GEOPHYSICAL RESEARCH LETTERS, VOL. ???, XXXX, DOI:10.1029/,

Density-driven Southern Hemisphere subpolar gyres in coupled climate models

Z. Wang and M. P. Meredith

British Antarctic Survey, High Cross, Madingley Road, Cambridge, UK,
CB3 0ET

British Antarctic Survey, High Cross, Madingley Road, Cambridge, UK, CB3 0ET. (zwa@bas.ac.uk)

We investigate the representation of Southern Hemisphere subpolar gyres in 20 IPCC AR4 climate models. The models reproduce three southern subpolar gyres: the Weddell Gyre, Ross Gyre, and Australian-Antarctic Gyre, in *agreement* with observations. Some models simulate the presence of a subpolar “supergyre”, with strong connectivity between the three gyres. The gyre strengths and structures show a great range across the models. It is found that the link between the gyre strengths and wind stress curls is weak, indicating that the Sverdrup balance does not hold for the modelled southern subpolar gyres; instead, the simulated gyre strengths are mainly determined by upper layer meridional density gradients, which are themselves determined predominantly by the salinity gradients. These findings suggest that a correct simulation of salinity is crucial in the simulation of southern subpolar ocean circulation.

1. Introduction

Southern Hemisphere subpolar gyres (hereafter subpolar gyres) are cyclonic ocean circulations that circulate to the south of the Antarctic Circumpolar Current (ACC) and are bounded by the Antarctic continent. These gyres are important as sites of dense water production and export, significant ice production and advection, and as regions of intermediate climate separating the glaciated Antarctic continent from the comparatively warm waters of the ACC. Consequently, prediction of the climate evolution of Antarctica and its impact on lower-latitude (including planetary) climate requires accurate representation and validation of the subpolar gyres. However, the subpolar gyres are difficult locations from which to obtain measurements since the perennial ice cover and harsh climate makes observations very difficult. In this study, we investigate the simulated subpolar gyres and examine the relative roles of wind forcing and density structure in determining the gyre structures and strengths, through analysing the output of IPCC AR4 coupled climate models.

There are two conventionally defined subpolar gyres, i.e., the Weddell Gyre (WG) and the Ross Gyre (RG). The WG is a zonally elongated cyclonic gyre, which extends from the Antarctic Peninsula (AP) to immediately west of the Kerguelen Plateau (KP) [Gordon et al. 1981; Park and Gambéroni 1995]. Its meridional extent is relatively small, being bounded by the Antarctic continent and the South Scotia Ridge, North Weddell Ridge, and the Southwest Indian Ridge. The RG is a compact cyclonic gyre in the Ross Sea embayment [Gouretski 1998]. Recently, based on hydrographic data and direct-velocity measurements, McCartney and Donohue [2007] suggested that there is a deep cyclonic gyre in the Australian-Antarctic basin, i.e., the Australian-Antarctic Gyre (AG).

It has been thought that subpolar gyres are primarily driven by wind and buoyancy forcing, and are constrained by topography. *Beckmann et al. [1999] used a coupled ocean-ice regional model to demonstrate the important role of wind forcing in driving the WG.* Here, we analyse the output of the IPCC AR4 coupled climate models to investigate the relative roles of wind forcing and density structure in the setting of the gyre strengths *in these models.*

2. Results

2.1. Strengths of the subpolar gyres

The strengths of the WG, RG and AG in 20 IPCC AR4 models are listed in Table 1. The descriptions of these models can be found at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php. We analyze the 50-year means (1950-1999) from their 20th century runs. The gyre strengths are defined as the maximum westward transports across the Prime Meridian, 150°W and 110°E for the WG, RG, and AG respectively, in order to compare the simulated results with the available observational estimates across these longitudes. *The transports across these three longitudes are generally slightly lower than the transports across the longitudes of the gyre centres, and we note that there are good linear relationships between the former and the latter in these models.*

Carmack and Foster [1975] estimated the strength of the WG as 97 Sv using current-meter referencing. Gordon et al. [1981] used wind stress data to give an estimation of

76 Sv. By using shipboard acoustic Doppler current profilers (SADCP) data, Schröder and Fahrbach [1999] estimated the westward transport at the Prime Meridian of 66 Sv. Some earlier estimations without using SADCP data and with bottom level of no motion had less than half that value. Based on 4.5 year-duration moored current measurements, Klatt et al. [2005] gave the updated westward transport of 56 ± 8 Sv across the Prime Meridian. The simulated WG strength ranges from 1.6 Sv to 93.3 Sv in the 20 models with most models having a weaker WG than that observed.

For the RG, an estimate using hydrographic data with the ocean bottom as reference level of no motion gave the baroclinic transport of 8.5 Sv across 150°W [Gouretski 1999]. However, in the subpolar region with weak stratification and equivalent barotropic structure, neglecting the barotropic component of velocity can lead to a significant underestimation of the total transport [Park and Gambéroni 1995]. Indeed, for the WG it has been noted that the baroclinic westward transport across the Prime Meridian is only around one third of the total transport [Klatt et al. 2005]. If the same were true of the RG (for which fewer data exist), the total transport across 150°W could be very much larger than the stated baroclinic transport. Accordingly, those models that give the maximum transports of lower than or close to 8.5 Sv possibly underestimate the strength of the RG.

Early studies using hydrographic data did not show clearly the existence of the AG. Through resolving the barotropic component, the altimeter data from the TOPEX/POSEIDON mission suggest that there is a cyclonic subpolar gyre to the east of the KP [Park and Gambéroni 1995]. 12 models produce the westward transport across 110°E of more than 5 Sv, supporting the existence of the AG. Using summer hydrographic data and independent direct-velocity measurements, McCartney and Donohue [2007] estimated the westward flow across 110°E as 76 ± 26 Sv, much higher than those simulated by all models.

2.2. Structures of the subpolar gyres

Vertically integrated zonal transports (westward negative) in 6 selected models are shown in Fig. 1. *These models are selected to cover the range of simulated gyre strengths: models 6 and 20 with intermediate WG strengths or close to that observed, models 9 and 14 with very weak WG, and models 12 and 15 with very strong WG.* By only showing the negative total transport (net westward transport), we are able to clearly see the spatial structures of the subpolar gyres.

Models 6, 12, 15 and 20 produce the structure with gyres in the Weddell-Enderby basin, the Ross Sea, and the Australia-Antarctic basin, although there are no clear boundaries between two gyres in some cases. Whilst the western boundary of the WG is fixed by the AP, its eastern boundary is less consistent between the models. Model 20 has its eastern boundary at around 45°E, but the WG in model 14 extends further east to the west side of the KP. For models 6, 12 and 15, the westward flow along the Antarctic coast even extends from the Australian-Antarctic basin. The large variation of the eastern boundary is likely caused by different simulations of the interactions between the ACC and the KP.

The RG fills the Ross Sea, with its eastern boundary being at about 140°W. Although its eastern limb extends into the Bellingshausen and the Amundsen Sea in models 6, 12, 15 and 20, the meridional extents of westward flow in models 6, 12 and 20 are small. Analysis of hydrographic data shows that the eastern boundary of the RG is at 140°W, being constrained by bottom topography [Gouretski 1999]. Unlike the WG, the RG has no pronounced western boundary, due to the lack of a meridional barrier. In models 15 and 20, the westward flow extends into the Australian-Antarctic basin.

The simulations of the AG differ considerably in these models, ranging from no cyclonic circulation in models 9 and 14 to a strong cyclonic circulation in model 12. It is suggested by models 6, 15 and 20 that the western boundary is at the east side of the KP, where there is an observed northward transport of 48 Sv [McCartney and Donohue 2007], but no consistent eastern boundary.

A double cell structure of the WG with two sub-gyre centres sitting on each side of the Prime Meridian can be seen in model 6, 15 and 20. This double cell structure was observed by Orsi et al. [1993] and simulated by Beckmann et al. [1999]. The westward passing flow through the Princess Elizabeth Trough, to the south of the KP at around 80°E, that bridges the WG and the AG, is simulated by models 6, 12 and 15, and echoes the observation of McCartney and Donohue [2007]. The difference in the simulations of this passing flow reflects different representations of the dynamic topographic effects of the KP.

It is not clear whether the continuous westward flow from the Ross Sea to the Australian-Antarctic basin exists in reality. If there is an uninterrupted westward flow from the west side to the east side of the AP, there exists a “supergyre” structure around Antarctica, with three major localized gyres in the Weddell-Enderby basin, the Ross Sea and the Australian-Antarctic basin. Unlike the Northern Hemisphere subpolar gyres, the southern subpolar gyres are less bounded by continents in the zonal direction.

2.3. Wind-driven versus density-driven subpolar gyres

We plot the gyre strengths against the wind stress curls for the WG, RG, and AG in Fig. 2. The wind stress curls are area averaged values over three domains from the Antarctic coast to 55°S, and from 60°W to 60°E for the WG, from 165°E to 135°W for the RG, and from 80°E to 165°E for the AG respectively.

All models produce negative wind stress curls, i.e., cyclonic atmospheric circulations, over the three domains, except model 8 that produces a slightly positive value in the Australian-Antarctic basin. The curls are very different, with the curls in some models being about three or four times larger than the values of others. Although the best linear fits do suggest a slight tendency for stronger gyre strengths with increasing wind forcing over the WG and RG, the very large scatters and the reversed relationship for the AG indicate that the Sverdrup balance does not hold for the subpolar gyres. Further, no clear relationships can be found between the gyre strengths and the area-integrated westward wind stress or the areas of westward wind stress (not shown). These results indicate that the subpolar gyres are not set by wind forcing.

Fig. 3 shows the relationships between the gyre strengths and the meridional density gradients for the three gyres. The potential density is first vertically averaged over the upper 1000 m, and then zonally averaged over a specific longitudinal span (from 30°W to 30°E for the WG, 180°E to 120°W for the RG, and 80°E to 140°E for the AG). The meridional density gradient is then obtained by subtracting the averaged potential density at a higher latitude (gyre rim) (70°S, 75°S and 66°S respectively for the WG, RG and AG) from that at a lower latitude (gyre centre) (62°S, 70°S, and 60°S respectively for the

WG, RG and AG). Thus, a positive meridional density gradient means denser water in the north (gyre centre) and lighter water in the south (gyre rim), i.e., a domed isopycnal structure.

For all the three gyres, the best linear fits indicate a consistent relationship between the gyre strength and the meridional density gradient: *the lighter upper layer water in the south is associated with the stronger subpolar gyres.* This relationship is particularly clear for the WG, the strongest of the southern subpolar gyres.

From Fig. 2a, we see that models 10, 17 and 18 have almost the same wind stress curl, but very different WG strengths. This is due to very different meridional density gradients in these models, as seen from Fig. 3a. For other models with very different gyre strengths and almost the same value of wind stress curl (such as 1, 5 and 15; 20 and 12), this is also the case. Some exceptions in Fig. 3a and relatively large scatters in Fig. 3b and 3c imply that the effects of other dynamical processes are not negligible in some cases. Nevertheless, by considering the highly diverse model configurations and parameterizations of subgrid processes in the 20 IPCC AR4 models, it is clear that the gyre strengths are mainly determined by the meridional density gradients, particularly for the WG.

Fig. 4 shows the dependence of the derived meridional density gradients on the meridional gradients of potential temperature and salinity for the WG. All models, except 6 and 15, produce warmer temperatures in the north than the south (Fig 4a). Most models also simulate saltier (and therefore denser) water in the north compared with the south

(Fig. 4b). The very small scatters from the best linear fit in Fig. 4b clearly demonstrate that salinity gradients contribute dominantly to the density gradients.

Further analysis does not reveal a clear relationship between the surface freshwater forcing and salinity structure (not shown), suggesting that oceanic processes (including subgrid scale mixing processes) are also important in determining the salinity structure of the gyres.

3. Concluding remarks

We have presented the simulated subpolar gyres in 20 IPCC AR4 coupled climate models, and have compared the simulated gyres with the best available observational results. The models simulate the existence of three southern subpolar gyres, i.e., the WG, the RG, and the AG, however there being considerable discrepancies in the simulated gyre strengths and structures.

The observed double cell structure of the WG is simulated by some models. The different representations of the dynamical topographic effects of the KP lead to diverse simulations of the eastern boundary of the WG and the westward passing flow through the Princess Elizabeth Trough. Some models simulate the presence of a subpolar “supergyre”, with obvious connectivity between the three subpolar gyres.

Further analysis shows that the link between the simulated gyre strengths and wind stress curls is very weak, indicating that the Sverdrup balance does not hold for the subpolar gyres. Instead, the gyre strength is mainly determined by the meridional density gradient in the subpolar area (this is particularly so for the WG), which itself depends predominantly on the salinity gradient.

It has been found that the North Atlantic subpolar gyre is not sensitive to wind stress forcing [Bryan et al. 1995]. The recent observed decline of this gyre is attributed to the warming at the gyre centre, which leads to the decay of its domed isopycnal structure, despite wind stress curl increasing in this area [Häkkinen and Rhines 2004]. These findings suggest that buoyancy forcing plays a more important role than wind forcing in driving the subpolar gyre in the North Atlantic. Our results are consistent with these findings. However, it is important to note that the seawater temperature in the southern subpolar gyres is much colder than that in their northern counterparts. Consequently, the southern subpolar gyres are much more sensitive to salinity changes.

Southern high latitude salinity structure is determined by salt transport in the ocean and by freshwater forcing from surface processes, such as atmospheric moisture transport, sea ice melting/freezing, and even the mass balance of ice shelf or continental ice. A correct simulation of the southern subpolar gyres needs a complete understanding of water cycle in the southern high latitudes that involves these processes. Although challenging, this is needed if coupled climate models are to reliably simulate the structure and circulation of the subpolar gyres, and hence their impacts on e.g. dense water production and export, and ice formation and advection.

As a final point, it should be noted that hydrographic data in the southern high latitudes have historically been obtained almost exclusively during austral summer season. However, due to sea ice and atmospheric processes, salinity structure during the summer can be very different from that during other seasons, with consequences for gyre strengths. This should be carefully considered when deriving the climatology of subpolar ocean circulation using the summer-dominated hydrographic data.

Acknowledgments. *We acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset.*

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No.	model name	WG	RG	AG
1	cccma_cgcm3_1	10.3	0.4	0.7
2	cccma_cgcm3_1_t63	19.5	3.4	1.3
3	cnrm_cm3_0	23.2	3.6	10.6
4	csiro_mk3_0	14.0	17.2	0.0
5	csiro_mk3_5	28.2	13.4	5.8
6	gfdl_cm2_0	40.8	12.2	6.4
7	gfdl_cm2_1	24.1	10.7	1.7
8	giss_aom	19.9	22.6	8.2
9	giss_model_e_r	5.7	16.2	0.0
10	ingv_echam4	15.0	9.8	0.0
11	ipsl_cm4	44.7	6.9	18.6
12	miroc3_2_hires	93.3	24.9	18.6
13	miroc3_2_medres	35.5	0.1	1.3
14	miub_echo_g	1.6	0.9	0.0
15	mpi_echam5	79.4	52.0	17.1
16	mri_cgcm2_3_2a	12.9	2.7	14.9
17	ncar_ccsm3_0	35.5	13.4	5.5
18	ncar_pcm1	88.7	30.1	31.8
19	ukmo_hadcm3	17.0	19.1	9.6
20	ukmo_hadgem1	48.4	26.8	14.2

Table 1. Strengths (in Sv) of southern subpolar gyres in 20 IPCC AR4 coupled climate models.

Figure 1. Vertically integrated zonal transports of six IPCC AR4 models in the southern subpolar region.

Figure 2. Gyre strengths against wind stress curls for (a) the WG, (b) the RG, and (c) the AG. The black line is the best linear fit.

Figure 3. Gyre strengths against meridional density gradients for (a) the WG, (b)the RG, and (c) the AG. The black line is the best linear fit.

Figure 4. Meridional density gradients against (a) meridional temperature gradients and (b) meridional salinity gradients for the WG. The black line is the best linear fit.