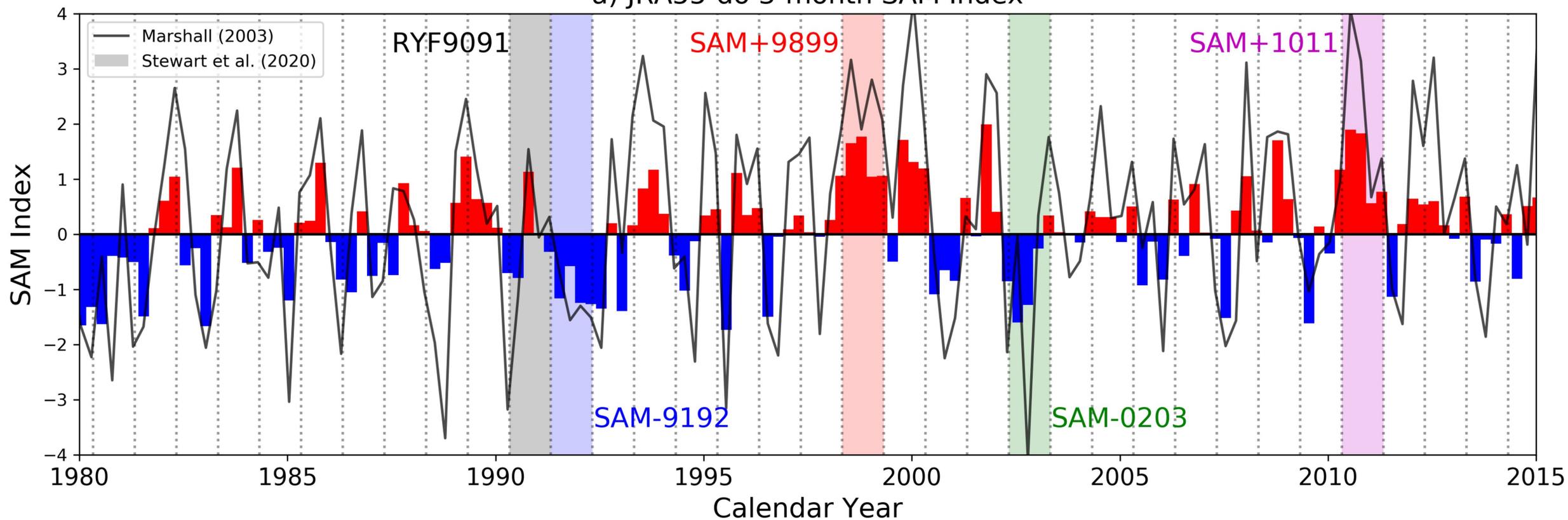
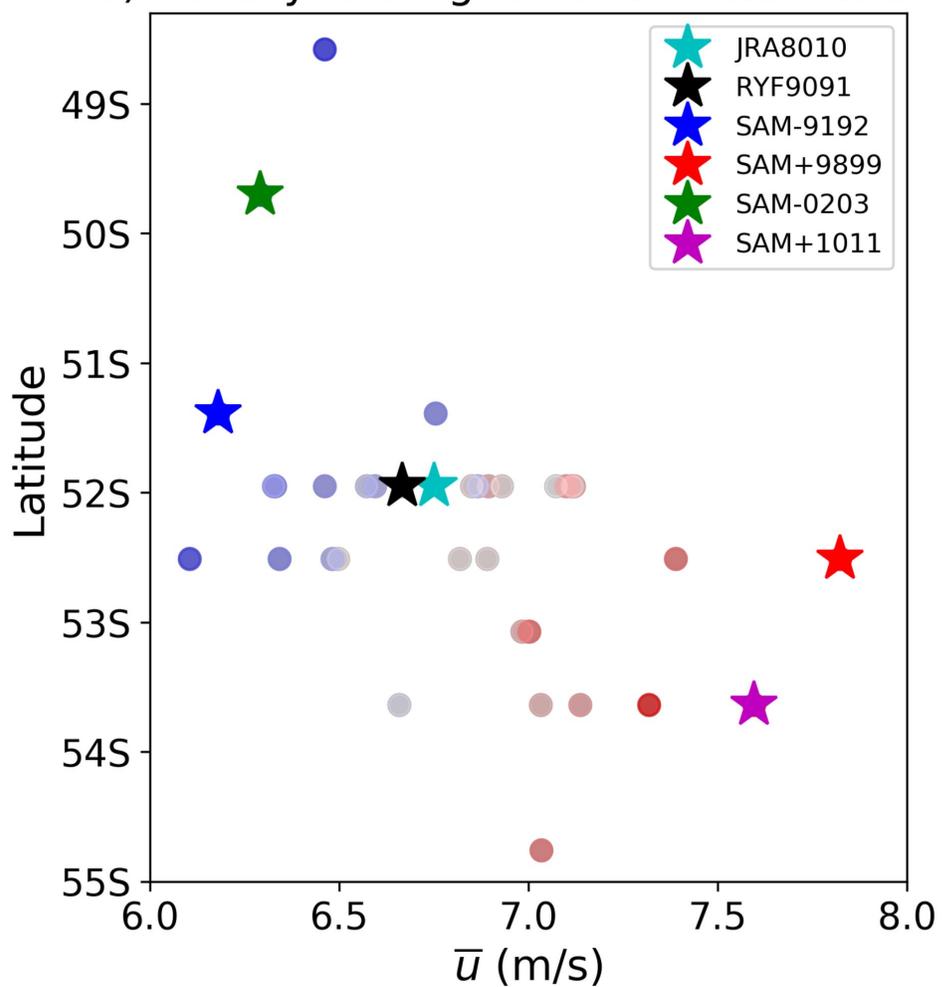


Figure 1.

a) JRA55-do 3-month SAM Index



b) Zonally-Averaged Zonal Wind Maxima



c) Zonally-Averaged Temperature, 200-500m

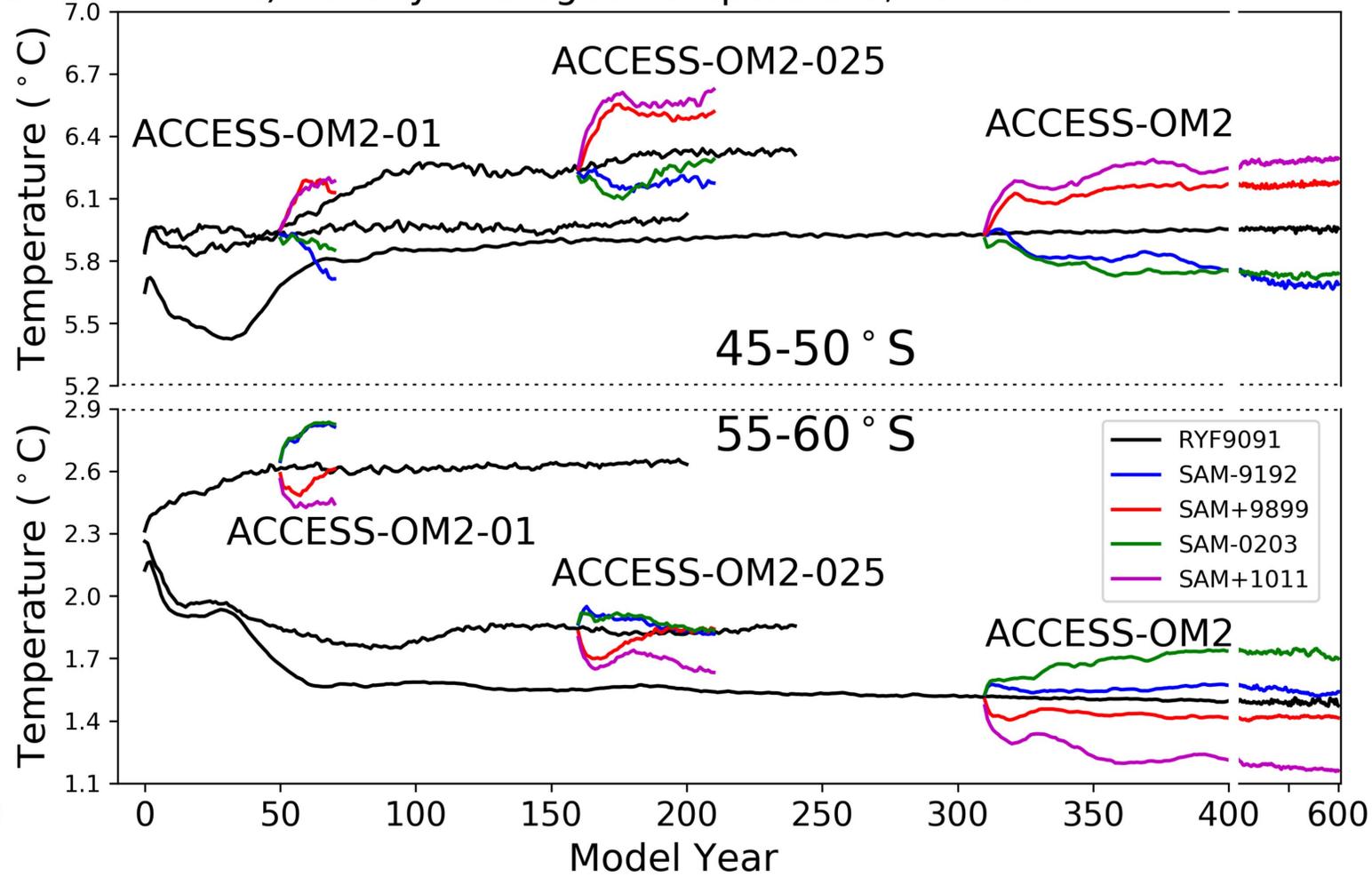


Figure 2.

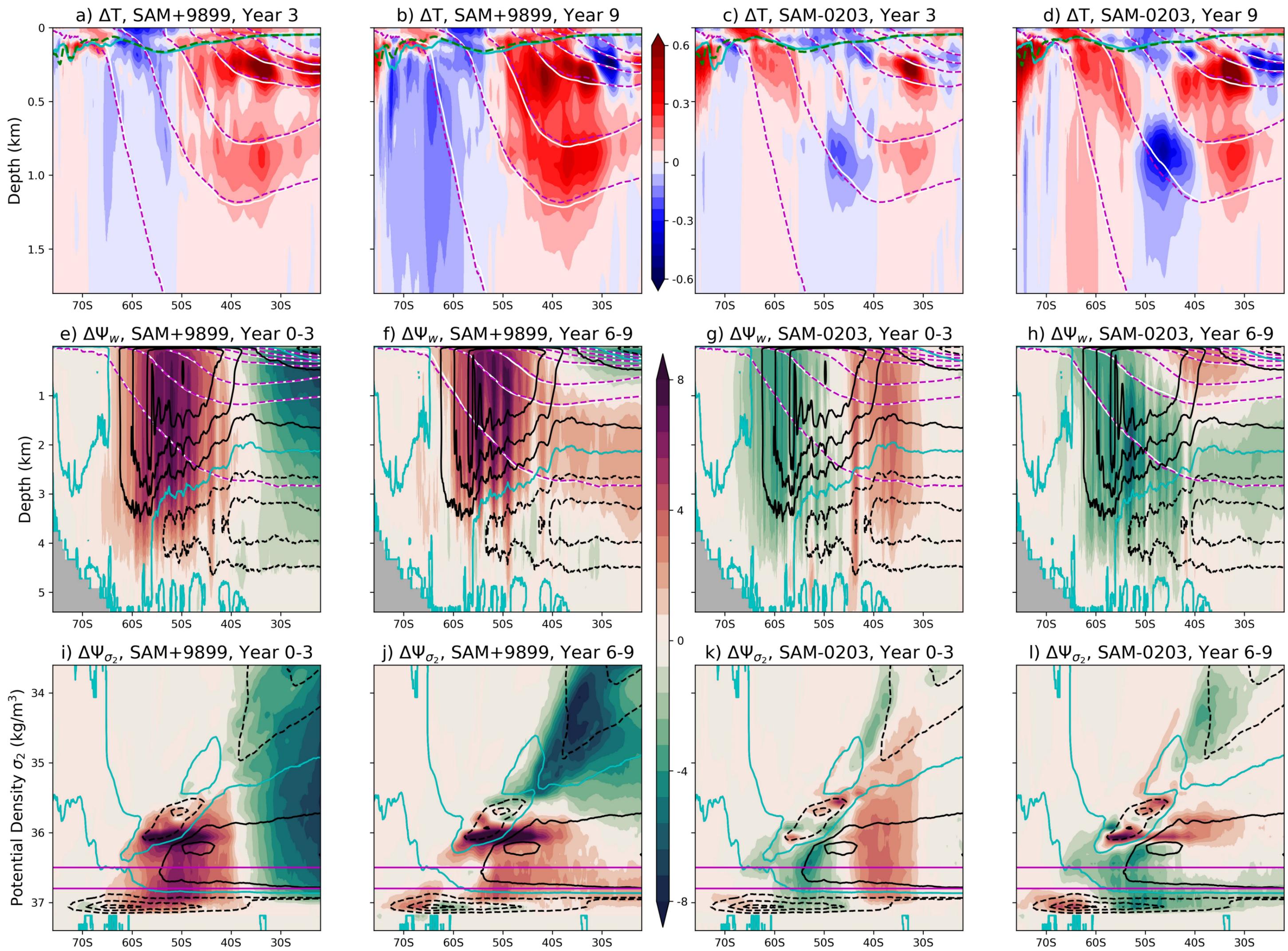


Figure 3.

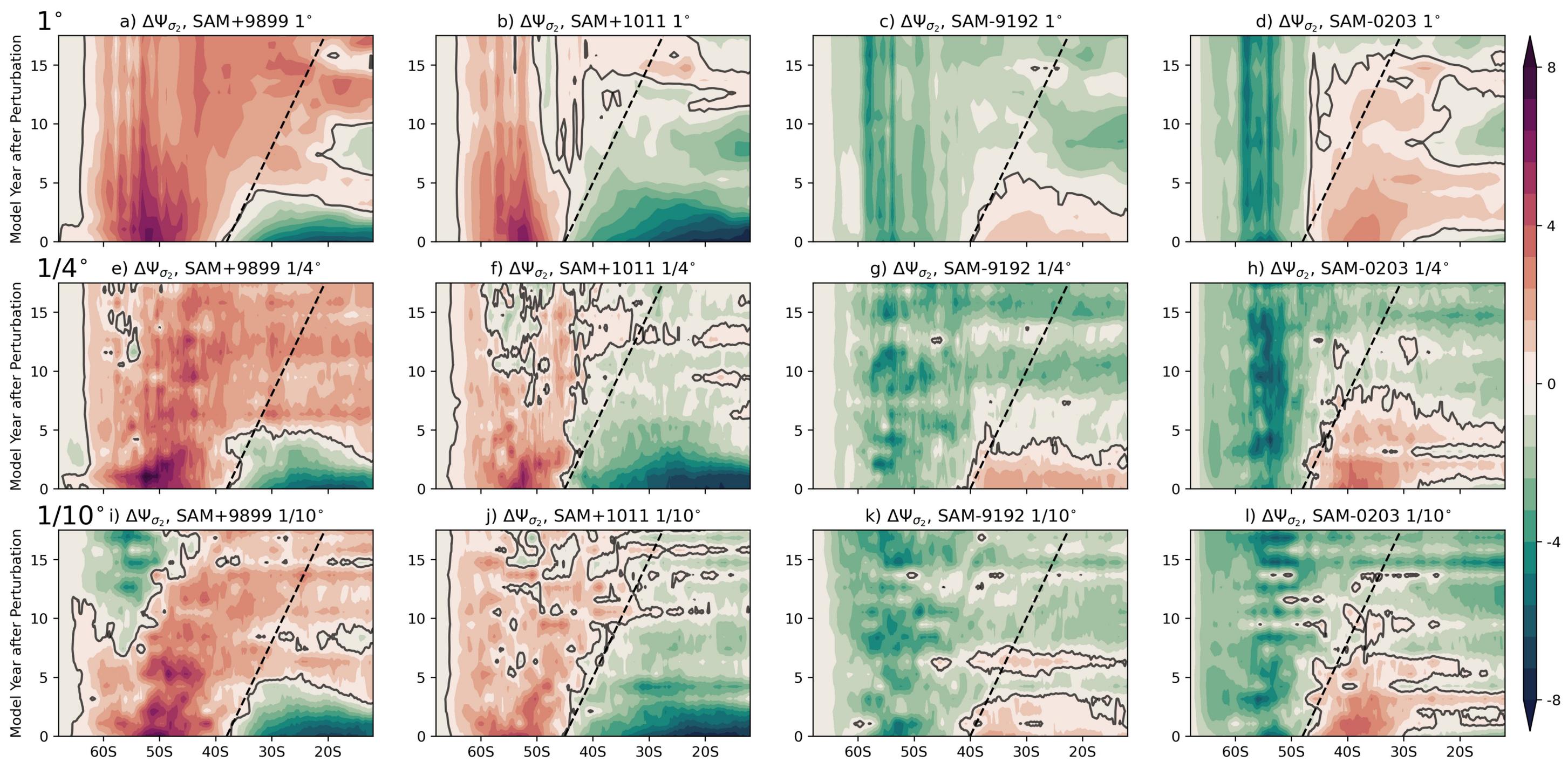
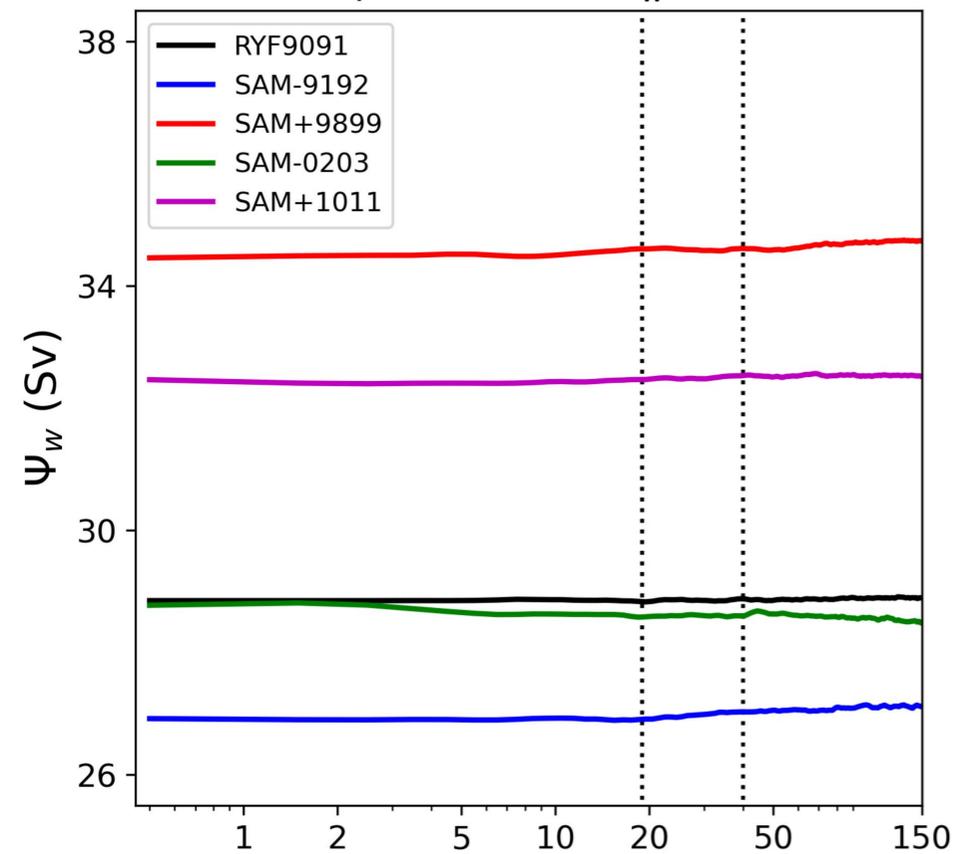
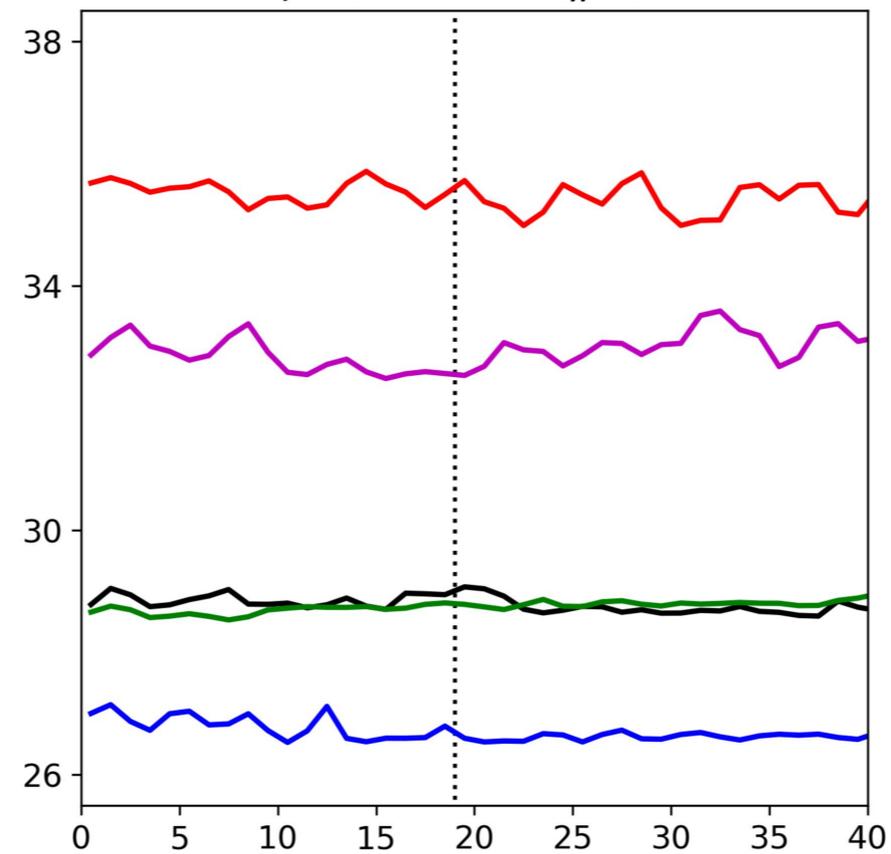
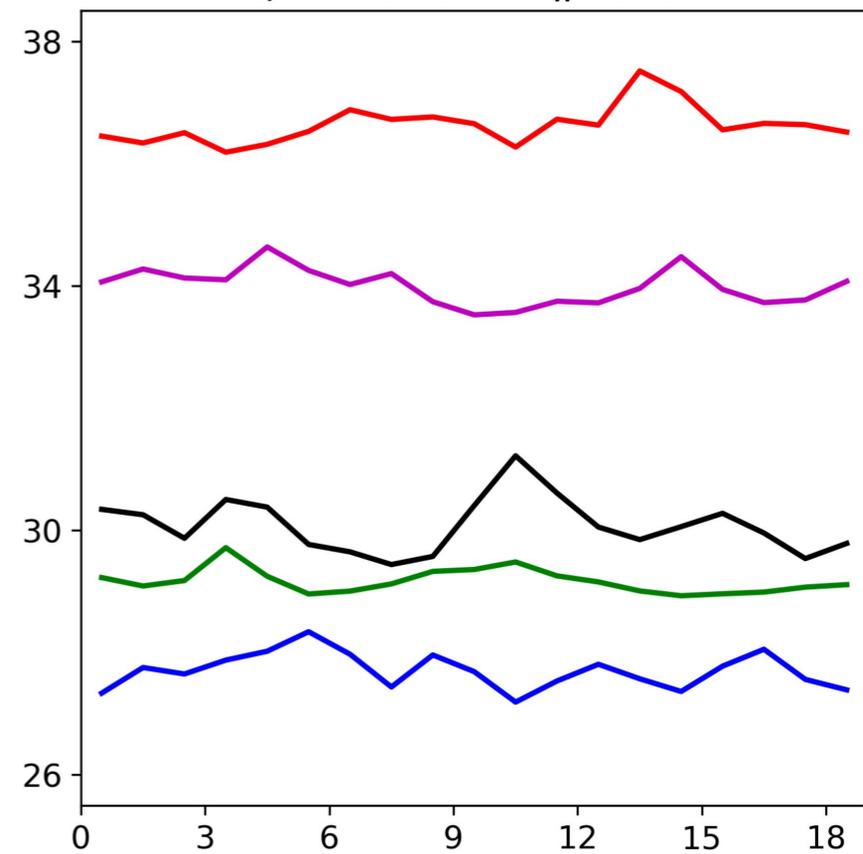
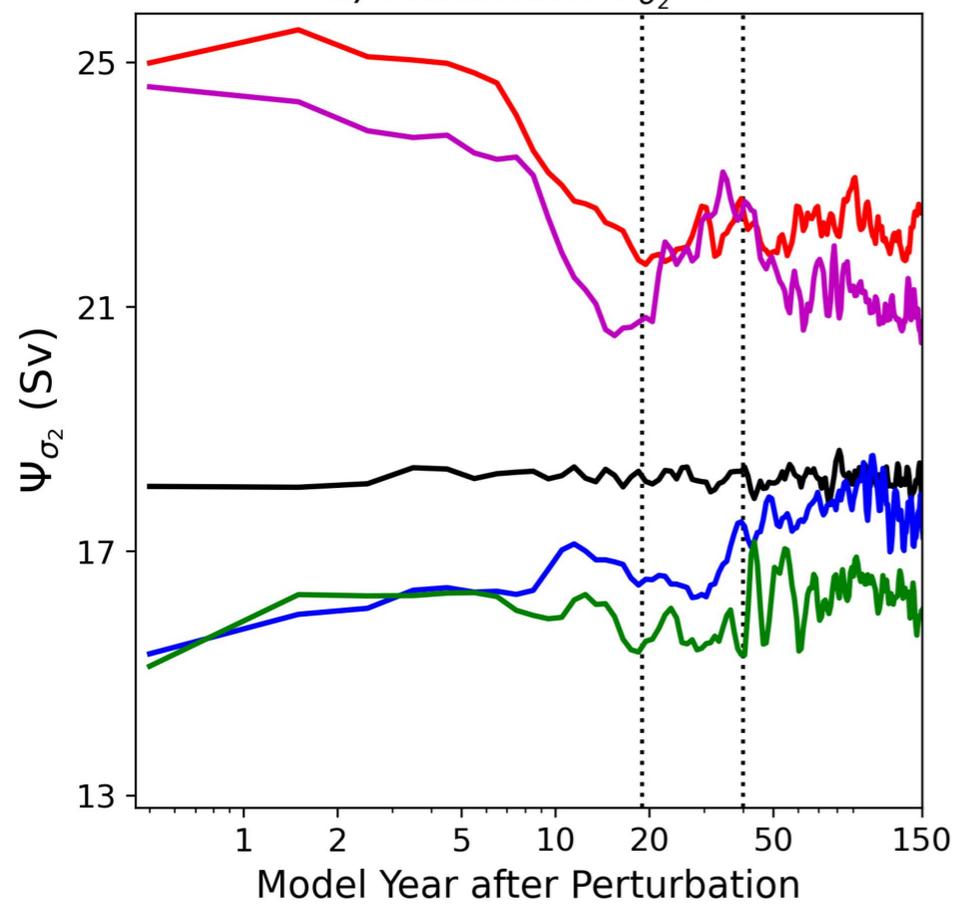
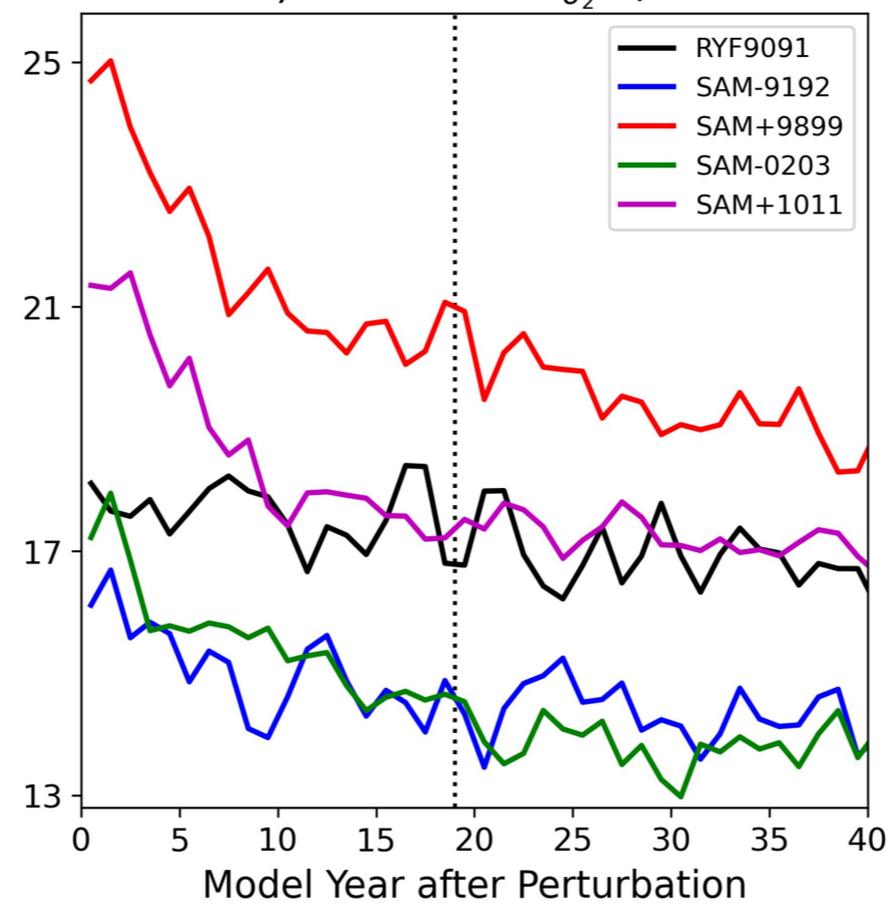
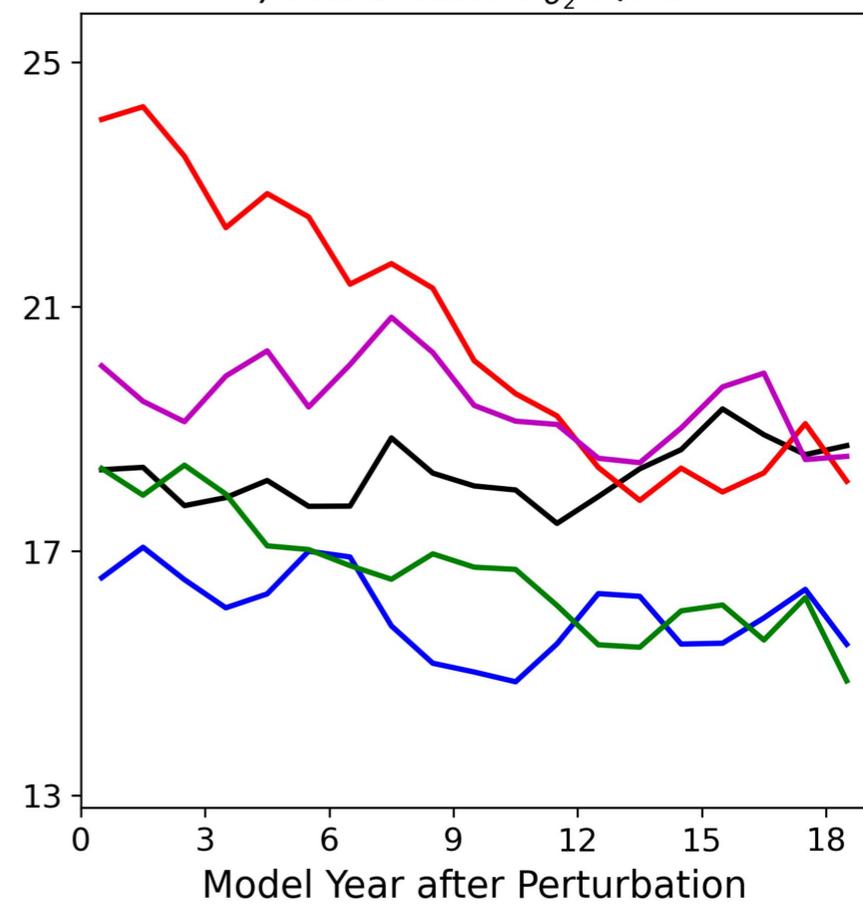


Figure 4.

a) Maximum Ψ_w 1° b) Maximum Ψ_w $1/4^\circ$ c) Maximum Ψ_w $1/10^\circ$ d) Maximum Ψ_{σ_2} 1° e) Maximum Ψ_{σ_2} $1/4^\circ$ f) Maximum Ψ_{σ_2} $1/10^\circ$ 

1 **Response of the Southern Ocean overturning**
2 **circulation to extreme Southern Annular Mode**
3 **conditions**

4 **K.D. Stewart^{1,2}, A.McC. Hogg^{1,3}, M.H. England^{2,3}, and D.W. Waugh^{4,5}**

5 ¹Research School of Earth Sciences, Australian National University, Canberra, Australia

6 ²Climate Change Research Centre, University of New South Wales, Sydney, Australia

7 ³Australian Research Council Centre of Excellence for Climate Extremes

8 ⁴Department of Earth and Planetary Sciences, The Johns Hopkins University, Baltimore, USA

9 ⁵School of Mathematics and Statistics, University of New South Wales, Sydney, Australia

10 **Key Points:**

- 11 • New methodology to examine the Southern Ocean response to climate extremes
12 using perturbation simulations with realistic atmospheric forcing
13 • Southern Ocean overturning circulation exhibits a rapid response that is sustained
14 in depth-latitude space, but decays in density-latitude space
15 • Adjustment of the ocean interior occurs along isopycnals at a rate of order 1° lat-
16 itude per year, depending of the representation of eddies

Corresponding author: K.D. Stewart, kial.stewart@anu.edu.au

Abstract

The positive trend of the Southern Annular Mode (SAM) will impact the Southern Ocean's role in Earth's climate, however the details of the Southern Ocean's response remain uncertain. We introduce a methodology to examine the influence of SAM on the Southern Ocean, and apply this method to a global ocean–sea-ice model run at three resolutions (1° , $1/4^\circ$ and $1/10^\circ$). Our methodology drives perturbation simulations with realistic atmospheric forcing of extreme SAM conditions. The thermal response agrees with previous studies; positive SAM perturbations warm the upper ocean north of the windspeed maximum and cool it to the south, with the opposite response for negative SAM. The overturning circulation exhibits a rapid response that increases/decreases for positive/negative SAM perturbations and is insensitive to model resolution. The longer term adjustment of the overturning circulation, however, depends on the representation of eddies, and is faster at higher resolutions.

Plain Language Summary

The Southern Ocean has accounted for the vast majority of the global ocean heat uptake since the early 2000s. The atmospheric winds over the Southern Ocean play a leading role in its ability to uptake heat, by way of driving much of the Southern Ocean circulation. Observations of these winds indicate that they have been steadily changing over the past few decades, and hence, so too is the Southern Ocean heat uptake. However, despite recent research efforts, the details of the Southern Ocean's response to these changing winds remain uncertain. Here we introduce a novel methodology to examine the Southern Ocean's response to changing winds. We perform numerical simulations with a global ocean–sea-ice model suite that spans a hierarchy of spatial resolutions and driven by realistic atmospheric forcing conditions. The initial response of the Southern Ocean circulation to changes in winds is robust across the model suite and insensitive to model resolution; longer-term response, however, depends on the representation of eddies in the model.

1 Introduction

The Southern Ocean has accounted for between 67%–98% of the total ocean heat uptake since 2005 (Roemmich et al., 2015; Llovel & Terray, 2016). This Southern Ocean heat uptake, which is predominantly in the upper 2 km, results from the intricate interplay between surface fluxes of heat and momentum, ocean circulation, and the associated redistribution of existing oceanic heat reservoirs (Frölicher et al., 2015; J. Marshall et al., 2015; Armour et al., 2016). Southern Hemisphere winds play a leading role in these proposed mechanisms of Southern Ocean heat uptake. It follows that Southern Ocean heat uptake, and thus global ocean warming, will be sensitive to processes that govern Southern Hemisphere winds.

The Southern Annular Mode (SAM) is the primary mode of climate variability in the extratropical Southern Hemisphere (Thompson & Wallace, 2000; Thompson et al., 2000). The SAM dynamically influences the strength and latitudinal location of the Southern Hemisphere midlatitude westerly winds. Following Gong and Wang (1999), the SAM can be characterised by a SAM index based on the normalized monthly zonal mean sea level pressure difference between 40°S and 65°S . Observations indicate there has been a positive trend in the SAM index since the 1950s (Thompson & Solomon, 2002; G. Marshall, 2003), which is projected to continue due to anthropogenic forcing (Zheng et al., 2013). It is anticipated that this trend in the SAM index, and the associated trends in the strength and position of the Southern Hemisphere midlatitude westerly winds, will influence Southern Ocean warming (e.g., Armour et al., 2016).

65 Examining the influence of the SAM on the Southern Ocean often employs regres-
 66 sion and/or correlation analysis techniques, instantaneous or time-lagged, to ascribe changes
 67 in the ocean state with the value of the SAM index. This approach is particularly use-
 68 ful for studies that use satellite- or Argo-based observations, coupled climate model out-
 69 put, or reanalysis products (e.g. Lovenduski & Gruber, 2005; Kosempa & Chambers, 2014;
 70 Sen Gupta & England, 2006; Hazel & Stewart, 2019). Another approach is to examine
 71 composites of ocean states based on SAM index thresholds to average out signals that
 72 are not SAM-related (e.g., Sall e et al., 2010; Li et al., 2019). Such methodologies are
 73 convenient since the independent variable (the SAM index) is unable to be controlled
 74 in these datasets; however, the transient response of the system may act to obscure cor-
 75 relations. These approaches demonstrate that of all the atmospheric variability associ-
 76 ated with the SAM, the Southern Ocean is most sensitive to the SAM-related changes
 77 in wind forcing (e.g., Sen Gupta & England, 2006).

78 An alternative approach to understand the influence of SAM in the Southern Ocean
 79 uses perturbation simulations. Given that the Southern Ocean is most sensitive to the
 80 wind changes associated with SAM, these simulations typically consist of an extended
 81 duration control run driven by repeating year forcing, from which perturbation runs are
 82 branched. These perturbation simulations have some idealised modification of their wind
 83 forcing fields stylised on the SAM associated strengthening and/or poleward shifting of
 84 the Southern Hemisphere midlatitude westerly winds (e.g., Farneti et al., 2010; Gent &
 85 Danabasoglu, 2011; Hofmann & Morales-Maqueda, 2011; Spence et al., 2014; Waugh et
 86 al., 2019). Note that the focus of these SAM-influenced perturbation studies has been
 87 to understand the response of the Southern Ocean to the observed positive trend in the
 88 SAM, and as such they generally do not impose forcing anomalies representative of neg-
 89 ative SAM conditions. Nevertheless, this approach has the advantage, and disadvantage,
 90 that the idealised wind anomalies can be manipulated in time, space, structure and mag-
 91 nitude, such that the permutations of the anomaly configuration are without limit. Given
 92 the multitude of anomaly permutations, a sensible approach is to keep the anomaly con-
 93 figuration as simple as possible, which begs the question: is the Southern Ocean response
 94 fundamentally different if *any* complexity is added to the anomaly? Another important
 95 consideration for such experiments is that the idealised wind anomalies are typically ap-
 96 plied without regard to other aspects of the climate that then become physically incon-
 97 sistent. For instance, a real poleward shifting of the wind field would be accompanied
 98 by a shift of the storm tracks, as well as the cloud cover and air temperatures; these forc-
 99 ing fields typically remain unmodified in the perturbation simulations.

100 Here we introduce a new methodology to simulate and examine the influence of SAM
 101 on the Southern Ocean in a global ocean–sea-ice model that uses realistic, reanalysis-
 102 based, repeating year atmospheric forcing to drive both control and SAM perturbation
 103 simulations. For the control forcing, the repeating year is a period of climatologically-
 104 neutral conditions; for the perturbations, the repeating years are periods of both extreme
 105 positive and extreme negative SAM conditions. While this approach brings an increased
 106 level of complexity to the dynamical structure of the perturbation, it greatly reduces the
 107 subjectivity of the perturbation configuration, and maintains the physical consistency
 108 of its forcing fields. This methodology is described in §2, and the thermal response of
 109 the Southern Ocean to the extreme SAM forcing conditions is presented in §3. We then
 110 compare the response of the Southern Ocean overturning circulation to the extreme SAM
 111 forcing conditions, examining the overturning in both depth-latitude and density-latitude
 112 coordinates (§4). Finally §5 covers the summary of our results and conclusions.

113 2 Model & Methodology

114 We employ the Australian Community Climate and Earth System Simulator, ocean–
 115 sea-ice model version 2 (ACCESS-OM2; Kiss et al., 2020), a modelling suite developed
 116 by the Consortium for Ocean–Sea-Ice Modelling in Australia (COSIMA), to simulate the

117 global ocean–sea-ice response to changes in imposed atmospheric conditions. This suite
 118 includes global ocean–sea-ice model configurations with horizontal grid spacings of nom-
 119 inally 1° (ACCESS-OM2), 0.25° (ACCESS-OM2-025) and 0.1° (ACCESS-OM2-01) lat-
 120 itude and longitude; here we use all three configurations. Following Stewart et al. (2017),
 121 the grid spacings of the generalized z^* vertical coordinate of the ocean models are objectively-
 122 constructed to support the vertical structure of the baroclinic dynamics permitted by
 123 the horizontal grids. The two coarser configurations implement the Gent and McWilliams
 124 (1990) (GM) parameterisation to represent under-resolved mesoscale eddies with an as-
 125 sociated diffusivity that is flow-dependent (see Griffies et al., 2005) and scaled by the abil-
 126 ity of the horizontal grid to resolve the first baroclinic Rossby radius (as per Hallberg,
 127 2013), and the Redi (1982) parameterisation for along-isopycnal diffusion with a coef-
 128 ficient of $600 \text{ m}^2/\text{s}$ for ACCESS-OM2 and up to $200 \text{ m}^2/\text{s}$ for ACCESS-OM2-025 (scaled
 129 by the local grid resolution and Rossby radius). For further details and evaluation of the
 130 ACCESS-OM2 suite see Kiss et al. (2020).

131 The ACCESS-OM2 simulations are initialised with January temperature and salin-
 132 ity fields from the World Ocean Atlas 2013 (WOA13; Locarnini et al., 2013; Zweng et
 133 al., 2013). The simulations are forced with prescribed atmospheric conditions taken from
 134 the high-resolution, self-consistent Japanese atmospheric reanalysis dataset for driving
 135 ocean models (JRA55-do; Tsujino et al., 2018). These prescribed atmospheric conditions,
 136 described in detail by Stewart et al. (2020), are the 12-month period from 1st May 1990
 137 to 30th April 1991 used repeatedly to drive the simulations. In practice, the forcing runs
 138 from 1st January 1991 to 31st December 1990 with a sudden transition from 30th April
 139 1991 back to 1st May 1990; shifting the sudden transition away from the December sol-
 140 stice reduces the intensity of weather variability at the time of transition. This repeated
 141 year forcing period, referred to as RYF9091, has been identified as a quasi-climatological
 142 period of the JRA55-do dataset with neutral values of all major climate indices, includ-
 143 ing the SAM index (see Fig. 1a). These RYF9091 simulations have two primary purposes;
 144 they provide for an extended period of model adjustment from the WOA13 state over
 145 which the model drift can be assessed, and they serve as control simulations from which
 146 perturbation simulations can be branched and compared.

147 A further four forcing periods are identified from the JRA55-do record; these are
 148 12-month periods, running 1st May to 30th April of the following year, with anomalous
 149 (positive and negative) Southern Annular Mode conditions, collectively referred to as SAMx
 150 periods. The extreme negative SAMx periods (SAM- years) are 1991–1992 and 2002–
 151 2003, and the extreme positive SAMx periods (SAM+ years) are 1998–1999 and 2010–
 152 2011 (Fig. 1a); these periods are referred to as SAM-9192, SAM-0203, SAM+9899 and
 153 SAM+1011, respectively, and are used to drive perturbation simulations branched from
 154 the RYF9091 control simulations. The annual averages of the zonally-averaged zonal winds
 155 of the SAMx periods are shown in Figure 1b; the relationship between the SAM index
 156 and the wind speed strength and latitudinal distribution is evident, as well as the de-
 157 gree to which our identified SAMx periods are extreme. For reference, the relative dif-
 158 ferences in the zonally-averaged zonal winds between the SAMx and RYF9091 periods
 159 are distinct for the SAM+ and SAM- cases, and reach +30% for the SAM+ and -15%
 160 for the SAM- periods. While these large changes in the wind fields dominate the atmo-
 161 spheric signature of extreme SAM periods, our technique has the advantage that syn-
 162 chronous changes in other fields (including the buoyancy forcing) are naturally included.
 163 Additionally, the respective increase or decrease of the wind speed maxima for a given
 164 SAMx forcing period is mirrored northwards of $\sim 45^\circ\text{S}$, such that, for instance, the zonal
 165 wind speed of the SAM+ periods is less than the JRA55-do climatological mean; this
 166 is a forcing feature that is typically not included in experiments with idealised wind per-
 167 turbations (e.g., Spence et al., 2014).

168 The RYF9091 control simulations are initialised from rest with the WOA13 hydrog-
 169 raphy and run for 600, 240 and 200 years for the 1° , 0.25° and 0.1° model configurations,

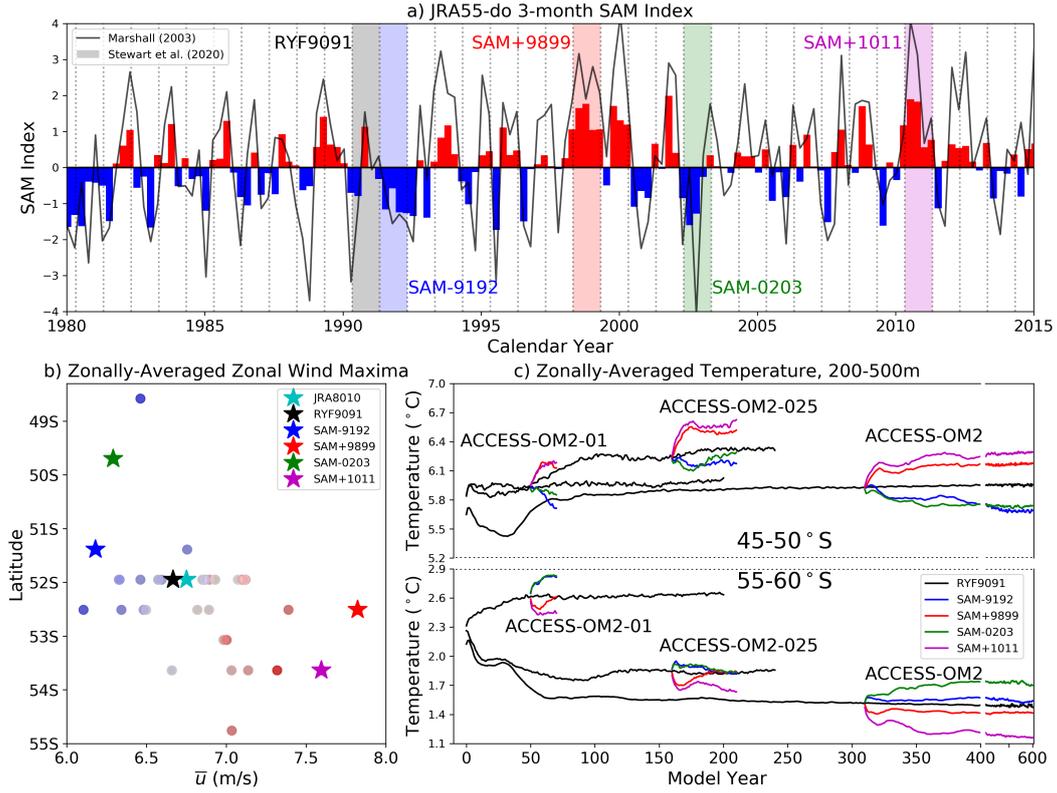


Figure 1. a) Three-monthly SAM index calculated from the JRA55-do dataset. The RYF9091 and four SAMx periods are shaded. For comparison, the equivalent observational station-based SAM index of G. Marshall (2003) is included in black. b) The zonally-averaged zonal wind maximum speed and latitudinal locations for the RYF9091 and SAMx periods. Also included is the 1980–2010 average of the JRA55-do dataset (JRA8010; cyan star) as a climatological reference, and all remaining May–April periods between 1980–2015 coloured blue–red by their respective SAM index (dots). c) Timeseries of the simulated zonally-averaged temperatures between 200–500m depth for 45–50°S (upper) and 55–60°S (lower); these latitudinal bands are selected to lie either side of the zonal wind speed maxima.

170 respectively. Following an initial adjustment period (310, 160 and 50 years for the 1°,
 171 0.25° and 0.1° model configurations, respectively; Fig. 1c), simulations with the SAMx
 172 forcing conditions are branched off and run alongside the control simulations for 290, 50
 173 and 20 years for the 1°, 0.25° and 0.1° model configurations, respectively. This method-
 174 ology allows for the direct comparison of the perturbation–control differences across the
 175 suite of model configurations. Whilst the primary focus of the analysis here is the re-
 176 sponse of the Southern Ocean overturning circulation, to begin with we briefly exam-
 177 ine the zonally-averaged thermal responses.

178 3 Thermal Response

179 The initial response of the upper Southern Ocean temperature to the sudden change
 180 in forcing is consistent with previous studies (e.g., Gent & Danabasoglu, 2011); north
 181 of the zonal wind speed maximum the upper ocean temperatures increase for SAM+ per-
 182 turbations (and decreases for SAM- perturbations) by approximately 0.2°C within 5 years,

183 with the opposite response occurring south of the zonal wind speed maximum (Fig. 1c).
 184 The magnitude and timescale of these initial responses are distinct from the gradual tem-
 185 perature changes arising from model drift, and insensitive to model resolution. Follow-
 186 ing an initial adjustment period, these thermal responses are either sustained for the du-
 187 ration of the perturbation simulations, or trend back towards the respective RYF9091
 188 simulation; importantly, they do not continue to grow with time.

189 Figure 2(a-d) depicts the depth-latitude distributions of the zonally-averaged tem-
 190 perature anomalies for the (a,b) SAM+9899 and (c,d) SAM-0203 forced ACCESS-OM2-
 191 01 simulations, averaged for the (a,c) third and (b,d) ninth years after the perturbation.
 192 The SAM+9899 perturbation exhibits thermal anomaly distributions that are consistent
 193 with the south–north cooling–warming response straddling the wind speed maximum pre-
 194 viously described by Sen Gupta and England (2006). The thermal response of the SAM-
 195 0203 perturbation exhibits relatively more structure, but of reduced intensity compared
 196 to the SAM+9899 response. Equivalent temperature anomaly distributions for the SAM+1011
 197 and SAM-9192 simulations are presented in Figure S1; the comparison of these figures
 198 highlights the consistent thermal response of the respective SAM+ and SAM- cases, par-
 199 ticularly south of 30°S for SAM+ and 40°S for SAM-. All cases exhibit local extrema
 200 in the thermal responses at around 800–900 m depth; for SAM+ this occurs between 35–
 201 45°S, and for SAM- between 40–50°S. Comparing the thermal anomaly distributions for
 202 the Year 3 and Year 9 responses shows that, whilst the thermal responses intensify in
 203 time, they retain their initial structure.

204 The zonally-averaged temperature anomalies are comprised of a combination of pro-
 205 cesses which include the wind-driven movement of isopycnals, defined as “heave” by Bindoff
 206 and McDougall (1994), and the change of temperature on isopycnals due to changes of
 207 along isopycnal transport and stirring. In the figures of zonally-averaged temperature
 208 anomaly, heave is evidenced by the spatial correlation between the vertical displacement
 209 of isopycnals and the sign of the thermal anomalies. The diagnosed contributions from
 210 heave and the change of temperature on isopycnals for the SAM+9899 and SAM-0203
 211 cases at all three model resolutions are shown in Figure S2. The contribution from heave
 212 is insensitive to model resolution, which is perhaps to be expected as to leading order
 213 heave is a wind-driven process. Heave is strongest north of 50°S and accounts for the
 214 local extrema in the thermal responses around 800–900 m depth. The contribution from
 215 temperature changes on isopycnals, however, is surface intensified, strongest south of 50°S,
 216 and resolution-dependent; this distribution makes sense considering the important role
 217 that eddies play in along isopycnal stirring and transport. Timeseries of these contribu-
 218 tions to the thermal anomalies north and south of the wind speed maxima show the longer-
 219 term thermal responses (Fig. S3); importantly, the SAM+ and SAM- perturbations are
 220 distinct in all cases. South of the wind speed maxima, the change of temperature on isopy-
 221 cnals dominates over the heave-associated response and strengthens with refined model
 222 resolution. North of the wind speed maxima, however, the heave and isopycnal temper-
 223 ature changes have contributions of similar magnitude and appears insensitive to model
 224 resolution.

225 4 Overturning Circulation Response

226 Considering the rapid timescale of thermal adjustment, the initial dominance of
 227 heave, and the structure of the thermal anomalies relative to the wind speed maxima,
 228 the thermal response indicates a wind-driven modification of the Southern Ocean over-
 229 turning circulation. To examine the response of the overturning circulation, we evalu-
 230 ate and compare two overturning streamfunctions independently diagnosed from the sim-
 231 ulations. Following Zika et al. (2012), the first streamfunction Ψ_w (m^2/s) is derived by
 232 integrating the vertical velocity in longitude and northward from the Antarctic coast-

233 line up a given latitude y , that is,

$$\Psi_w(y, z, t) = \int_{90^\circ S}^y \int w(x, y', z, t) dx dy', \quad (1)$$

234 where w is the annually-averaged vertical velocity, giving Ψ_w in depth-latitude-time co-
 235 ordinates. Taking σ_2 as the potential density of seawater referenced to 2000 dbar less 1000 kg/m^3 ,
 236 a second overturning streamfunction Ψ_{σ_2} (m^2/s) can be diagnosed by integrating the along-
 237 isopycnal meridional velocity in longitude and from the densest isopycnal class ($\sigma_2 >$
 238 38) to a given isopycnal σ_2 , as,

$$\Psi_{\sigma_2}(y, \sigma_2, t) = \int_{38}^{\sigma_2} \int v_{\sigma_2}(x, y, \sigma'_2, t) dx d\sigma'_2, \quad (2)$$

239 where v_{σ_2} is the along-isopycnal meridional velocity, returning Ψ_{σ_2} in density-latitude-
 240 time coordinates. We refer to these two overturning streamfunctions as the w -streamfunction
 241 and σ_2 -streamfunction, respectively.

242 The depth-latitude distributions of $\Delta\Psi_w$ for the ACCESS-OM2-01 cases of SAM+9899
 243 and SAM-0203 are shown in Figure 2e-h; these are 3-year averages for the Years 0-3 (e,g)
 244 and 6-9 (f,h). The initial responses of $\Delta\Psi_w$ are seemingly depth-independent above $\sim 3000 \text{ m}$.
 245 In time, the w -streamfunction anomalies equatorward of $40\text{-}45^\circ\text{S}$ develops vertical struc-
 246 ture that appears to propagate along isopycnals; note that the Ψ_w anomalies poleward
 247 of $40\text{-}45^\circ\text{S}$ maintain their initial structure and intensity. For the SAM+ cases, the struc-
 248 ture, magnitude and evolution of the Ψ_w response is similar to that of the high-resolution
 249 simulations reported in previous studies (e.g., Farneti & Delworth, 2010), however we
 250 do not find the Ψ_w response to be resolution dependent. Given the implementation of
 251 a variable, flow-dependent GM diffusivity in the ACCESS-OM2 simulations at coarser
 252 resolutions, this insensitivity of the Southern Ocean response to the model resolution is
 253 indeed to be expected (Gent, 2016).

254 The interior structure of the time-evolution of these overturning circulation responses
 255 is more apparent in the σ_2 -streamfunction anomalies (Fig. 2i-l). The Year 0-3 $\Delta\Psi_{\sigma_2}$ anom-
 256 alies depend primarily on latitude for densities greater than $\sim 35.5 \text{ kg/m}^3$. By Year 6-9 these
 257 anomalies have become more dependent on density and less dependent on latitude. The
 258 structure of the longer-term distributions of $\Delta\Psi_{\sigma_2}$, especially south of 40°S , tends to align
 259 with isopycnals and appears to propagate northwards.

260 The progression of the Ψ_{σ_2} anomalies into the interior along isopycnal pathways
 261 can be seen in time-latitude Hovmöller diagrams, for which we use the mean of the σ_2
 262 range $36.5\text{-}36.8 \text{ kg/m}^3$ (Fig. 3). The initial responses of all perturbations are insensitive
 263 to the model resolutions used here, and are characterised by regions of opposite signed
 264 signals either side of $\sim 40\text{-}45^\circ\text{S}$. In time, the equatorward signal diminishes, and in the
 265 cases of SAM+9899 and SAM-9192, vanishes within 5-8 years. For the SAM+ simula-
 266 tions with ACCESS-OM2-01, the boundary separating the opposite signed signals is ob-
 267 served to propagate equatorward at a rate of order 1° of latitude per year (dashed black
 268 lines in Fig. 3). For reference, this rate of propagation corresponds to an along-isopycnal
 269 diffusion with a coefficient of $390 \text{ m}^2/\text{s}$. The latitudinal progression of this signal rep-
 270 represents the adiabatic, along-isopycnal propagation of a wind-forcing perturbation into
 271 the ocean interior (e.g., Doddridge et al., 2016). That is, the perturbation of the wind
 272 field initially excites an Eulerian response that is largely barotropic in nature and with
 273 the same latitudinal structure as the wind perturbation (Fig. 2e,g); in time, this initial
 274 Eulerian response penetrates equatorward into the ocean interior, predominantly adi-
 275 abatically along isopycnals, a process that is likely dependent on eddies (parameterised
 276 or resolved), and hence model resolution. This demonstration of the initial and time-evolving
 277 adjustments reflects the multiple timescale responses that can arise from a changes in
 278 atmospheric forcing over the Southern Ocean (e.g., Armour et al., 2016; Waugh & Haine,
 279 2020).

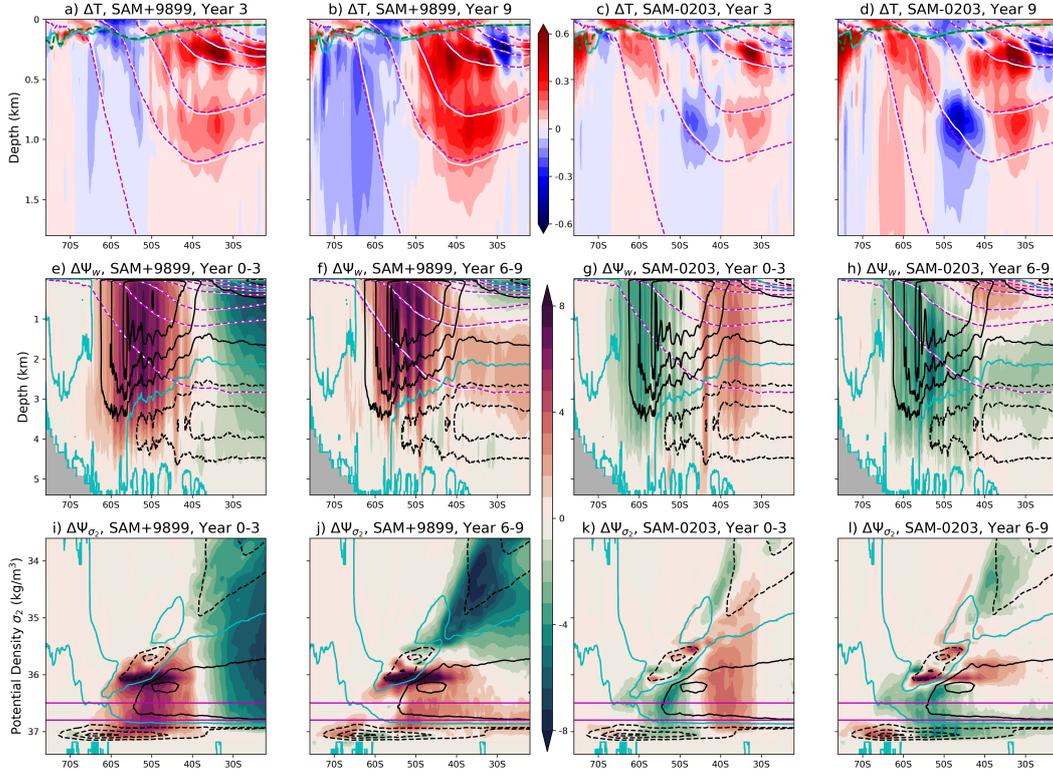


Figure 2. a-d) Distributions of the Year 3 (a,c) & 9 (b,d) temperature anomalies from the 0.1° ACCESS-OM2-01 for (a,b) SAM+9899 and (c,d) SAM-0203 simulations. The white and dashed magenta contours represent the SAMx and RYF9091 isopycnals at $\sigma_2 = 0.5 \text{ kg/m}^3$ intervals, respectively, spanning $\sigma_2 = 34\text{--}37 \text{ kg/m}^3$ inclusive, with the cyan and dashed green contours representing the respective mixed-layer depths. e-h) The w -streamfunction anomalies of the ACCESS-OM2-01 simulations with SAM+9899 (e,f) and SAM-0203 (g,h) averaged for the years 0-3 (e,g) and 6-9 (f,h). Contoured in black is the Ψ_w for the RYF9091 case at $\pm 7.5 \text{ Sv}$ intervals with the 0 Sv contour in cyan. The white and dashed magenta contours represent the same isopycnals as in (a-d). Panels (i-l) depict a similar analysis to panels (e-h) but for the σ_2 -streamfunction anomalies. The magenta lines in (i-l) at 36.5 and 36.8 kg/m^3 indicate the regions of interest for Figure 3.

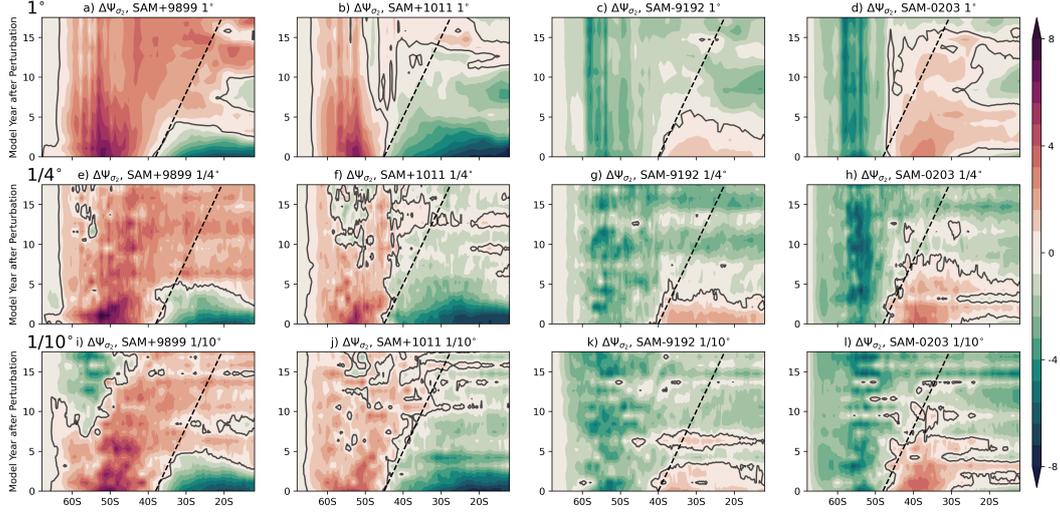


Figure 3. Hovmöller diagrams of the σ_2 -streamfunction anomalies for the SAM+9899, SAM+1011, SAM-9192 and SAM-0203 cases (columns 1-4, respectively) and the 1° , $1/4^\circ$ and $1/10^\circ$ simulations (rows top-to-bottom, respectively). The $\Delta\Psi_{\sigma_2}$ is calculated as the $36.5\text{--}36.8\text{kg/m}^3$ average, as indicated in Figure 2i-l. The $\Delta\Psi_{\sigma_2} = 0\text{ Sv}$ contour is included for reference, as well as the dashed slope which represents an along-isopycnal velocity of 1° latitude per year.

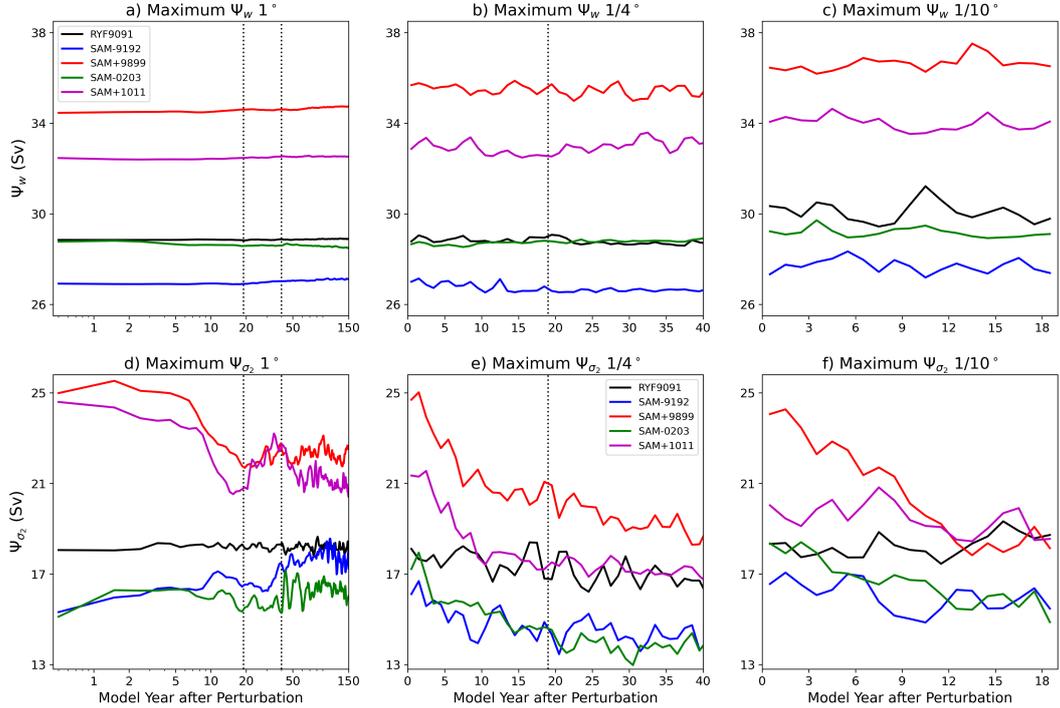


Figure 4. Timeseries of the maximum 24-month mean Ψ_w (a-c), Ψ_{σ_2} (d-f). Note the different time axes for different resolutions (columns); the vertical dotted lines in the ACCESS-OM2 and ACCESS-OM2-025 plots indicate the extent of the timeseries of the higher resolution panels.

280 An additional measure of the Southern Ocean overturning circulation response can
 281 be found by comparing the 24-month mean maxima of Ψ_w and Ψ_{σ_2} for the region of inter-
 282 est (south of 30°S). In the case of Ψ_w , the Southern Ocean maximum represents the
 283 strength of the “Deacon cell”, a localised wind-driven overturning of waters in Eulerian
 284 space with near-uniform properties such that it is unable to substantially contribute to
 285 the meridional transport of tracer (e.g., Zika et al., 2012). Figure 4a-c shows the South-
 286 ern Ocean maximum of Ψ_w increases for SAM+ and decreases for SAM- perturbations,
 287 and that this response does not evolve in time. This immediate and sustained response
 288 of the Ψ_w overturning streamfunction is consistent with the findings of Treguier et al.
 289 (2010), who report a high correlation ($r = 0.79$) between the Southern Ocean mean flow
 290 overturning and the SAM index in a global ocean–sea-ice simulation driven by atmospheric
 291 forcing with interannual variability.

292 The Southern Ocean maximum of Ψ_{σ_2} (Fig. 4d-f), however, initially exhibits a re-
 293 sponse that is of similar magnitude to the respective Ψ_w response, but is time depen-
 294 dent. The magnitude of the initial Ψ_{σ_2} maxima anomaly decreases as the model reso-
 295 lution is refined (compare the initial differences between the Ψ_{σ_2} maxima of SAMx and
 296 RYF9091 across the resolutions). For the SAM+ cases, the Ψ_{σ_2} maxima decays back to-
 297 wards the RYF9091 value with an adjustment timescale of approximately a decade for
 298 the 0.1° resolution case, and longer for the coarser resolutions. The Ψ_{σ_2} maxima of the
 299 SAM- cases are initially less than that of the RYF9091 and appear to continue decreas-
 300 ing for the first two decades; the longer, coarser resolution simulations suggest these Ψ_{σ_2}
 301 values stabilise for a couple of decades before returning towards the RYF9091 level. The
 302 initial response of the Ψ_{σ_2} is consistent with the results of Farneti et al. (2015), who found
 303 the correlation between the Southern Ocean upper cell overturning in density space and
 304 the SAM index of a multi-model ensemble to be high ($r = 0.67$), but not as high as that
 305 of Treguier et al. (2010) for the mean flow overturning. Farneti et al. (2015) also report
 306 that the Ψ_{σ_2} -SAM correlations of their various models are weaker for models with more
 307 responsive eddy fluxes ($r = 0.56$), and stronger for models with less responsive eddy fluxes
 308 ($r = 0.82$). In the context of our findings of the time-dependent Ψ_{σ_2} response, a stronger
 309 rate of decay, indicative of a weakening of the Ψ_{σ_2} -SAM correlation, can be interpreted
 310 as more responsive eddy fluxes, with the timescale of adjustment being set by the spin-
 311 up time of the eddy field. This interpretation is consistent with the increased initial Ψ_{σ_2}
 312 response for the coarser resolution simulations.

313 The results presented here demonstrate that the response of the Southern Ocean
 314 overturning circulation to sudden and extreme perturbations of SAM conditions is com-
 315 prised of;

- 316 • a rapid and sustained adjustment of the wind-driven Deacon cell, represented here
 317 as Ψ_w , that increases for SAM+ and decreases for SAM- perturbations, and is in-
 318 sensitive to model resolution; and
- 319 • an initial adjustment of the density-latitude overturning circulation, Ψ_{σ_2} , that is
 320 comparable to that of Ψ_w , but subsequently decays in time at a rate that depends
 321 on model resolution.

322 This analysis portrays the process by which the initial overturning response is ingested
 323 into the ocean interior; that is, adiabatically along isopycnals, which for the high reso-
 324 lutions simulations with SAM+ perturbations occurs at a rate of order 1° latitude per
 325 year.

326 5 Conclusion

327 We have presented a novel methodology for perturbing global ocean–sea-ice mod-
 328 els driven by prescribed atmospheric forcing. Here, this methodology employs periods
 329 of extreme SAM conditions identified in the JRA55-do dataset to branch perturbation

330 simulations from a control. By using periods of extreme yet realistic atmospheric con-
 331 ditions, as opposed to idealised modifications of control conditions, we maintain the phys-
 332 ical fidelity of the JRA55-do forcing across its fields. This approach provides confidence
 333 that the magnitude of the forcing perturbation is climatologically relevant, even if the
 334 timescale of the forcing perturbation is not. The focus here is on extreme SAM condi-
 335 tions, however, this methodology could be used to examine the ocean–sea-ice response
 336 to other major climate indices.

337 The analysis of the perturbation simulations demonstrates the utility of the new
 338 methodology for examining the response of the Southern Ocean to extreme SAM forc-
 339 ing conditions. The thermal response to the perturbed forcing, especially the contribu-
 340 tion from isopycnal heave, is insensitive to the model resolutions used here; the excep-
 341 tion to this is the change of temperature on isopycnals, which intensifies as model res-
 342 olution is refined, reflecting the important role of eddies in this process. The response
 343 of the Southern Ocean overturning circulation to extreme SAM conditions consists of
 344 a rapid and sustained adjustment of the wind-driven Deacon cell, and an initial adjust-
 345 ment of the density-latitude overturning circulation that decays in time. The overturn-
 346 ing circulation responses are found to project into the interior, propagating northward
 347 along isopycnals at a rate of order 1° of latitude per year. It is argued that the adjust-
 348 ment of the overturning in density-latitude coordinates represents the spin-up of the adi-
 349 abatic eddy field in response to the extreme SAM forcing conditions. Finally, consider-
 350 ing the continued strengthening trend of the SAM in the present-day climate, we can an-
 351 ticipate associated increases in the Southern Ocean overturning circulation in depth-latitude
 352 coordinates, and an ongoing adjustment of the overturning in density-latitude coordi-
 353 nates and Southern Ocean eddy field.

354 Acknowledgments

355 We acknowledge the support of this work from the Earth Systems and Climate Change
 356 Hub funded by the Australian Government’s National Environmental Science Program
 357 (NESP). Many thanks to Navid Constantinou, Ryan Holmes, Qian Li, Adele Morrison
 358 and Jan Zika for very helpful discussions, and to the COSIMA consortium (www.cosima.org.au)
 359 for making available the ACCESS-OM2 suite of models. We also thank Chris Chapman
 360 who proposed the idea of the repeating year extreme SAM perturbation experiments at
 361 the Australian Research Council Centre of Excellence for Climate Extremes 2018 SAM
 362 workshop. The numerical simulations and analysis were performed with the resources
 363 of the National Computational Infrastructure (Canberra, Australia). The ACCESS-OM2
 364 model output is in the process of being uploaded to the COSIMA Model Output Col-
 365 lection; when this process is complete the data will be available from [doi:10.4225/41/5a2dc8543105a](https://doi.org/10.4225/41/5a2dc8543105a).

366 References

- 367 Armour, K., Marshall, J., Scott, J., Donohoe, A., & Newsom, E. (2016). Southern
 368 Ocean warming delayed by circumpolar upwelling and equatorward transport.
 369 *Nature Geoscience*, *9*, 549–554. doi: 10.1038/NGEO2731
- 370 Bindoff, N., & McDougall, T. (1994). Diagnosing Climate Change and Ocean Venti-
 371 lation Using Hydrographic Data. *Journal of Physical Oceanography*, *24*, 1137–
 372 1152. doi: 10.1175/1520-0485(1994)024<1137:DCCA0V>2.0.CO;2
- 373 Doddridge, E., Marshall, D., & Hogg, A. (2016). Eddy Cancellation of the Ekman
 374 Cell in Subtropical Gyres. *Journal of Physical Oceanography*, *46*, 2995–3010.
 375 doi: 10.1175/JPO-D-16-0097.1
- 376 Farneti, R., & Delworth, T. (2010). The role of mesoscale eddies in the remote
 377 oceanic response to altered Southern Hemisphere winds. *Journal of Physical*
 378 *Oceanography*, *40*, 2348–2354. doi: 10.1175/2010JPO4480.1
- 379 Farneti, R., Delworth, T., Rosati, A., Griffies, S., & Zeng, F. (2010). The role

- 380 of mesoscale eddies in the rectification of the Southern Ocean response to
 381 climate change. *Journal of Physical Oceanography*, *40*, 1539–1557. doi:
 382 10.1175/2010JPO4353.1
- 383 Farneti, R., Downes, S., Griffies, S., Marsland, S., Behrens, E., Bentsen, M., ...
 384 Yeager, S. (2015). An assessment of Antarctic Circumpolar Current and
 385 Southern Ocean meridional overturning circulation during 1958–2007 in a
 386 suite of interannual CORE-II simulations. *Ocean Modelling*, *93*, 84–120. doi:
 387 10.1016/j.ocemod.2015.07.009
- 388 Frölicher, T., Sarmiento, J., Paynter, D., Dunne, J., Krasting, J., & Winton, M.
 389 (2015). Dominance of the Southern Ocean in anthropogenic carbon and
 390 heat uptake in CMIP5 models. *Journal of Climate*, *28*, 862–886. doi:
 391 10.1175/JCLI-D-14-00117.1
- 392 Gent, P. (2016). Effects of Southern Hemisphere Wind Changes on the Meridional
 393 Overturning Circulation in Ocean Models. *Annual Review of Marine Science*,
 394 *8*, 79–94. doi: 10.1146/annurev-marine-122414-033929
- 395 Gent, P., & Danabasoglu, G. (2011). Response to Increasing Southern Hemisphere
 396 Winds in CCSM4. *Journal of Climate*, *24*, 4992–4998. doi: 10.1175/JCLI-D-10
 397 -05011.1
- 398 Gent, P., & McWilliams, J. (1990). Isopycnal mixing in ocean circulation models.
 399 *Journal of Physical Oceanography*, *20*, 150–155. doi: 10.1175/1520-0485(1990)
 400 020<0150:IMIOCM>2.0.CO;2
- 401 Gong, D., & Wang, S. (1999). Definition of Antarctic Oscillation Index. *Geophysical*
 402 *Research Letters*, *26*, 459–462. doi: 10.1029/1999GL900003
- 403 Griffies, S., Gnanadesikan, A., Dixon, K., Dunne, J., Gerdes, R., Harrison, M., ...
 404 Zhang, R. (2005). Formulation of an ocean model for global climate simula-
 405 tions. *Ocean Science*, *1*, 45–79. doi: 10.5194/os-1-45-2005
- 406 Hallberg, R. (2013). Using a resolution function to regulate parameterizations of
 407 oceanic mesoscale eddy effects. *Ocean Modelling*, *72*, 92–103. doi: 10.1016/J
 408 .OCEMOD.2013.08.007.
- 409 Hazel, J., & Stewart, A. (2019). Are the Near-Antarctic Easterly Winds Weakening
 410 in Response to Enhancement of the Southern Annular Mode? *Journal of Cli-*
 411 *mate*, *32*, 1895–1918. doi: 10.1175/JCLI-D-18-0402.1
- 412 Hofmann, M., & Morales-Maqueda, M. (2011). The response of Southern Ocean
 413 eddies to increased midlatitude westerlies: A non-eddy resolving model study.
 414 *Geophysical Research Letters*, *38*, L03605. doi: 10.1029/2010GL045972
- 415 Kiss, A., Hogg, A., Hannah, N., Dias, F., Brassington, G., Chamberlain, M., ...
 416 Zhang, X. (2020). ACCESS-OM2: A Global Ocean–Sea-Ice Model at
 417 Three Resolutions. *Geoscientific Model Development*, *13*, 401–442. doi:
 418 10.5194/gmd-13-401-2020
- 419 Kosempa, M., & Chambers, D. (2014). Southern Ocean velocity and geostrophic
 420 transport fields estimated by combining Jason altimetry and Argo data.
 421 *Journal of Geophysical Research: Oceans*, *119*, 4761–4776. doi: 10.1002/
 422 2014JC009853
- 423 Li, Q., Lee, S., England, M., & McClean, J. (2019). Seasonal-to-Interannual Re-
 424 sponse of Southern Ocean Mixed Layer Depth to the Southern Annular Mode
 425 from a Global 1/10° Ocean Model. *Journal of Climate*, *32*, 6177–6195. doi:
 426 10.1175/JCLI-D-19-0159.1
- 427 Llovel, W., & Terray, L. (2016). Observed Southern Upper-Ocean Warming Over
 428 2005–2014 and Associated Mechanisms. *Environmental Research Letters*, *11*,
 429 124023. doi: 10.1088/1748-9326/11/12/124023
- 430 Locarnini, R., Mishonov, A., Antonov, J., Boyer, T., Garcia, H., Baranova, O., ...
 431 Seidov, D. (2013). World Ocean Atlas 2013, Volume 1: Temperature. *NOAA*
 432 *Atlas NESDIS*, *73*.
- 433 Lovenduski, N., & Gruber, N. (2005). Impact of the Southern Annular Mode on
 434 Southern Ocean circulation and biology. *Geophysical Research Letters*, *32*,

- 435 L11603. doi: 10.1029/2005GL022727
- 436 Marshall, G. (2003). Trends in the Southern Annular Mode from observations and
437 reanalyses. *Journal of Climate*, *16*, 4134–4143. doi: 10.1175/1520-0442(2003)
438 016<4134:TITSAM>2.0.CO;2
- 439 Marshall, J., Scott, J., Armour, K., Campin, J.-M., Kelley, M., & Romanou,
440 A. (2015). The ocean’s role in the transient response of climate to
441 abrupt greenhouse gas forcing. *Climate Dynamics*, *44*, 2287–2299. doi:
442 10.1007/s00382-014-2308-0
- 443 Redi, M. (1982). Oceanic Isopycnal Mixing by Coordinate Rotation. *Journal of*
444 *Physical Oceanography*, *12*, 1154–1158. doi: 10.1175/1520-0485(1982)012<1154:
445 OIMBCR>2.0.CO;2
- 446 Roemmich, D., Church, J., Gilson, J., Monselesan, D., Sutton, P., & Wijffels, S.
447 (2015). Unabated planetary warming and its ocean structure since 2006.
448 *Nature Climate Change*, *5*, 240–245. doi: 10.1038/nclimate2513
- 449 Sallée, J., Speer, K., & Rintoul, S. (2010). Zonally asymmetric response of the
450 Southern Ocean mixed-layer depth to the Southern Annular Mode. *Nature*
451 *Geoscience*, *3*, 273–279. doi: 10.1038/NGEO812
- 452 Sen Gupta, A., & England, M. (2006). Coupled Ocean–Atmosphere–Ice Response to
453 Variations in the Southern Annular Mode. *Journal of Climate*, *19*, 4457–4485.
454 doi: 10.1175/JCLI3843.1
- 455 Spence, P., Griffies, S., England, M., Hogg, A., Saenko, O., & Jourdain, N. (2014).
456 Rapid subsurface warming and circulation changes of Antarctic coastal waters
457 by poleward shifting winds. *Geophysical Research Letters*, *41*, 4601–4610. doi:
458 10.1002/2014GL060613
- 459 Stewart, K., Hogg, A., Griffies, S., Heerdegen, A., Ward, M., Spence, P., & England,
460 M. (2017). Vertical resolution of baroclinic modes in global ocean models.
461 *Ocean Modelling*, *113*, 50–65. doi: 10.1016/j.ocemod.2017.03.012
- 462 Stewart, K., Kim, W., Urakawa, S., Hogg, A., Yeager, S., Tsujino, H., . . . Dan-
463 abasoglu, G. (2020). JRA55-do-based repeat year forcing datasets
464 for driving ocean–sea-ice models. *Ocean Modelling*, *147*, 101557. doi:
465 10.1016/j.ocemod.2019.101557
- 466 Thompson, D., & Solomon, S. (2002). Interpretation of recent Southern Hemisphere
467 climate change. *Science*, *296*, 895–899. doi: 10.1126/science.1069270
- 468 Thompson, D., & Wallace, J. (2000). Annular Modes in the Extratropical Circula-
469 tion. Part I: Month-to-Month Variability. *Journal of Climate*, *13*, 1000–1016.
470 doi: 10.1175/1520-0442(2000)013(1000:AMITEC)2.0.CO;2
- 471 Thompson, D., Wallace, J., & Hegerl, G. (2000). Annular Modes in the Extratrop-
472 ical Circulation. Part II: Trends. *Journal of Climate*, *13*, 1018–1036. doi: 10
473 .1175/1520-0442(2000)013(1018:AMITEC)2.0.CO;2
- 474 Treguier, A., Sommer, J. L., Molines, J., & Cuevas, B. d. (2010). Response of the
475 Southern Ocean to the Southern Annular Mode: Interannual Variability and
476 Multidecadal Trend. *Journal of Physical Oceanography*, *40*, 1659–1668. doi:
477 10.1175/2010JPO4364.1
- 478 Tsujino, H., Urakawa, S., Nakano, H., Small, R., Kim, W., Yeager, S., . . . Ya-
479 mazaki, D. (2018). JRA-55 based surface dataset for driving ocean–sea-
480 ice models (JRA55-do). *Ocean Modelling*, *130*, 79–139. doi: 10.1016/
481 j.ocemod.2018.07.002
- 482 Waugh, D., & Haine, T. (2020). How rapidly do the southern subtropical oceans re-
483 spond to wind stress changes? *Journal of Geophysical Research: Oceans*. doi:
484 10.1029/2020JC016236
- 485 Waugh, D., Hogg, A., Spence, P., England, M., & Haine, T. (2019). Response of
486 Southern Ocean Ventilation to Changes in Midlatitude Westerly Winds. *Jour-
487 nal of Climate*, *32*, 5345–5361. doi: 10.1175/JCLI-D-19-0039.1
- 488 Zheng, F., Li, J., Clark, R., & Nnamchi, H. (2013). Simulation and Projection of the
489 Southern Hemisphere Annular Mode in CMIP5 Models. *Journal of Climate*,

- 490 26, 9860–9879. doi: 10.1175/JCLI-D-13-00204.1
491 Zika, J., England, M., & Sijp, W. (2012). The Ocean Circulation in Thermohaline
492 Coordinates. *Journal of Physical Oceanography*, 42, 708–724. doi: 10.1175/
493 JPO-D-11-0139.1
494 Zweng, M., Reagan, J., Antonov, J., Locarnini, R., Mishonov, A., Boyer, T., ... Bid-
495 dle, M. (2013). World Ocean Atlas 2013, Volume 2: Salinity. *NOAA Atlas*
496 *NESDIS*, 74.