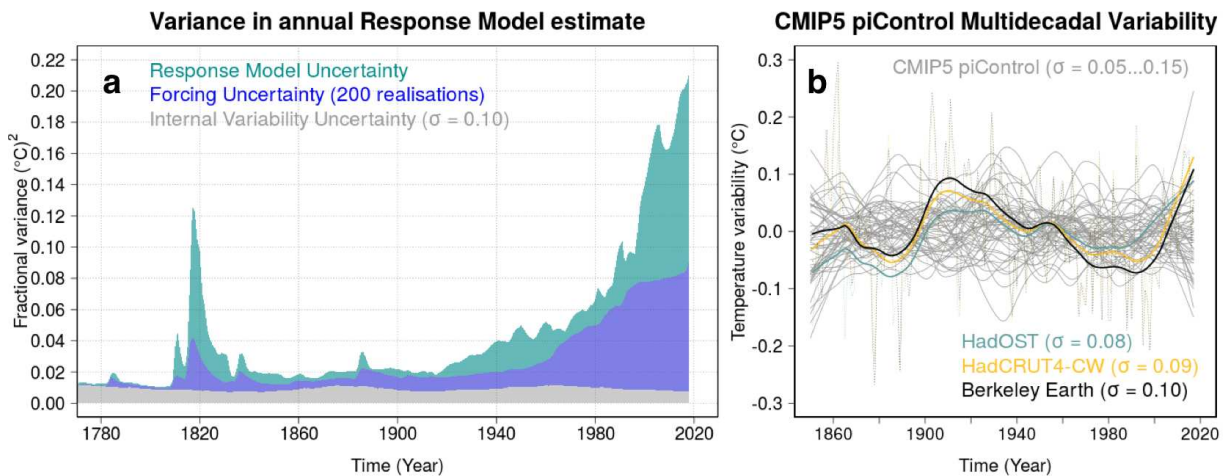
Fast response time: 8 yrs ... Boucher and Reddy 2008
Slow response time: 320 yrs ... Geoffroy et al. 2013b
Equilibrium Sensitivity (ECS): 3.0 K best estimate with range of 2.0-4.0 K
Transient Response (TCR): 1.6 K best estimate with range of 1.1-2.1 K
TCR/ECS ratio: 0.53 based on CMIP5 model mean

AER ERF: Forest 2018; revised net effective aerosol forcing (0.75 W/m²)
AER RF: AR5 Ch.8; individual aerosol forcing components (0.55 W/m²)
AER estimated: minor tuning of model deduced warming ratio (= 3.5*/ = 2.4**) scaled w/ coupling factor to balance the sum (= 3.9*/ = 2.1**)
VOL fast: direct model estimate (derived from fast forcing regime only)

* NHem/SHem area weighting factor = 0.50/0.50 (* for NHem/SHem) (* for NHem/SHem = 1.47/0.38)
 ** Land/Ocean area weighting factor = 0.32/0.68 (** for Land/Ocean) (** for Land/Ocean = 1.46/0.70)

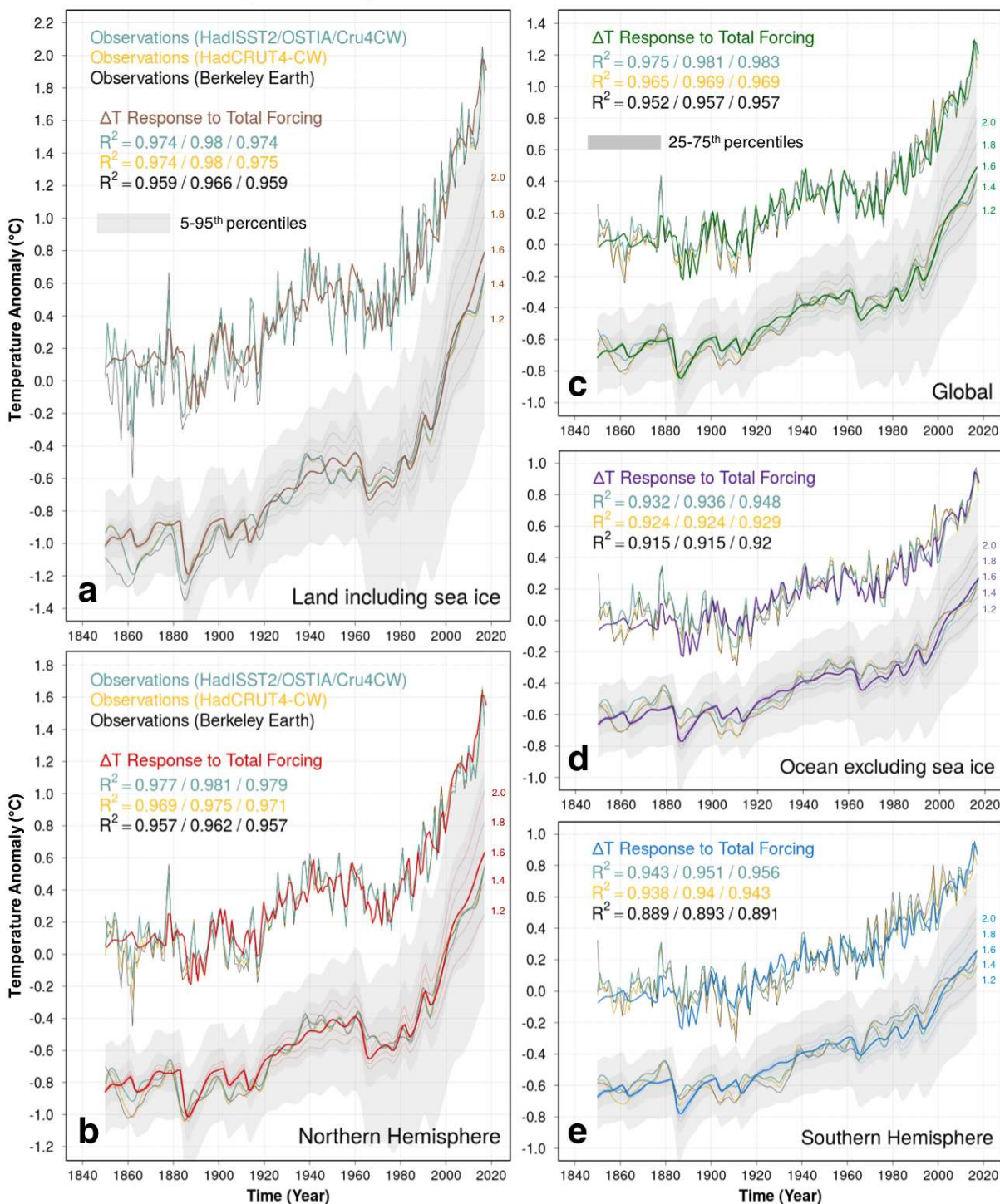


1283 FIG. 3. Summary panel for all the necessary response model parameter, including their justification. Global,
 1284 hemispheric and Land/Ocean TCR scaling factors for WMGHGs, anthropogenic aerosols (AER) and volcanic
 1285 eruptions (VOL) based on the findings shown in Fig. 1 (top box). Forcing response time estimates and sensitiv-
 1286 ities used in this analysis are provided, including their source (bottom box). Colour codes for better readability.
 1287 The pink labels in the lower box refer to the original AER-TWRD. In grey the associated coupling factors.
 1288 Surface temperature trends in HadOST (a), CMIP5 (b) and HadCM3 (c) from 1978-2017.



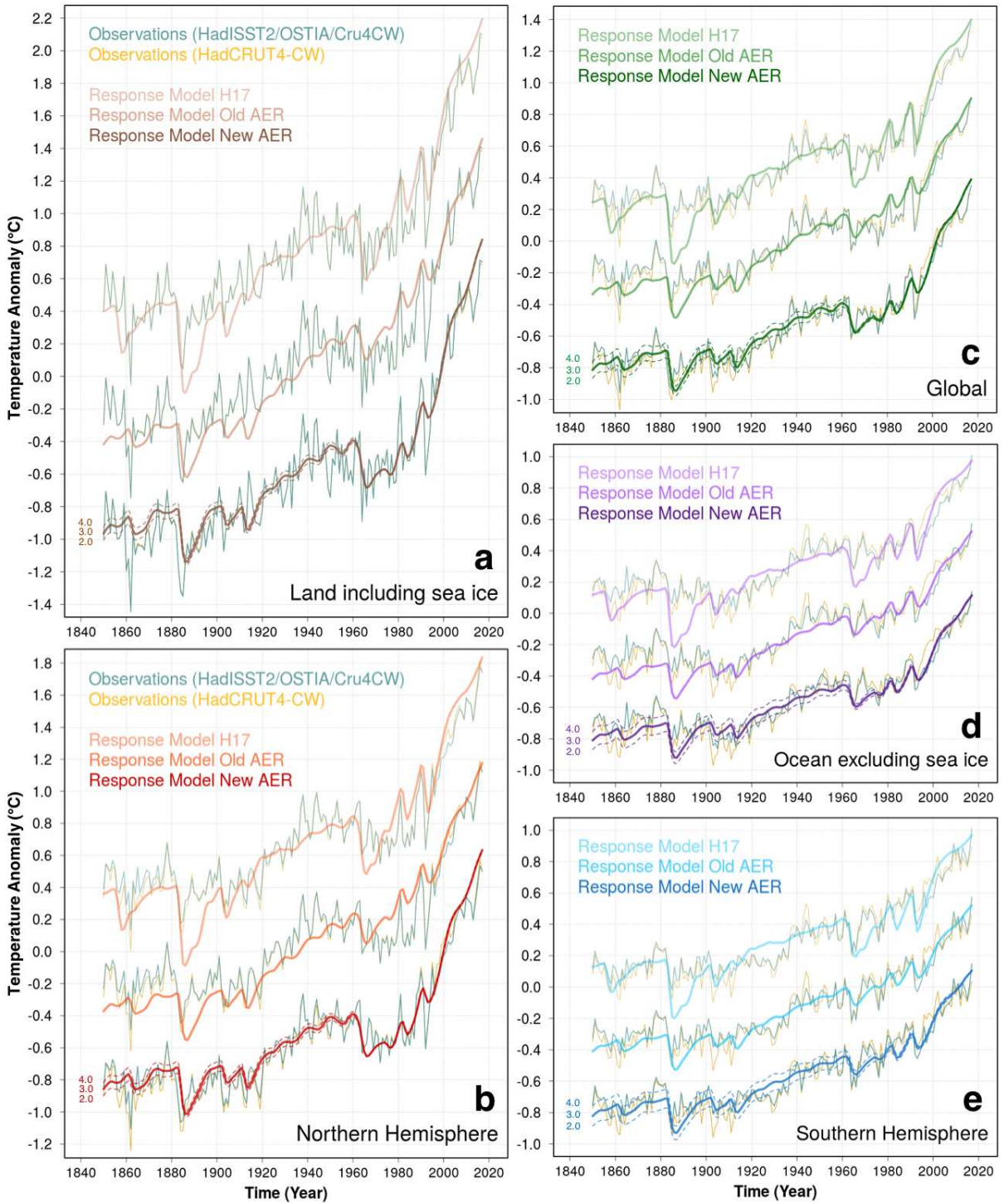
1289 FIG. 4. Fractional variance (square of the model error) for impulse response model uncertainty (green), total
 1290 radiative forcing uncertainty (blue) and internal variability uncertainty (grey) in (a). The 1σ (32-68th percentiles)
 1291 range is shown. We note that internal variability is no response model uncertainty in a strict sense as it is added
 1292 post-hoc (i.e. onto the calculated temperature). The peaks in the response model uncertainty coincide with
 1293 volcanic eruptions (e.g. Tambora in 1816) eruption. The Internal variability from selected CMIP5 piControl
 1294 runs is contrasted with the unforced residuals from the GMST datasets used in this study (b). Observed and
 1295 modelled timeseries are low-pass filtered with a 30 year smoothing radius. The standard error is provided in
 1296 brackets.

Impulse Response Model vs ENSO/MEI (1850-2017)

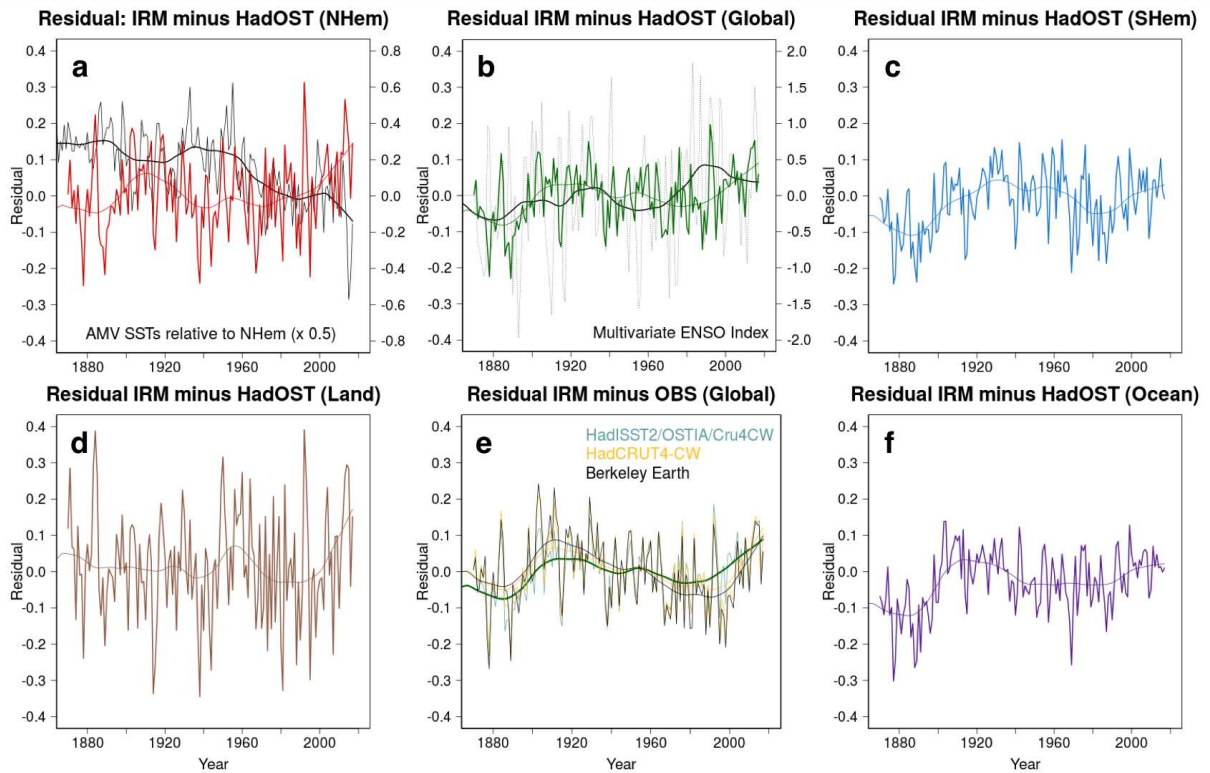


1297 FIG. 5. Illustration of the ENSO influence on our results. In the upper graph in each panel, the observations
1298 are plotted against the response after adding MEI variability to the time series. The lower graph shows the
1299 raw impulse response model results against the ENSO-corrected suite of observational data. Land (including
1300 sea ice grid points) is shown on the upper left (brown), NHem on the lower left (red), GMST on the upper
1301 right (green), Ocean (excluding sea ice grid points) in the centre right (purple), and SHem on the lower right
1302 (blue). Observations from the HadOST composite (pale grey), Cru4CW (yellow), and BE (black) are shown.
1303 Explained variances (R^2) are given for non-ENSO corrected, model-adjusted (MEI), and observation-adjusted
1304 (MEI) (Foster and Rahmstorf 2011) low-pass-filtered correlations. The WWII correction factors are applied to
1305 both instrumental temperature timeseries in each panel (except Land). TCR values associated with alternative
1306 response model results are provided on the right of each panel (1.2-2.0K).

Evolution of the Impulse Response Model

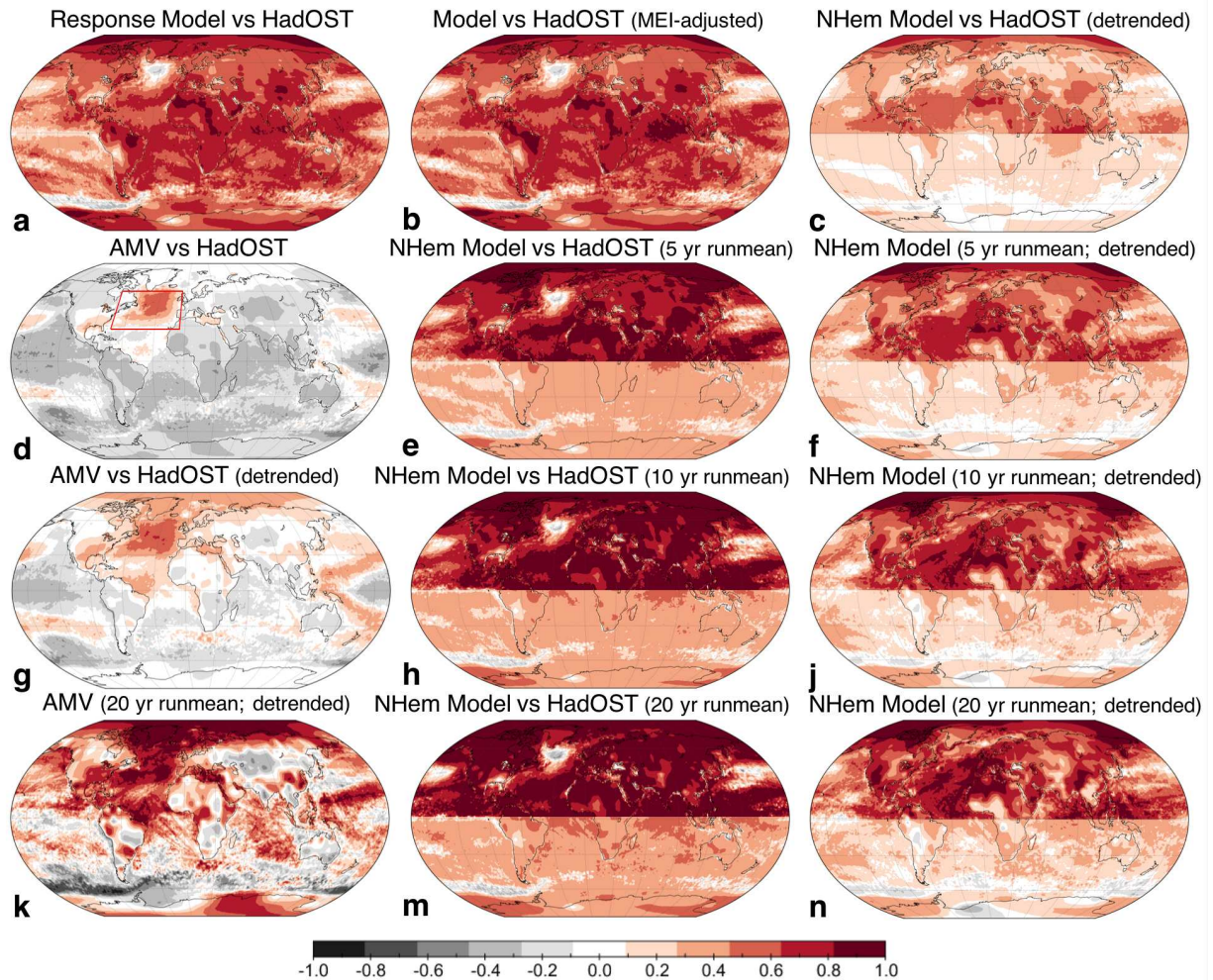


1307 FIG. 6. Evolution of the response model from forcing and response times as applied in Haustein et al. (2017)
1308 (H17), with AER as used in CMIP5 (old AER) and the current version using CEDS AER (new AER). Note that
1309 the WWII bias correction is only applied in case of new AER in order to illustrate the impact (no change in Land
1310 only). The results are shown for Land (a), NHem (b), Global (c), Ocean (d) and SHem (e). The two dashed lines
1311 in the lower graph of each panel indicate the variability of the result as a function of the ECS value applied in
1312 the response model. The default value of 3.0K corresponds with our central estimate.



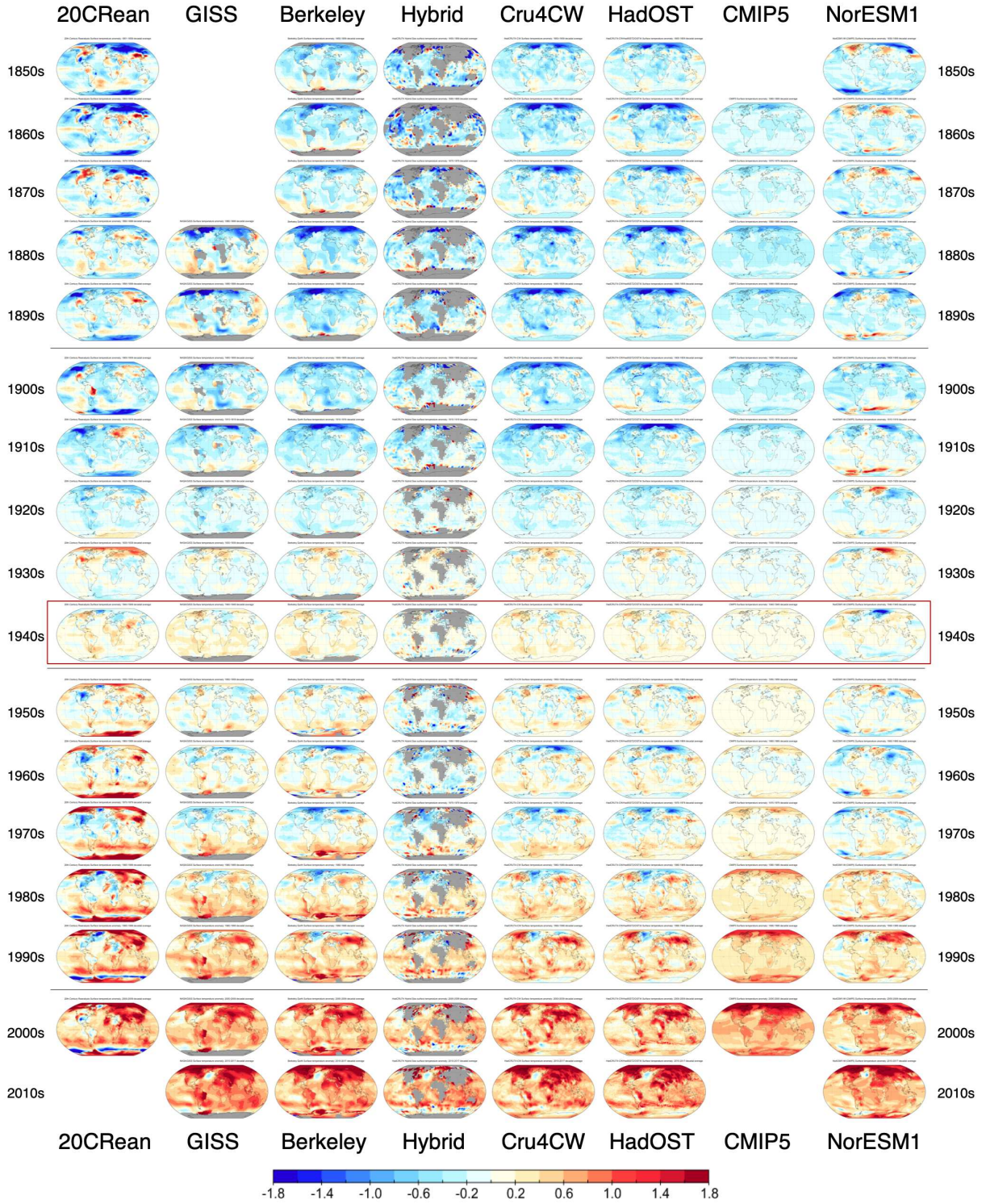
1313 FIG. 7. Unforced residual observed variability. Impulse Response Model (IRM) minus HadOST for NHem
 1314 (a), Global (b), SHem (c), Land (d), and Ocean (f). HadOST Global as in (b) is compared to CruCW4 and BE
 1315 Global in (e). A 30 year lowess smooth is added in each plot. The revised AMV index is shown in (a). The
 1316 Multivariate ENSO Index is added in (b). Note that the rhs y-axis labels for AMV (a) and MEI (b) are different.

Correlation Coefficient between (NHem) Response Model, AMV and HadOST (1850-2016)



1317 FIG. 8. Spatial map of correlation coefficients (R) over time between 1850-2016. Positive correlations in
 1318 red and negative correlations in black. Annual means are used. (a) Time series of the global response model
 1319 vs HadOST composite. (b) As (a) but with MEI noise added to the global response model time series. (c)
 1320 Timeseries of the NHem response model vs HadOST. (d) The improved AMV index (van Oldenborgh et al.
 1321 2009) vs HadOST. The AMV/NAVI region is highlighted with a red box. (e) As (c), but with 5 year running
 1322 means applied to both NHem and HadOST. (f) Combination of (c) and (e) where both regressors are detrended
 1323 and low-pass filtered with a 5 year running mean. (g) As (d), but with both AMV and HadOST being detrended.
 1324 (h) As (e) but with 10 year running mean. (j) as (f) but with 10 year running mean. (k) As (d), but with both
 1325 AMV and HadOST being detrended and low-pass filtered with a 20 year running mean. (m) As (e) but with 20
 1326 year running mean. (n) As (f) but with 20 year running mean. SHem area is shown in semi-transparent colours
 1327 to highlight the NHem region of interest.

Comparison of decadal air surface temperature averages (1850-2017)



1328 Fig. B1. Decadal GMST anomalies for the 20th century Reanalysis, all observational data used in this
1329 study including the new Hybrid SST dataset (Cowtan et al. 2017), CMIP5 subset and the NorESM1-M global
1330 circulation model. Decade from 1850-59 (top) to 2010-17 (bottom) are shown in each row. All anomalies are
1331 given relative to the 1901-2000 baseline period. The 1940-49 decade that is affected by the WWII warm bias is
1332 highlighted by the red box.