

*The influence of eddy parameterizations  
on the transport of the Antarctic  
Circumpolar Current in coupled climate  
models*

Article

Accepted Version

Kuhlbrodt, T. ORCID: <https://orcid.org/0000-0003-2328-6729>,  
Smith, R. S. ORCID: <https://orcid.org/0000-0001-7479-7778>,  
Wang, Z. and Gregory, J. M. ORCID: <https://orcid.org/0000-0003-1296-8644> (2012) The influence of eddy  
parameterizations on the transport of the Antarctic  
Circumpolar Current in coupled climate models. *Ocean  
Modelling*, 52-53. pp. 1-8. ISSN 1463-5003 doi:  
<https://doi.org/10.1016/j.ocemod.2012.04.006> Available at  
<https://centaur.reading.ac.uk/28371/>

It is advisable to refer to the publisher's version if you intend to cite from the  
work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1016/j.ocemod.2012.04.006>

Publisher: Elsevier

All outputs in CentAUR are protected by Intellectual Property Rights law,  
including copyright law. Copyright and IPR is retained by the creators or other  
copyright holders. Terms and conditions for use of this material are defined in

the [End User Agreement](#).

[www.reading.ac.uk/centaur](http://www.reading.ac.uk/centaur)

## **CentAUR**

Central Archive at the University of Reading

Reading's research outputs online

## ABSTRACT

1  
2 The transport of the Antarctic Circumpolar Current (ACC) varies strongly across the cou-  
3 pled GCMs (general circulation models) used for the IPCC AR4. This note shows that a  
4 large fraction of this across-model variance can be explained by relating it to the param-  
5 eterization of eddy-induced transports. In the majority of models this parameterization is  
6 based on the study by Gent and McWilliams (1990). The main parameter is the quasi-  
7 Stokes diffusivity  $\kappa$ . The ACC transport and the meridional density gradient both correlate  
8 strongly with  $\kappa$  across those models where  $\kappa$  is a prescribed constant. In contrast, there is no  
9 correlation with the isopycnal diffusivity  $\kappa_{iso}$  across the models. The sensitivity of the ACC  
10 transport to  $\kappa$  is larger than to the zonal wind stress maximum. Experiments with the fast  
11 GCM FAMOUS show that changing  $\kappa$  directly affects the ACC transport by changing the  
12 density structure throughout the water column. Our results suggest that this limits the role  
13 of the wind stress magnitude in setting the ACC transport in FAMOUS. The sensitivities  
14 of the ACC and the meridional density gradient are very similar across the AR4 GCMs (for  
15 those models where  $\kappa$  is a prescribed constant) and among the FAMOUS experiments. The  
16 strong sensitivity of the ACC transport to  $\kappa$  needs careful assessment in climate models.

17 The influence of eddy parameterizations on the transport of the  
18 Antarctic Circumpolar Current in coupled climate models

19 T. Kuhlbrodt<sup>a</sup>, R. S. Smith<sup>a</sup>, Z. Wang<sup>b</sup>, J. M. Gregory<sup>a,c</sup>

20 <sup>a</sup>*NCAS-Climate, Department of Meteorology, University of Reading, UK*

21 *Email: t.kuhlbrodt@reading.ac.uk, phone: +44 (0)118 378 6014, fax: +44 (0)118 378 8316*

22 <sup>b</sup>*British Antarctic Survey, Cambridge, UK*

23 <sup>c</sup>*Met Office, Exeter, UK*

---

24 *Keywords:* Antarctic Circumpolar Current, IPCC AR4 GCMs, Southern Ocean, Eddy  
25 parameterizations, Eddy-induced transports, Isopycnal diffusivity

---

## 26 1. Introduction

27 The Antarctic Circumpolar Current (ACC) is the strongest current in the world ocean.  
28 Its volume transport, measured in the Drake Passage, amounts to  $137 \pm 9$  Sv (Cunningham  
29 et al. 2003). Its presence has a strong influence on the climate in Antarctica, and the  
30 meridional overturning circulation across the ACC transports substantial amounts of heat,  
31 carbon and other tracers (Shaffrey et al. 2009; Woloszyn et al. 2011).

32 In the coupled general circulation models (GCMs) used for the Fourth Assessment Report  
33 (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007), the ACC transport  
34 varies over almost one order of magnitude, between 37 Sv and 337 Sv (Fig. 1a). Russell et al.  
35 (2006) identified, in a qualitative way, the relevance of the resolved fields (like wind stress  
36 or salinity and temperature gradients) to this large spread, but a quantitative explanation  
37 has not been fully established yet.

38 The GCMs used for the AR4 come with ocean components that have a typical horizontal

39 resolution of one to two degrees. Therefore the mesoscale eddies are not resolved and their  
40 effects on the large-scale circulation need to be parameterized. Almost all IPCC AR4 GCMs  
41 use parameterizations that go back to (Gent and McWilliams 1990, hereafter cited as GM90).  
42 One objective of the present note is to show the strong influence of this parameterization  
43 (often dubbed simply “GM”) on the oceanic density field and the ACC transport across the  
44 AR4 coupled climate models.

45 It is known that the GM parameterization generally improves the circulation in ocean  
46 models (Danabasoglu and McWilliams (1995) and others; see Griffies et al. (2000) and  
47 references therein). On a global scale, its effect is strongest in the Southern Ocean due  
48 to the widespread outcropping of isopycnal layers. The density structure is improved, and  
49 excessive open-ocean convection is significantly reduced. The sensitivity of the ACC to the  
50 GM parameterization has been studied before in individual models (e.g. Danabasoglu and  
51 McWilliams 1995; Gent et al. 2001) in an ocean-only setting. Our results show that the  
52 across-model sensitivity within a subset of the AR4 coupled climate models is very similar  
53 to the sensitivity of individual models.

54 We further explored the influence of GM on the ACC transport by conducting a sensitivity  
55 study with a fast atmosphere-ocean GCM (AOGCM). This is an advantage over the earlier  
56 sensitivity studies regarding  $\kappa$  that used an ocean-only setting with prescribed surface forcing,  
57 precluding a reaction of the surface fluxes on the density changes in the ocean. In addition,  
58 the fast AOGCM allows for runs that are long enough to let the ACC fully adjust—something  
59 that could not be done in other recent studies of the GM parameterization using a coupled  
60 GCM (e.g. Farneti and Gent 2011).

61 The isopycnal diffusivity  $\kappa_{iso}$  influences circulation and density structure, too (e.g. Sijp

62 et al. 2006), and equals  $\kappa$  in many models. We therefore tested the sensitivity of the ACC  
63 against  $\kappa_{iso}$  across the AR4 models as well as in FAMOUS.

64 The parameterized eddy-induced transports typically add up to a deep overturning cell  
65 across the ACC. However, for the AR4 climate models this overturning could not be di-  
66 agnosed as the eddy-induced transports were not among the list of suggested variables for  
67 the CMIP3 exercise, and thus are not available. It was however possible to collect the in-  
68 formation about the implementation of the GM parameterization in the individual models  
69 from various sources. We use the data of the 25 GCMs that participated in the Coupled  
70 Model Intercomparison Project Phase 3 (CMIP3) that was part of the IPCC AR4. The data  
71 are available at the Program for Climate Model Diagnosis and Intercomparison (PCMDI,  
72 [http://www-pcmdi.llnl.gov/ipcc/about\\_ipcc.php](http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php)). We have not considered the data  
73 that are currently being produced for the upcoming IPCC AR5 because at the time of  
74 writing data relevant for this study were available for only a small number of GCMs.

75 There are processes that the eddy parameterizations used by the AR4 climate models  
76 do not capture. One example is eddy saturation (Hallberg and Gnanadesikan 2006; Farneti  
77 et al. 2010). We do not address these processes here. Instead, our aim is to point out that  
78 the GM parametrization plays a strong role in setting the ACC transport and can dominate  
79 the wind stress as a driving force. This holds not only for individual models, but also across  
80 various AR4 climate models. We consider it likely that this will be true for the AR5 models  
81 too.

## 82 2. Parameterizing eddy-induced transports in GCMs

### 83 a. Parameterizations

84 Using an isopycnal framework, GM90 showed that, in a statistically steady state, the di-  
85 vergence of the flux of the mean density field by the mean velocity is approximately balanced  
86 by the divergence of a mean density flux due to mesoscale eddies. As a parameterization  
87 of this effect in non-eddy-resolving models they suggested a diffusion of isopycnal thickness  
88  $h = -\partial z / \partial \rho$ , with the potential density  $\rho$  referenced to local pressure.

89 Gent et al. (1995) (hereafter cited as GWMM95) suggested formulating the thickness  
90 diffusion, in depth level coordinates, as an eddy-induced velocity that is added to the tracer  
91 advection equations:

$$\mathbf{u}^* = -\frac{\partial}{\partial z} (\kappa \mathbf{S}) ; w^* = \nabla_h \cdot (\kappa \mathbf{S}) , \quad (1)$$

92 where  $\mathbf{u}^*$  and  $w^*$  are the horizontal and vertical eddy-induced velocities,  $\kappa$  the eddy-induced  
93 thickness diffusivity and  $\mathbf{S}$  the slope of the isopycnals, defined as  $\mathbf{S} = -\nabla_h \rho / \frac{\partial \rho}{\partial z}$ . This  
94 parameterization conserves the volume of isopycnal layers and thus can maintain fronts  
95 much better than pure horizontal diffusion. The term “thickness diffusivity” for  $\kappa$  is not  
96 entirely accurate. GM is actually a parameterization for the quasi-Stokes streamfunction  
97 (McDougall and McIntosh 2001) and  $\kappa$  should hence be called “quasi-Stokes diffusivity”.

98 The actual value of  $\kappa$  is not well constrained. GM90 themselves pointed out that  $\kappa$   
99 can vary strongly in space and time. As an example, if  $\kappa$  is diagnosed from eddy-resolving  
100 models, it is found that there is considerable vertical structure. In the model used by Eden  
101 et al. (2007),  $\kappa$  takes values larger than  $1000 \text{ m}^2\text{s}^{-1}$  close to the surface of the Southern

102 Ocean, but it decreases by up to one order of magnitude at depth.

103 The approach chosen by GWMM95 was to calculate the streamfunction of the eddy-  
104 induced velocities from an observational data set (Levitus 1982) using a constant  $\kappa =$   
105  $1000 \text{ m}^2\text{s}^{-1}$ . Since this reproduced the meridional heat transports with approximately correct  
106 magnitude and meridional distribution, they suggested using a value for  $\kappa$  of this order.

107 Seeking to improve on using a constant  $\kappa$ , Visbeck et al. (1997) (hereafter cited as Vis97)  
108 suggested diagnosing it from the stratification, i.e. the local horizontal and vertical density  
109 gradients. Vis97 studied several idealized cases and found that  $\kappa$  varies between  $300 \text{ m}^2\text{s}^{-1}$   
110 and  $2000 \text{ m}^2\text{s}^{-1}$ . Since the vertical density gradient is close to zero in the mixed layer,  
111 parameterizations of the Vis97 type can give unrealistically large values for  $\kappa$ . Therefore,  
112 tapering schemes must be applied at the boundaries to ensure that the eddy-induced velocity  
113 field is non-divergent everywhere (Treguier et al. 1997; Large et al. 1997).

114 When discussing quasi-Stokes diffusion it is important to point out that, away from the  
115 boundaries, the mixing of ocean tracers occurs mainly along isopycnal surfaces (Redi 1982;  
116 Griffies et al. 1998; McDougall and Jackett 2005, and many others). This process can  
117 be parameterized as downgradient diffusion along the isopycnals, with an isopycnal mixing  
118 coefficient  $\kappa_{iso}$ .

119 Griffies (1998) (hereafter cited as Grif98) formulated the eddy-induced transports in a  
120 more elegant and computationally more efficient way than GM90 by writing them as a skew  
121 diffusion, instead of a velocity as in (1). The quasi-Stokes diffusivity  $\kappa$  is then incorporated  
122 into the mixing tensor and appears in the same terms as  $\kappa_{iso}$ . To simplify the mixing tensor,  
123 it is often chosen to have  $\kappa_{iso} = \kappa$ . A downside of this approach is that the eddy-induced  
124 transports are not calculated explicitly anymore, meaning that they are often not available



125 as a model output.

126 More recent suggestions to improve the GM parameterization, for instance by diagnosing  
127  $\kappa$  as a three-dimensional field (Hofmann and Maqueda 2011), show an improved response,  
128 i.e. closer to what is seen in eddy-resolving models, of the circulation in the Southern Ocean  
129 on changes in the surface forcing. However, these approaches are not discussed further here  
130 since they have not been used in the AR4 models.

### 131 *b. Implementations*

132 For the present intercomparison study we gathered information about the individual  
133 implementations of the GM parameterization from the documentation available at PCMDI,  
134 from the published literature and from personal communication with the modelers. Table 1  
135 shows the results of this effort and goes beyond Russell et al. (2006) and Sen Gupta et al.  
136 (2009) in providing these details. Of the 24 models that were studied, three models do not  
137 use the GM parameterization (index  $N$ ), thirteen models use an implementation of GM with  
138 a fixed  $\kappa$  (index  $F$ ), and eight models diagnose  $\kappa$  from the stratification (index  $V$ ). That is,  
139 in the  $V$  models  $\kappa$  is a two-dimensional field in latitude and longitude calculated at every  
140 time step. The methods vary, but usually involve a vertical integral over the stratification.  
141  $V$  refers to Vis97 as one of the first papers introducing this method of calculating  $\kappa$ .

142 In some models  $\kappa$  is a function of the latitude or mesh size (see footnotes in Table 1), and  
143 we used the value at the latitudes of the ACC in these cases. We have classified them as  $F$   
144 since  $\kappa$  is then still a constant at any given grid point. Whether the skew flux formulation  
145 of Grif98 was employed was not taken into the account for our GM index since, in the light

146 of the above discussion, this does not affect the strength of the parameterized eddy-induced  
147 transports.

148 For the type  $F$  models, the value of  $\kappa$  ranges from  $100 \text{ m}^2\text{s}^{-1}$  to  $2000 \text{ m}^2\text{s}^{-1}$  (see also  
149 Fig. 1a). Some of the type  $F$  models are actually isopycnal models, meaning that they use  
150 density as a vertical coordinate. These models typically employ interface smoothing. This is  
151 physically equivalent to applying GM90 in a depth level model and was therefore subsumed  
152 in the same model type. The inter-model spread of  $\kappa$  in the type  $F$  models is by and large  
153 the same spread that is possible within an individual model of type  $V$ , with the exception  
154 of the later versions of the OPA ocean model where  $\kappa$  can be as low as  $15 \text{ m}^2\text{s}^{-1}$ .

### 155 **3. The Antarctic Circumpolar Current in the AR4 mod-** 156 **els and in FAMOUS**

#### 157 *a. Model data*

158 The ACC is balanced geostrophically by a meridional density gradient that extends from  
159 the surface down to below the thermocline. It is still not fully understood how the ACC is  
160 driven, however the existing theoretical work (Rintoul et al. 2001; Marshall and Radko 2003)  
161 suggests that this meridional density gradient is maintained by fluxes of heat and freshwater  
162 at the surface as well as by wind-driven upwelling of dense waters south of the ACC and  
163 wind-driven downwelling, or Ekman pumping, north of the ACC. While this wind-driven  
164 meridional overturning acts to increase the meridional density gradient, or to steepen the  
165 isopycnals, there are substantial eddy-induced transports that flatten the isopycnals. This

166 mesoscale eddy activity arises from baroclinic instability.

167 The main quantities used by Russell et al. (2006) in their analysis of the AR4 climate  
168 models are the ACC transport, the maximum zonal wind stress and the meridional density  
169 difference across the ACC. The actual parameterized eddy-induced transports are not avail-  
170 able at the CMIP3 database and therefore could not be analysed. However,  $\kappa$  gives an  
171 indication of the strength of the eddy-induced transports (see eq. 1). Therefore we use  $\kappa$   
172 as well as similar diagnostics as Russell et al. (2006) to analyse the type  $F$  models. In  
173 addition,  $\kappa_{iso}$  is included in the analysis.

174 We analysed the last twenty years of the control runs (picntrl, averaged from monthly  
175 means) and used run 1 if several control runs were available. For the sake of completeness, we  
176 obtained additional model data for some models from other public databases (for the GFDL  
177 models and for GISS\_EH\_2) or from the modelling groups directly (for MPIECHAM5).  
178 The control runs were chosen because in almost all of them the ACC is close to a statistical  
179 equilibrium, with the length of the control runs typically many centuries. To assess possible  
180 drifts we analysed the trends of the ACC transport over the last 100 years and found that  
181 only three models (4, 5 and 9) have drifts larger than an absolute value of 1 Sv/decade, while  
182 seven models have no significant drift, and the rest has drifts of an absolute value of around  
183 0.5 Sv/decade or less. The drift in model 4 is consistently negative over the full length  
184 of the control run (500 yr), and therefore we excluded it from the detailed analysis of the  
185 type  $F$  models. By contrast, in model 5 the magnitude of the drift is decreasing during the  
186 control run (length 380 yr), and therefore we retained this model for the detailed analysis.  
187 In Figs. 1b) to d) and Figs. 2a) and c), model 11 was left out due to lack of data for the  
188 ACC, and model 10 was left out since it uses GM as well as interface smoothing, such that

189  $\kappa$  is not representative for all parameterized eddy-induced transports.

190 The ACC transport was defined as the difference of the barotropic streamfunction across  
191 Drake Passage. For five models the barotropic streamfunction was not available. Instead, we  
192 calculated the volume transport through Drake Passage from the zonal velocity integrated  
193 along 69°W and over the full depth. Using the zonal velocities for all models, instead of  
194 the barotropic streamfunction, leads to some minor differences that do not affect our results.  
195 Likewise, considering only the baroclinic transports (in the definition by Marshall and Radko  
196 2003) yields similarly small differences for most models, against which our results are robust.

197 In addition to the AR4 model data, we use the fast atmosphere-ocean GCM (AOGCM)  
198 FAMOUS (version XFXWB; Smith et al. 2008; Smith 2011) to explore the impacts of chang-  
199 ing  $\kappa$  on the stratification. It is based on the well-established coupled climate model HadCM3  
200 (Gordon et al. 2000). In FAMOUS the resolution was lowered to 2.5° by 3.75° with 20 levels  
201 in the ocean and 5° by 7.5° with 11 levels in the atmosphere, with a few resulting adjustments  
202 of the model physics. FAMOUS runs fast, simulating up to 250 years per day on 8 processors  
203 of a modern server, and thus gives us the opportunity to conduct millennial-scale runs. This  
204 is necessary for the full ocean density field to adjust to parameter changes. Yet with most  
205 of the AR4 models such long runs could not be conducted due to constraints in computing  
206 resources. FAMOUS is a model of type  $F$  and uses  $\kappa = 1000 \text{ m}^2\text{s}^{-1}$ . The control run is  
207 more than 5000 years long, and after year 4000 the centennial trends of globally averaged  
208 quantities are very small. In model year 4000, two runs were spawned off with  $\kappa = 600 \text{ m}^2\text{s}^{-1}$   
209 and  $\kappa = 2000 \text{ m}^2\text{s}^{-1}$ , sampling the range of the values found among the AR4 models of type  
210  $F$ . These two runs, which we call K600 and K2000, were integrated for 1000 years each.  
211 In two further runs of 1000 years length,  $\kappa_{iso}$  was varied along with  $\kappa$ , with the same two

212 values of  $\kappa = \kappa_{iso} = 600 \text{ m}^2\text{s}^{-1}$  and  $\kappa = \kappa_{iso} = 2000 \text{ m}^2\text{s}^{-1}$ . The quantities shown in the  
213 figures below are 20-year averages from year 4980 to 5000 of all FAMOUS runs. In terms  
214 of globally volume-averaged potential temperature and salinity, the K600 and K2000 runs  
215 show clear trends and are not in equilibrium after 1000 yr. However, the ACC transports  
216 show no long-term drift after 200 years (not shown).

### 217 *b. Results*

218 Fig. 1a groups the models' ACC transports by the type of eddy parameterization. Leaving  
219 the models without the GM parameterization aside (type *N*), there is no clear distinction  
220 between the type *F* and the type *V* models. The type *V* models have a slight tendency  
221 towards a stronger ACC: all but one of the models have an ACC transport of 110 Sv or more.  
222 Conversely, the type *F* models have a cluster of somewhat weak ACCs around 100 Sv, with  
223 the exception of model 5.

224 Our main result is that there is a clear and significant correlation ( $r = -0.79$ ) of the ACC  
225 transport with  $\kappa$  across the type *F* models (Fig. 1b). We chose logarithmic axes in this Figure  
226 to better capture the large range of  $\kappa$  values. On linear scales the correlation is  $r = -0.68$   
227 and is significant too. The significance is indicated by the low p-value ( $p < 0.05$ ; however  
228 the p-value might be an overly confident estimate because the climate models were treated  
229 as independent for the calculation of the p-value. Pennell and Reichler (2011) suggest that  
230 the actual number of degrees of freedom is lower than the number of AR4 climate models.)

231 The slope of the regression line in Fig. 1b, based on the AR4 models, is  $-0.43 \pm -0.29$   
232 (95% confidence interval from a Student's t-test). This estimate is in line with Danabasoglu

233 and McWilliams (1995) who used three different values for  $\kappa$  in an ocean-only model. Their  
234 resulting ACC transports aligned roughly along a -1/3 slope (their Fig. 3). In addition, a  
235 slope of -0.56 can be diagnosed from two runs in Gent et al. (2001). The current estimate  
236 includes this value too.

237 The three FAMOUS runs (red diamonds) align well with the AR4 models in Fig. 1b ,  
238 suggesting that the spread of ACC transports across the AR4 models can be explained, to  
239 some extent, by the spread of  $\kappa$ . This also means that the sensitivities with regard to  $\kappa$  are  
240 similar within one model and across different models.

241 The correlation of the meridional density difference  $\Delta\rho_y$  across the ACC with  $\kappa$  is even  
242 larger ( $r = -0.86$ ; Fig. 1c).  $\Delta\rho_y$  is defined as the density difference between the averaged  
243 latitude bands  $65^\circ\text{S}$  to  $62^\circ\text{S}$  on the one hand and  $45^\circ\text{S}$  to  $42^\circ\text{S}$  on the other hand, 0-1500 m  
244 depth. (With a linear scale for  $\kappa$ ,  $r = -0.74$ .) The pattern of the AR4 models is very similar  
245 to Fig. 1b, which is not surprising since  $\Delta\rho_y$  represents the geostrophic balance of the ACC.  
246 The FAMOUS runs again align very well with the AR4 models, showing that one individual  
247 GCM like FAMOUS can map the across-model sensitivity of the AR4 models.

248 Given the importance of isopycnal diffusion (cf. sec. 2a), we tested whether the ACC  
249 transport correlates with  $\kappa_{iso}$  across the type  $F$  models (Fig. 1d). It turns out that six  
250 out of the nine type  $F$  models have  $\kappa_{iso} = 1000 \text{ m}^2\text{s}^{-1}$ , precluding a significant correlation.  
251 The FAMOUS runs with  $\kappa_{iso} = \kappa$  (green diamonds in Fig. 1d) show an ACC sensitivity  
252 that is very similar to the K600 and K2000 runs, with a somewhat larger response of the  
253 ACC transport. In other words, whether only  $\kappa$  or both  $\kappa_{iso}$  and  $\kappa$  are changed makes  
254 no substantial difference. This suggests that  $\kappa$  dominates in setting the ACC transport in  
255 FAMOUS.

256 The correlation between the ACC transport and  $\Delta\rho_y$  is strong (Fig. 2a) and is retained  
257 when all AR4 models are considered (Fig. 2b). Again, this is to be expected because of the  
258 geostrophic balance of the ACC. The three FAMOUS runs align very well with the type  $F$   
259 models.

260 The influence of  $\kappa$  on the structure of the density field can be seen in more detail in Fig. 3.  
261 It shows  $\Delta\rho_y(z)$ , the zonally averaged density difference across the ACC as a function of  
262 depth.  $\Delta\rho_y(z)$  is defined like  $\Delta\rho_y$  above, apart from the vertical averaging. The dashed lines  
263 in Fig. 3 show a selection of the AR4 models, while observations (WOA05 Locarnini et al.  
264 2006; Antonov et al. 2006) are plotted with a dash-dotted line and the FAMOUS runs are  
265 represented by solid lines.

266 The vertical structure of  $\Delta\rho_y(z)$  differs substantially among the models in Fig. 3. For  
267 instance, above 2300m depth model 20 has a larger  $\Delta\rho_y(z)$  than model 18, while below  
268 2300m depth model 20 has a small  $\Delta\rho_y(z)$  that even turns negative below 3500m depth.  
269 This explains plausibly why model 18 has the greater ACC transport (Fig. 1b) in spite of  
270 the smaller  $\Delta\rho_y(z)$  above 2300m depth. The vertical density structure in the latitude band  
271 north of the ACC can also have a marked impact on projected changes of the ACC transport  
272 (Wang et al. 2011).

273 The differences of  $\Delta\rho_y(z)$  among the FAMOUS runs (solid lines in Fig. 3) are consistent  
274 with the differences between the AR4 models. Compared with observations (dash-dotted),  
275 the ACC in FAMOUS is too strong in the top 500 m and too weak below that. Still, Fig. 3  
276 shows the top-to-bottom influence of  $\kappa$  on the horizontal density gradient: increasing  $\kappa$  leads  
277 to a larger tendency to restratify, reducing  $\Delta\rho_y(z)$ . Note that the deviation of FAMOUS from  
278 observations is not an outlier in comparison with the full set of AR4 models (not shown).

279 We looked at the density changes in FAMOUS in more detail. Fig. 4 shows the zonally  
280 averaged density fields of the control run (Fig. 4a) and the anomalies of both K600 (Fig. 4b)  
281 and K2000 (Fig. 4c). Below the surface layer (top 100 m) the changes are as expected. In  
282 the K600 run there is a smaller tendency for restratification. Thus the isopycnals have  
283 a larger tilt, leading to lighter waters (blue shading) north of the ACC and denser waters  
284 (red shading) south of the ACC. In the K2000 run this effect is reversed. In the surface  
285 layer however this simple relationship does not hold. While the surface density anomalies  
286 are in line with the subsurface anomalies in the K2000 run, there is a positive density  
287 anomaly everywhere in the surface layer in the K600 run. This effect is predominantly due  
288 to salinity anomalies (not shown) and might come from the surface tapering used in the  
289 GM parameterization. These surface effects merit a deeper investigation, which is beyond  
290 the scope of this note.

291 We now discuss the correlation of the ACC transport with the maximum of the zonally  
292 averaged wind stress  $\tau^x$  in the AR4 models as well as in FAMOUS. Fig. 2 shows the corre-  
293 lations for the type  $F$  models (panel c) and, for comparison, for all AR4 models (panel d).  
294 For the type  $F$  models (Fig. 2c), the correlation of the ACC transport with  $\tau^x$  is somewhat  
295 lower than with  $\kappa$  or with  $\Delta\rho_y$ , and if all AR4 models are considered (Fig. 2d) there is no  
296 significant correlation any more. The FAMOUS runs (red diamonds) do not align with the  
297 AR4 models because the wind stress changes are very small. These results indicate that  
298 the wind stress is not the dominant factor in explaining the spread of the simulated ACC  
299 transports. This can also be seen by comparing pairwise some of the AR4 models. For  
300 instance, models 3 and 20 have virtually the same maximum zonally averaged zonal wind  
301 stress  $\tau^x$ , but their ACC transports differ by more than 50 Sv (Fig. 2c). This discrepancy is



302 well explained by the difference in  $\kappa$ , which is  $200 \text{ m}^2\text{s}^{-1}$  for model 20 and  $1000 \text{ m}^2\text{s}^{-1}$  for  
303 model 3 (Fig. 1b). Model 18 and model 2 compare in a very similar way, and the  $\Delta\rho_y(z)$   
304 profiles in these four models are consistent with their ACC transports (Fig. 3). Still, for  
305 models with the same value of  $\kappa$  (e.g. models 2, 3 and 13 in Fig. 1b), the varying strength  
306 of the wind stress can explain the different ACC transports.

307 We believe that we analysed the most important diagnostics with regard to influence on  
308 the ACC transport. There are however more diagnostics that could be studied. For example,  
309 we have not investigated the dependence of the ACC transport on horizontal viscosity be-  
310 cause its influence on the ACC is unclear so far. Sensitivity studies with fully coupled GCMs  
311 can show, for a lower viscosity, a strengthened ACC transport (Griffies et al. (2005), with  
312 GFDL CM 2.1) or a weakened ACC transport (Jochum et al. (2008), with NCAR CCSM3).  
313 A clarification of the role of viscosity in setting the ACC transport would be a study in its  
314 own right and is not pursued here. One other property that is relevant for the ACC dynamics  
315 is the bottom topography. It can influence the ACC transport by its role in defining the  
316 bottom form stress, which balances the wind stress at the surface. Calculating the bottom  
317 form stress from the available AR4 model data turned out to be not feasible because of  
318 the loss of accuracy from the spatial interpolation of the data which was applied to many  
319 models' output. Using simple measures of the models' bottom topography instead, we could  
320 not find a correlation of the ACC with, for instance, the maximum unobstructed depth at  
321 Drake Passage latitudes or with the width of Drake Passage in grid points across the models.

## 4. Discussion

In this note we have investigated the role of parameterized eddy-induced transports in determining the transport of the ACC across the control runs of the AR4 models and in a coarse-resolution GCM. Due to the lack of data on eddy-induced transports from the AR4 models, we used the main parameter of the GM parameterization for this purpose. For those models where this quasi-Stokes diffusivity  $\kappa$  is not diagnosed from the density field and therefore not time-dependent (type  $F$ ),  $\kappa$  is a powerful parameter. The ACC transport and the meridional density difference  $\Delta\rho_y$  correlate significantly with  $\kappa$ . Experiments with the fast AOGCM FAMOUS reproduce the across-model relationship between the ACC transport,  $\kappa$  and the meridional density gradient. In other words, the dependence of the ACC as well as the meridional density gradient on  $\kappa$  is very similar across the type  $F$  subset of the AR4 ensemble, containing nine different models, and among several runs of an individual model (FAMOUS).

For the isopycnal diffusivity  $\kappa_{iso}$  an across-model correlation with the ACC transport could not be found. Additional FAMOUS experiments show that the ACC transport is more sensitive to  $\kappa$  than to  $\kappa_{iso}$ .

The correlation of the ACC with the maximum of the zonally averaged zonal wind stress is weaker than with  $\kappa$ . Variations in  $\kappa$  can explain the varying ACC transport between type  $F$  models with the same wind stress maximum. The FAMOUS experiments show as well that different equilibrium ACC transports can exist under very similar maximum zonal wind stresses. All this indicates that the density structure in the ocean is dominant over the maximum of the zonal wind stress in setting the ACC transport. The use of a fully

344 coupled climate model for this purpose is an advantage over earlier GM sensitivity studies  
345 (Danabasoglu and McWilliams 1995; Gent et al. 2001) that used an ocean-only setup.

346 It would have been very interesting to include the type  $V$  models by diagnosing the  $\kappa$   
347 values from their density fields. This is however cumbersome as the exact details of the  
348 implementation of the GM parameterization would have to be known, given that for the  
349 AR4 models the actual eddy-induced transports are not available. Also, previous studies  
350 show that there is no consensus at all about the projected 21st century changes of the  
351 ACC, not even about the sign (Sen Gupta et al. 2009; Wang et al. 2011). The role of the  
352 parameterized eddy-induced transports in these diverse responses needs to be understood.  
353 For these reasons, it would be of great value within the ongoing CMIP5 intercomparison if  
354 modelling groups would diagnose these transports and make the data available.

355 The latest generation of GCMs, which is currently being used to produce simulations  
356 for the upcoming Fifth Assessment Report of the IPCC, begins to have eddy-permitting  
357 oceans with resolutions of  $1/3^\circ$  or higher, where the GM parameterization is not employed  
358 any more (Shaffrey et al. 2009; Delworth et al. 2012). If eddies are resolved (or permitted)  
359 the response of the ACC to changes in wind stress becomes clearly smaller (Hallberg and  
360 Gnanadesikan 2006; Farneti et al. 2010). However, the computational cost of eddy-permitting  
361 ocean components is still far too high if they carry many tracers, for instance as part of a  
362 carbon cycle model. Therefore in the nearer future the GM parameterization will still be in  
363 use, and the present note demonstrates that  $\kappa$  is likely to be the strongest determinant of  
364 the transport of the ACC in models. We therefore recommend testing the sensitivity of the  
365 circulation against varying  $\kappa$ .

## Acknowledgments

366 We acknowledge the modeling groups for making their model output available for analy-  
367 sis, the PCMDI for collecting and archiving this data, and the WCRP's Working Group  
368 on Coupled Modelling (WGCM) for organizing the model data analysis activity. We are  
369 grateful to Johann Jungclaus for giving us access to the control run of MPI\_ECHAM5. The  
370 research leading to these results has received funding from the European Research Council  
371 under the European Community's Seventh Framework Programme (FP7/2007-2013), ERC  
372 grant agreement number 247220, project "Seachange". In addition, TK was supported by  
373 a Marie Curie Intra-European Fellowship within the 7th European Community Framework  
374 Programme. FAMOUS was integrated on HECToR, the UK National Supercomputing re-  
375 source.

## REFERENCES

- 379 Antonov, J. I., Locarnini, R. A., Boyer, T. P., Mishonov, A. V., , Garcia, H. E., 2006. World  
380 Ocean Atlas 2005. Vol. 2 of NOAA Atlas NESDIS 62. U.S. Government Printing Office,  
381 Washington, D.C., US, p. 182.
- 382 Bleck, R., 2002. An oceanic general circulation model framed in hybrid isopycnic-Cartesian  
383 coordinates. *Ocean Modelling* 37, 55–88.
- 384 Cunningham, S. A., Alderson, S. G., King, B. A., Brandon, M. A., 2003. Transport and vari-  
385 ability of the Antarctic Circumpolar Current in Drake Passage. *J. Geophys. Res.* 108 (C5),  
386 8084.
- 387 Danabasoglu, G., Large, W. G., Tribbia, J. J., Gent, P. R., Briegleb, B. P., 2006. Diurnal  
388 coupling in the tropical oceans of CCSM3. *J. Clim.* 19, 2347–2365.
- 389 Danabasoglu, G., McWilliams, J., 1995. Sensitivity of the global ocean circulation to param-  
390 eterizations of mesoscale tracer transports. *J. Clim.* 8, 2967–2987.
- 391 Delworth, T. L., Rosati, A., Anderson, W., Adcroft, A. J., Balaji, V., Benson, R., Dixon,  
392 K., Griffies, S. M., Lee, H.-C., Pacanowski, R. C., Vecchi, G. A., Wittenberg, A. T.,  
393 Zeng, F., Zhang, R., 2012. Simulated climate and climate change in the GFDL CM2.5  
394 high-resolution coupled climate model. *J. Clim.* 25 (8), 2755–2781.
- 395 Diansky, N. A., Bagno, A. V., Zalesny, V. B., 2002. Sigma model of global ocean circulation

396 and its sensitivity to variations in wind stress. *Izvestiya, Atmospheric and Oceanic Physics*  
397 38 (4), 477–494.

398 Eden, C., Greatbatch, R. J., Willebrand, J., 2007. Diagnosis of thickness fluxes in an eddy-  
399 resolving model. *J. Phys. Oceanogr.* 37, 727–742.

400 Farneti, R., Delworth, T. L., Rosati, A. J., Griffies, S. M., Zeng, F., 2010. The role of  
401 mesoscale eddies in the rectification of the Southern Ocean response to climate change. *J.*  
402 *Phys. Oceanogr.* 40, 1539–1557.

403 Farneti, R., Gent, P. R., 2011. The effects of the eddy-induced advection coefficient in a  
404 coarse-resolution coupled climate mode. *Ocean Modelling* 39 (1-2), 135–145.

405 Furevik, T., Bentsen, M., Drange, H., Kindem, I. K. T., Kvamstø, N. G., Sorteberg, A.,  
406 2003. Description and validation of the Bergen Climate Model: ARPEGE coupled with  
407 MICOM. *Clim. Dyn.* 21, 27–51.

408 Gent, P. R., Large, W. G., Bryan, F. O., 2001. What sets the mean transport through Drake  
409 Passage? *J. Geophys. Res.* 106 (C2), 2693–2712.

410 Gent, P. R., McWilliams, J. C., 1990. Isopycnal mixing in ocean circulation models. *J. Phys.*  
411 *Oceanogr.* 20, 150–155.

412 Gent, P. R., Willebrand, J., McDougall, T. J., McWilliams, J. C., 1995. Parameterizing  
413 eddy-induced tracer transports in ocean circulation models. *J. Phys. Oceanogr.* 25, 463–  
414 474.

415 Gordon, C., Cooper, C., Senior, C., Banks, H., Gregory, J., Johns, T., Mitchell, J., Wood,

416 R., 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of  
417 the Hadley Centre coupled model without flux adjustments. *Clim. Dyn.* 16, 147–168.

418 Gordon, H., O’Farrell, S., Collier, M., Dix, M., Rotstayn, L., Kowalczyk, E., Hirst, T.,  
419 Watterson, I., 2010. The CSIRO Mk3.5 climate system model. CAWCR Technical Report  
420 No.021.

421 Gordon, H., Rotstayn, L., McGregor, J., Dix, M., Kowalczyk, E., O’Farrell, S., Waterman,  
422 L., Hirst, A., Wilson, S., Collier, M., Watterson, I., Elliott, T., 2002. The CSIRO Mk3  
423 climate system model. CSIRO Atmospheric Research Technical Paper No.60.

424 Griffies, S. M., 1998. The Gent–McWilliams skew flux. *J. Phys. Oceanogr.* 28, 831–841.

425 Griffies, S. M., Böning, C., Bryan, F. O., Chassignet, E. P., Hasumi, H., Hirst, A., Treguier,  
426 A.-M., Webb, D., 2000. Developments in ocean climate modelling. *Ocean Modelling* 2,  
427 123–192.

428 Griffies, S. M., Gnanadesikan, A., Dixon, K., Dunne, J. P., Gerdes, R., Harrison, M. J.,  
429 Rosati, A., Russell, J. L., Samuels, B. L., Spelman, M. J., M.Winton, Zhang, R., 2005.  
430 Formulation of an ocean model for global climate simulations. *Ocean Science* 1, 45–79.

431 Griffies, S. M., Gnanadesikan, A., Pacanowski, R. C., Larichev, V. D., Dukowicz, J. K.,  
432 Smith, R. D., 1998. Isonutral diffusion in a z-coordinate ocean model. *J. Phys. Oceanogr.*  
433 28, 805–830.

434 Hallberg, R., Gnanadesikan, A., 2006. The role of eddies in determining the structure and  
435 response of the wind-driven Southern Hemisphere overturning: Results from the modeling  
436 eddies in the Southern Ocean project. *J. Phys. Oceanogr.* 36, 2232–2252.

437 Hasumi, H., Emori, S., K-1 model developers, September 2004. K-1 Coupled GCM (MIROC)  
438 description. K-1 Technical Report No. 1.

439 Hofmann, M., Maqueda, M. A. M., 2011. The response of Southern Ocean eddies to increased  
440 midlatitude westerlies: A non-eddy resolving model study. *Geophys. Res. Lett.* 38, L03605,  
441 doi:10.1029/2010GL045972.

442 IPCC, 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working*  
443 *Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate*  
444 *Change.* S. Solomon and D. Qin and M. Manning and Z. Chen and M. Marquis and K.B.  
445 Averyt and M. Tignor and H.L. Miller (eds.): Cambridge University Press, Cambridge,  
446 UK, and New York, NY, USA, 996 pp.

447 Jochum, M., Danabasoglu, G., Holland, M., Kwon, Y.-O., Large, W. G., 2008. Ocean vis-  
448 cosity and climate. *J. Geophys. Res.* 113, C06017.

449 Kim, S.-J., Flato, G., Boer, G., McFarlane, N., 2002. A coupled climate model simulation  
450 of the Last Glacial Maximum, Part 1: transient multi-decadal response. *Clim. Dyn.* 19,  
451 515–537.

452 Large, W. G., Danabasoglu, G., Doney, S. C., McWilliams, J. C., 1997. Sensitivity to surface  
453 forcing and boundary layer mixing in a global ocean model: Annual-mean climatology. *J.*  
454 *Phys. Oceanogr.* 27 (11), 2418–2447.

455 Levitus, S., 1982. *Climatological atlas of the world ocean.* Tech. Rep. NTIS PB83-184093,  
456 NOAA/ERL GFDL, Princeton, N.J.



457 Locarnini, R. A., Mishonov, A. V., Antonov, J. I., Boyer, T. P., Garcia, H. E., 2006. World  
458 Ocean Atlas 2005. Vol. 1 of NOAA Atlas NESDIS 61. U.S. Government Printing Office,  
459 Washington, D.C., US, p. 182.

460 Madec, G., Delecluse, P., Imbard, M., Lévy, C., Dec. 1998. OPA 8.1 Ocean General Circu-  
461 lation Model reference manual. Notes du Pôle de Modélisation, No. 11.

462 Marshall, J., Radko, T., 2003. Residual-mean solution for the Antarctic Circumpolar Current  
463 and its associated overturning circulation. *J. Phys. Oceanogr.* 33, 2341–2354.

464 Marsland, S., Haak, H., Jungclaus, J., Latif, M., Röske, F., 2003. The Max-Planck-Institute  
465 global ocean/sea ice model with orthogonal curvilinear coordinates. *Ocean Modelling* 5,  
466 91–127.

467 McDougall, T. J., Jackett, D. R., 2005. The material derivative of neutral density. *J. Mar.*  
468 *Res.* 63, 159–185.

469 McDougall, T. J., McIntosh, P., 2001. The temporal-residual-mean velocity. Part II: isopy-  
470 cnal interpretation and the tracer and momentum equations. *J. Phys. Oceanogr.*, 1222–  
471 1246.

472 Pennell, C., Reichler, T., 2011. On the effective number of climate models. *J. Clim.* 24,  
473 2358–2367.

474 Redi, M., 1982. Oceanic isopycnal mixing by coordinate rotation. *J. Phys. Oceanogr.* 12,  
475 1154–1158.

476 Rintoul, S. R., Hughes, C. W., Olbers, D., 2001. The Antarctic Circumpolar Current system.  
477 In: Siedler, G. (Ed.), *Ocean Circulation and Climate*. Academic Press, pp. 271–301.

478 Risien, C. M., Chelton, D. B., 2008. A global climatology of surface wind and wind stress  
479 fields from eight years of QuikSCAT scatterometer data. *J. Phys. Oceanogr.* 38, 2379–2413.

480 Roberts, M. J., 2004. The Gent and McWilliams parameterisation scheme, including Visbeck  
481 and biharmonic GM schemes. *Unified Model Documentation Paper UMDP54*, 23 pp.

482 Russell, G. L., Miller, J. R., Rind, D., 1995. A coupled atmosphere-ocean model for transient  
483 climate change studies. *Atmosphere-Ocean* 33 (4), 683–730.

484 Russell, J. L., Stouffer, R. J., Dixon, K., 2006. Intercomparison of the Southern Ocean  
485 circulations in IPCC model control simulations. *J. Clim.* 19, 4560–4575.

486 Saenko, O. A., Fyfe, J. C., England, M. H., 2005. On the response of the oceanic wind-driven  
487 circulation to atmospheric CO<sub>2</sub> increase. *Clim. Dyn.* 25 (4), 415–426.

488 Sen Gupta, A., Santoso, A., Taschetto, A. S., Ummenhofer, C. C., Trevena, J., England,  
489 M. H., 2009. Projected changes to the southern hemisphere ocean and sea ice in the IPCC  
490 AR4 climate models. *J. Clim.* 22, 3047–3078.

491 Shaffrey, L. C., Stevens, I., Norton, W. A., Roberts, M. J., Vidale, P. L., Harle, J. D.,  
492 Jrrar, A., Stevens, D. P., Woodage, M. J., Demory, M. E., Donners, J., Clark, D. B.,  
493 Clayton, A., Cole, J. W., Wilson, S. S., Connolley, W. M., Davies, T. M., Iwi, A. M.,  
494 Johns, T. C., King, J. C., New, A. L., Slingo, J. M., Slingo, A., Steenman-Clark, L.,  
495 Martin, G. M., 2009. U.K. HiGEM: The new U.K. high-resolution global environment  
496 model—Model description and basic evaluation. *J. Clim.* 22, 1861–1896.

497 Sijp, W. P., Bates, M., England, M., 2006. Can isopycnal mixing control the stability of the  
498 thermohaline circulation in ocean climate models? *J. Clim.* 19 (21), 5637–5651.

499 Smith, R. S., 2011. The FAMOUS climate model (versions XFXWB and XFHCC): descrip-  
500 tion update to version XDBUA. *Geoscientific Model Development Discussions* 4, 3047–  
501 3065.

502 Smith, R. S., Gregory, J. M., Osprey, A., 2008. A description of the FAMOUS (version  
503 XDBUA) climate model and control run. *Geoscientific Model Development* 1 (1), 53–68.

504 Sun, S., Bleck, R., 2006. Multi-century simulations with the coupled GISS–HYCOM climate  
505 model: control experiments. *Clim. Dyn.* 26, 407–428.

506 Treguier, A., Held, I., Larichev, V., 1997. Parameterization of quasigeostrophic eddies in  
507 primitive equation ocean models. *J. Phys. Oceanogr.* 27, 567–580.

508 Visbeck, M., Marshall, J., Haine, T., Spall, M., 1997. Specification of eddy transfer coeffi-  
509 cients in coarse-resolution ocean circulation models. *J. Phys. Oceanogr.* 27, 381–402.

510 Wang, Z., Kuhlbrodt, T., Meredith, M. P., 2011. On the response of the Antarctic Circum-  
511 polar Current transport to climate change in coupled climate models. *J. Geophys. Res.*  
512 116, C08011.

513 Woloszyn, M., Mazloff, M., Ito, T., 2011. Testing an eddy-permitting model of the Southern  
514 Ocean carbon cycle against observations. *Ocean Modelling* 39 (1-2), 170–182.

515 Wright, D. K., 1997. A new eddy mixing parametrization and ocean general circulation  
516 model. *International WOCE Newsletter* 26, 27–29.

517 Yukimoto, S., Noda, A., Kitoh, A., Sugi, M., Kitamura, Y., Hosaka, M., Shibata, K., Maeda,  
518 S., Uchiyama, T., Feb 2001. The new Meteorological Research Institute Coupled GCM  
519 (MRI-CGCM2) – Model climate and variability. Papers in Meteorology and Geophysics  
520 51 (2), 47–88.

TABLE 1. Parameterizations of eddy-induced transports in the IPCC AR4 global coupled climate models. The GM index  $i_{GM}$  is either  $N$  if such a parameterization is absent,  $F$  for a fixed quasi-Stokes diffusivity  $\kappa$  or  $V$  if  $\kappa$  varies as a function of the density field at each time step. “IS” stands for the interface smoothing that is used in isopycnal models. It is equivalent to applying GM. Of the references the first one (before the slash) gives the actual value of  $\kappa$ , if applicable. “PCMDI” refers to the online documentation available at [http://www-pcmdi.llnl.gov/ipcc/model\\_documentation/ipcc\\_model\\_documentation.php](http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php).

No.	GCM name	Ocean model	Eddy parameterization	$i_{GM}$	$\kappa$ [m <sup>2</sup> s <sup>-1</sup> ]	References for GM implementation
1	BCCR_BCM2_0	MICOM 2.8	IS (isopycnal model)	F	–	–/ Furevik et al. (2003)
2	CCCMA_CGCM3_1_T47	MOM1.1	GM90	F	1000	Saenko et al. (2005)/ Kim et al. (2002)
3	CCCMA_CGCM3_1_T63	MOM1.1	GM90	F	1000	Saenko et al. (2005)/ Kim et al. (2002)
4	CNRM_CM3	OPA8.1	GM90	F	2000	PCMDI/ Madec et al. (1998)
5	CSIRO_MK3_0	MOM2.2	GM90, Grif98	F	100	Gordon et al. (2002)
6	CSIRO_MK3_5	MOM2.2	Vis97, Grif98	V	100 to 600 <sup>a</sup>	Gordon et al. (2010)
7	GFDL_CM2_0	OM3.0	Griffies et al. (2005), Grif98	V	100 to 600 <sup>a</sup>	Griffies et al. (2005)
8	GFDL_CM2_1	OM3.1	Griffies et al. (2005), Grif98	V	100 to 600 <sup>a</sup>	Griffies et al. (2005)
9	GISS_AOM	Russell	none	N	–	–/ Russell et al. (1995)
10	GISS_EH_2	HYCOM	GM90 and IS (isopycnal model)	F	1000 to 4000 <sup>b</sup>	Sun and Bleck (2006)
11	GISS_E_H	HYCOM	IS (isopycnal model)	F	100 <sup>c</sup>	PCMDI/ Bleck (2002)
12	GISS_E_R	Russell	Vis97, Grif98	V	–	–/ Russell et al. (1995), PCMDI
13	IAP_FGOALS1_0_G	LICOM1.0	GM90	F	1000	Hailong Liu, pers. comm./ PCMDI
14	INGV_ECHAM4	OPA8.2	Treguier et al. (1997)	V	15 to 2000 <sup>a</sup>	PCMDI/ Madec et al. (1998)
15	INMCM3_0	<sup>d</sup>	none ( $\sigma$ levels)	N	–	–/ Diansky et al. (2002)
16	IPSL_CM4	OPA8.1	Treguier et al. (1997)	V	15 to 2000 <sup>a</sup>	PCMDI/ Madec et al. (1998)
17	MIROC3_2_HIRES	COCO3.0	GWMM95	F	700 <sup>e</sup>	Hasumi et al. (2004)
18	MIROC3_2_MEDRES	COCO3.0	GWMM95	F	700	Hasumi et al. (2004)
19	MIUB_ECHO_G	HOPE-G	none	N	–	–
20	MPIECHAM5	MPI-OM	GWMM95, Grif98	F	200 <sup>f</sup>	Johann Jungclaus, pers. comm./ Marsland et al. (2003)
21	MRI_CGCM2_3_2	<sup>d</sup>	GM90	F	2000	Yukimoto et al. (2001)
22	NCAR_CCSM3_0	POP	GM90, Grif98	F	600	Danabasoglu et al. (2006)
23	NCAR_PCM1 <sup>g</sup>	–	–	–	–	–
24	UKMO_HADCM3	<sup>d</sup>	GWMM95, Vis97, Wright (1997)	V	300 to 2000 <sup>a</sup>	Wright (1997)
25	UKMO_HADGEM1	<sup>d</sup>	Vis97, Grif98, Roberts (2004)	V	150 to 2000 <sup>a</sup>	Roberts (2004)

<sup>a</sup>min. to max. range imposed on variable  $\kappa$  formulation

<sup>b</sup>depends on mesh size as a function of latitude only

<sup>c</sup>estimated equivalent value

<sup>d</sup>no well-known name as a stand-alone model

<sup>e</sup>value south of 50° lat.;  $\kappa=0$  north of 40° lat., with a linear increase in between

<sup>f</sup>value in latitudes of the ACC; actual value depends on mesh size in rotated grid

<sup>g</sup>disregarded for this study since no control run available

## 521 List of Figures

522 1 (a) The AR4 climate models (blue squares; numbers see Table 1) sorted by the  
523 ACC transport (volume transport through Drake Passage) and the GM index  
524 (see text for definition). Red diamond: FAMOUS control run. (b) The ACC  
525 transport against the value of the quasi-Stokes diffusivity  $\kappa$  on logarithmic  
526 scales. Blue squares show the AR4 models, but only the type  $F$  models, where  
527  $\kappa$  is constant or at most a function of latitude, are included. Red diamonds  
528 show the FAMOUS model runs. (c) The zonally averaged meridional density  
529 gradient across the ACC against  $\kappa$ , for the type  $F$  AR4 models (blue squares)  
530 and those FAMOUS runs where  $\kappa$  was varied (red diamonds). The scale for  
531  $\kappa$  is logarithmic. (d) The ACC transport against  $\kappa_{iso}$ , for the type  $F$  models  
532 (blue squares) and those FAMOUS runs where  $\kappa$  and  $\kappa_{iso}$  were varied (green  
533 diamonds). The scale for  $\kappa_{iso}$  is logarithmic. Here and in Fig. 2, the black  
534 lines are the regression lines, and the correlation and regression coefficients  
535 are calculated from the AR4 models, excluding FAMOUS. In panel d) the  
536 first regression coefficient is not significant.

31

537 2 Upper row: the ACC transport against the meridional density difference  
538  $\Delta\rho_y$  across the ACC for (a) the type  $F$  models and (b) all AR4 models.  
539 Lower row: the ACC transport against the maximum zonally averaged wind  
540 stress  $\tau^x$  over the Southern Ocean for (c) the type  $F$  models and (d) all AR4  
541 models. In all panels, the red diamonds represent the FAMOUS model runs  
542 (where only  $\kappa$  was varied). There is no significant correlation with  $\tau^x$  if all  
543 AR4 models are considered, while a correlation with  $\Delta\rho_y$  is retained. In (d)  
544 the crosses denotes the mean value from the last 100 years of the control  
545 runs, and the error bars show one standard deviation (of the annual means).  
546 Since the standard deviations are very small for most models, simple squares  
547 represent the models in the other panels as well as in Fig. 1. In all panels the  
548 black asterisk indicates observational values. These are from Cunningham et  
549 al., 2003, for the ACC; Risien and Chelton, 2008, for the wind stress (from  
550 QuikSCAT); and the World Ocean Atlas 2005 (Locarnini et al., 2006; Antonov  
551 et al., 2006) for the density difference. 32

552 3 Zonally averaged density difference  $\Delta\rho_y(z)$  across the ACC, as a function of  
553 depth, for the FAMOUS runs (solid lines), four of the AR4 models (dashed  
554 lines) and from observations (World Ocean Atlas 2005; dash-dotted). The  
555 dotted vertical line marks  $\Delta\rho_y(z) = 0$ .  $\Delta\rho_y(z)$  is defined as the potential  
556 density ( $\sigma_0$ ) difference between the averaged latitude bands 65°S to 62°S on  
557 the one hand and 45°S to 42°S on the other hand. 33

558 4 Potential density  $\sigma_0$  of the FAMOUS model runs in the Southern Ocean,  
559 averaged zonally and over the last 20 years of the runs. (a) Control run; (b)  
560 anomalies of K600; (c) anomalies of K2000. Below 100m depth, the patterns  
561 in (b) and (c) are very similar, but with the opposite sign, reflecting the effect  
562 on the stratification of decreasing/ increasing  $\kappa$ .

34



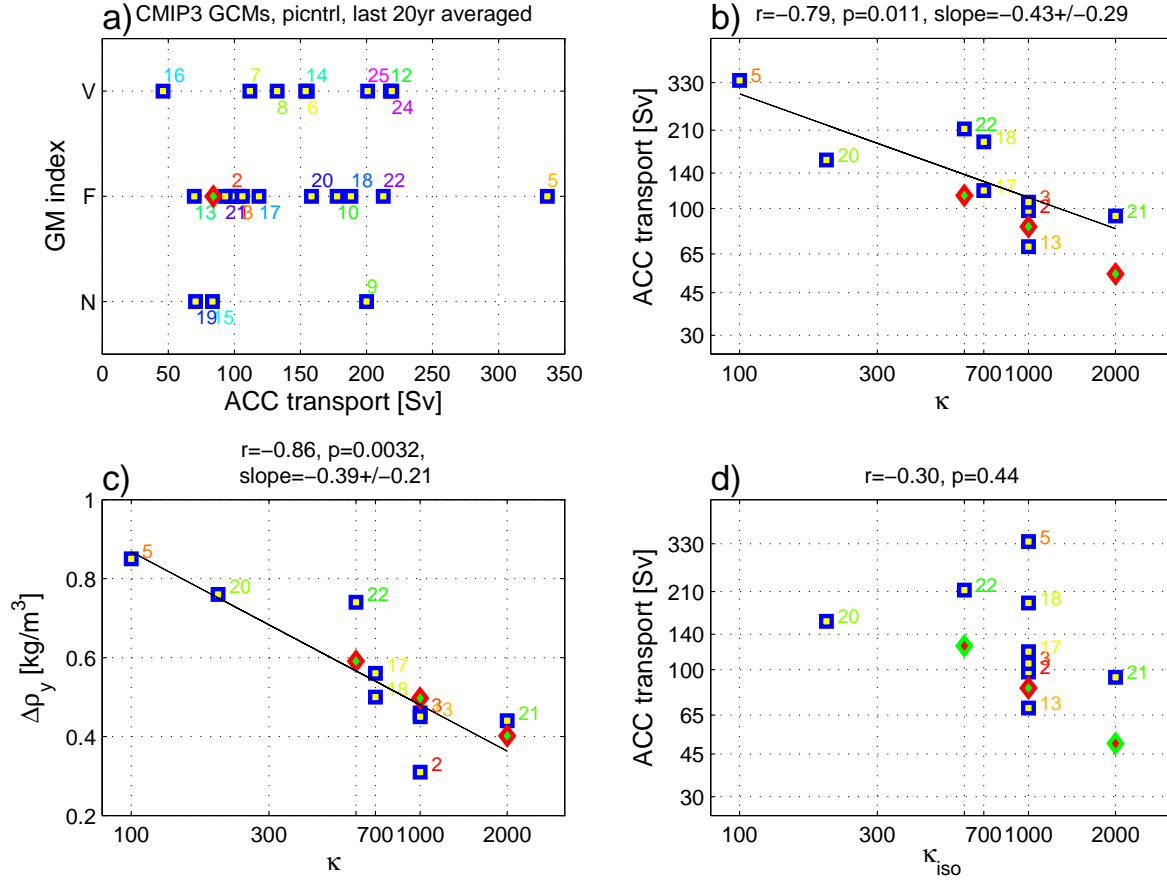


FIG. 1. (a) The AR4 climate models (blue squares; numbers see Table 1) sorted by the ACC transport (volume transport through Drake Passage) and the GM index (see text for definition). Red diamond: FAMOUS control run. (b) The ACC transport against the value of the quasi-Stokes diffusivity  $\kappa$  on logarithmic scales. Blue squares show the AR4 models, but only the type *F* models, where  $\kappa$  is constant or at most a function of latitude, are included. Red diamonds show the FAMOUS model runs. (c) The zonally averaged meridional density gradient across the ACC against  $\kappa$ , for the type *F* AR4 models (blue squares) and those FAMOUS runs where  $\kappa$  was varied (red diamonds). The scale for  $\kappa$  is logarithmic. (d) The ACC transport against  $\kappa_{iso}$ , for the type *F* models (blue squares) and those FAMOUS runs where  $\kappa$  and  $\kappa_{iso}$  were varied (green diamonds). The scale for  $\kappa_{iso}$  is logarithmic. Here and in Fig. 2, the black lines are the regression lines, and the correlation and regression coefficients are calculated from the AR4 models, excluding FAMOUS. In panel d) the first regression coefficient is not significant.

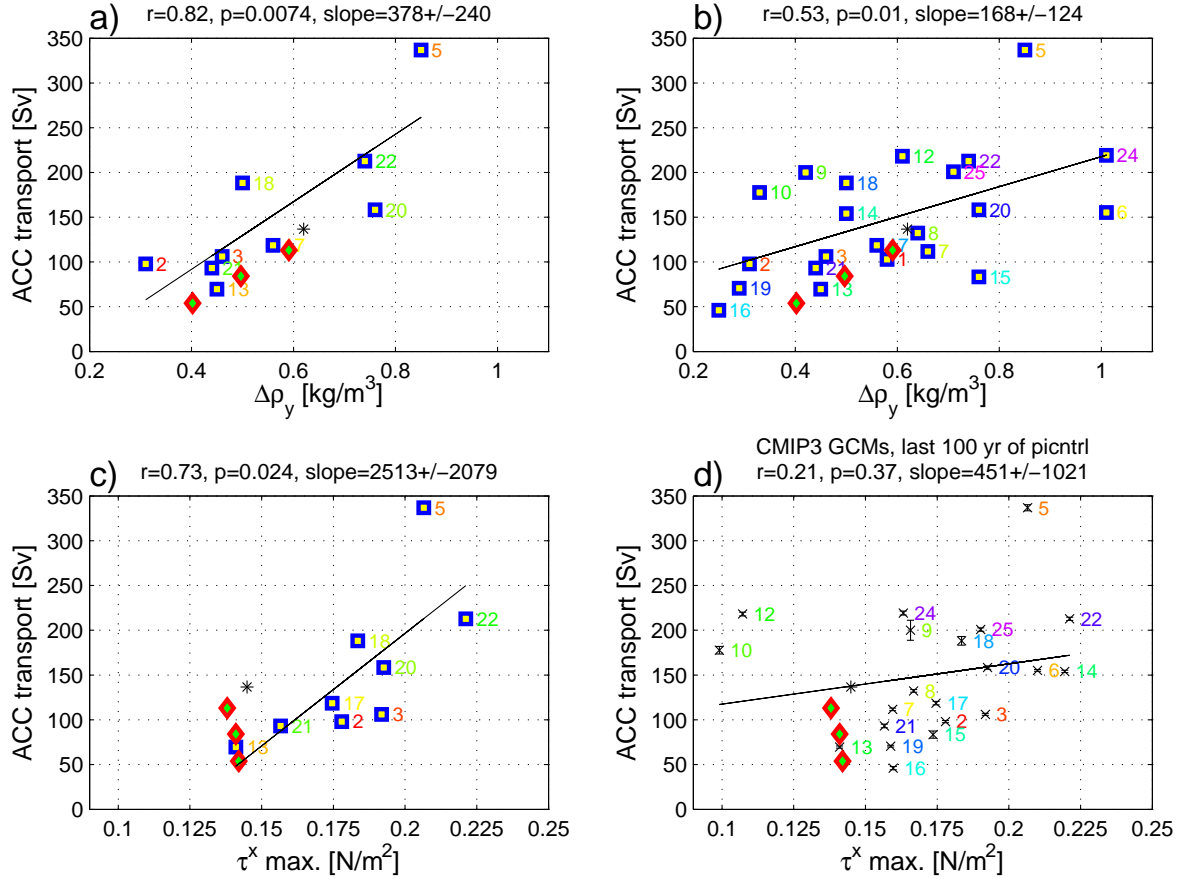


FIG. 2. Upper row: the ACC transport against the meridional density difference  $\Delta\rho_y$  across the ACC for (a) the type *F* models and (b) all AR4 models. Lower row: the ACC transport against the maximum zonally averaged wind stress  $\tau^x$  over the Southern Ocean for (c) the type *F* models and (d) all AR4 models. In all panels, the red diamonds represent the FAMOUS model runs (where only  $\kappa$  was varied). There is no significant correlation with  $\tau^x$  if all AR4 models are considered, while a correlation with  $\Delta\rho_y$  is retained. In (d) the crosses denotes the mean value from the last 100 years of the control runs, and the error bars show one standard deviation (of the annual means). Since the standard deviations are very small for most models, simple squares represent the models in the other panels as well as in Fig. 1. In all panels the black asterisk indicates observational values. These are from Cunningham et al., 2003, for the ACC; Risien and Chelton, 2008, for the wind stress (from QuikSCAT); and the World Ocean Atlas 2005 (Locarnini et al., 2006; Antonov et al., 2006) for the density difference.

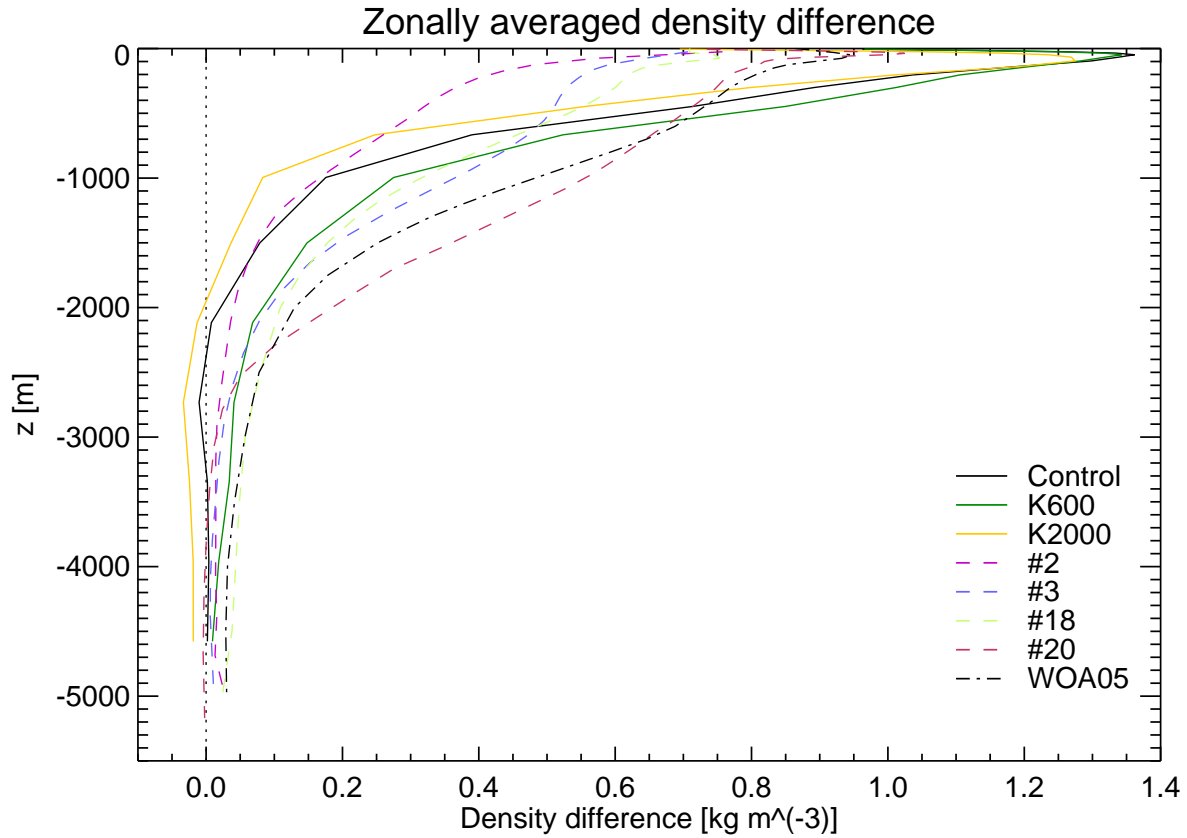


FIG. 3. Zonally averaged density difference  $\Delta\rho_y(z)$  across the ACC, as a function of depth, for the FAMOUS runs (solid lines), four of the AR4 models (dashed lines) and from observations (World Ocean Atlas 2005; dash-dotted). The dotted vertical line marks  $\Delta\rho_y(z) = 0$ .  $\Delta\rho_y(z)$  is defined as the potential density ( $\sigma_0$ ) difference between the averaged latitude bands  $65^\circ\text{S}$  to  $62^\circ\text{S}$  on the one hand and  $45^\circ\text{S}$  to  $42^\circ\text{S}$  on the other hand.

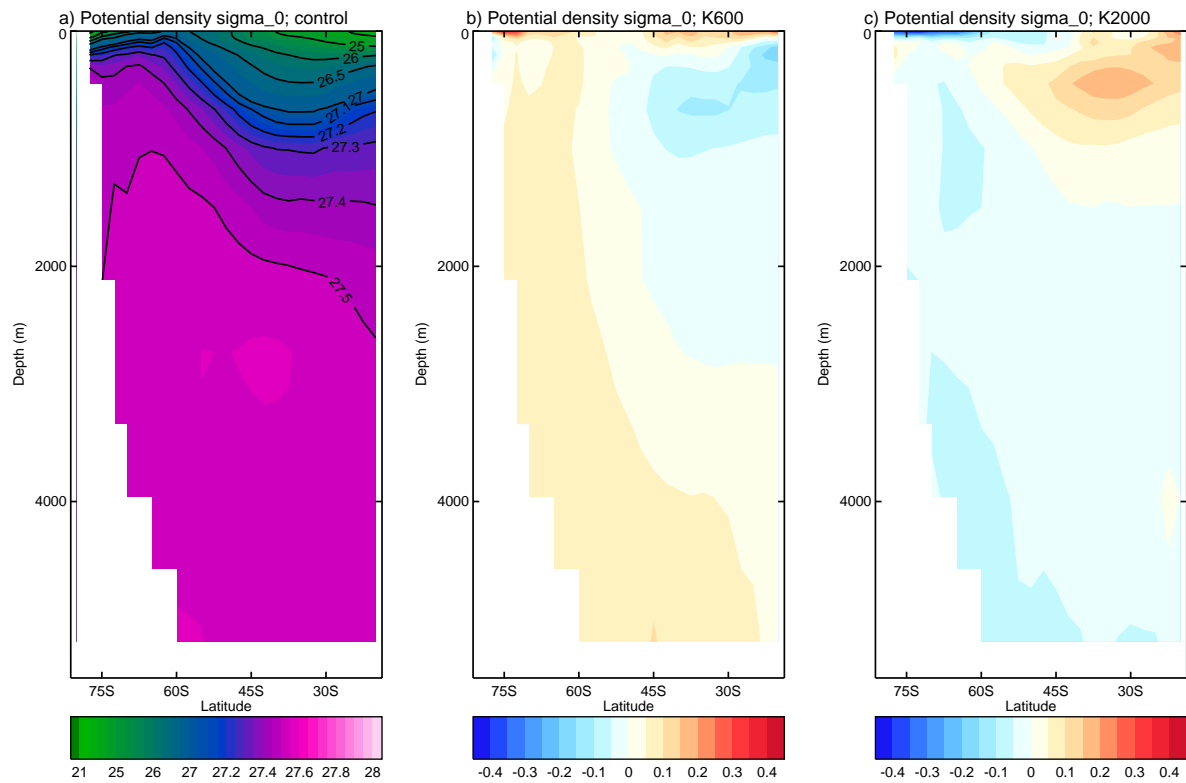


FIG. 4. Potential density  $\sigma_0$  of the FAMOUS model runs in the Southern Ocean, averaged zonally and over the last 20 years of the runs. (a) Control run; (b) anomalies of K600; (c) anomalies of K2000. Below 100m depth, the patterns in (b) and (c) are very similar, but with the opposite sign, reflecting the effect on the stratification of decreasing/ increasing  $\kappa$ .