CHANGES TO THE SOUTHERN HEMISPHERE EXTRATROPICAL OCEAN AND SEA-ICE IN THE IPCC COUPLED CLIMATE MODELS

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1. INTRODUCTION

Over recent decades the extratropical Southern Hemisphere has experienced one of the most profound and robust climate trends – a southward shift in the extratropical wind field, often associated with an increasingly positive state of the dominant mode of Southern Hemisphere extratropical variability, the Southern Annular Mode (SAM, e.g. Kushner et al., 2001, Thompson et al., 2000). The observed shift is simulated in most of the state-of-the-art climate models. Furthermore, these models generally show a continuing trend into the future. This mode is known to have a strong influence on the extratropical ocean and sea-ice systems (e.g. Sen Gupta and England, 2006). As such, the surface signature of this atmospheric rearrangement has the potential to significantly modify characteristics of the ocean and sea-ice system including the ocean's ability to sequester heat and anthropogenic gases. This is on the backdrop of, and intimately related to, unprecedented, large-scale increases in global temperatures and modifications to the hydrological cycle.

In this study, we investigate the ability of a diverse range of IPCC AR4 coupled climate models constituting the Coupled Model Intercomparison Project (CMIP3), to realistically simulate the large-scale features of the SH extratropical ocean and sea-ice systems for the end of the 20th century (20C). In particular we assess surface properties, mixed layer depths, water mass characteristics and lateral and overturning circulation. A further investigation is made of the projected changes to these properties over the 21st century under the SRES A1B forcing scenario (21C). A major motivation of this work is the possibility that changes to this region may have a significant impact on the ability of the Southern Ocean to sequester CO2 (Sabine et al., 2004) and heat (Gille, 2002). For more detail see Sen Gupta et al. (2009).

2. RESULTS

2.1 Model Drift

A model integrated forward in time from some set of initial conditions will tend to 'drift' until a quasi-equilibrium state is reached. Unfortunately, it is not feasible to integrate these computationally expensive climate models for such periods and the various forced simulations are generally started from control runs that have been integrated out for a few hundred years at best. As a result, some model drift is to be expected particularly within the ocean. An examination of zonally averaged temperature shows that in some of the models a sizeable drift persists sometimes exceeding 0.5ºC/century in certain regions. It is clearly of great importance to take account of any model drift when investigating changes in the ocean interior particularly when analyzing changes at smaller spatial scales or in the deep ocean.

2.2 Changes to the boundary forcing

Over the 21st century, both the wind-stress maximum (at ~50ºS) and the wind stress curl (at ~40ºS) are projected to intensify and shift southwards (Fig. 1a,b). As simulated by Cai et al. (2005) and Saenko et al.(2005) in climate model experiments, this has the potential to cause a spin up of the subtropical gyres and a southward intensification of the ACC. Evidence of recent intensification of the Pacific gyre has already been observed (Roemmich et al., 2007). At the same time there is an intensification of the hydrological cycle with increased precipitation in the tropical and mid-to-high latitude regions and reduced precipitation in the subtropics (Fig. 1c). At midlatitudes this is related to a poleward intensification of the mid-latitude precipitation linked to a shift in the Southern Hemisphere storm track. Such shifts in the storm tracks have already been observed (e.g. Simmonds and Keay 2000). These wind-induced modifications are consistent with an increasingly positive SAM. The pattern of heat flux change is more complex (Fig. 1d). Overall, there is a shift in the balance of turbulent heat fluxes from the ocean to the atmosphere: a reduction in sensible heat loss is counteracted by an increase in latent heat loss, although regional variations abound. Overall, there is an increased radiative flux into the ocean, most pronounced at high latitudes where there is also a reduction in summer albedo. Most of the additional heat entering the Southern Hemisphere oceans does so to the south of 50º.

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2.3 Stratification

All models show an increase in SST across the SH extratropics, that is minimum at higher latitudes, as a result of enhanced northward Ekman transport. At the same time there is a freshening at higher latitudes, driven in part by the intensified hydrological cycle. This leads to an increase in stratification throughout the extratropics driven primarily by salinity changes at high latitudes, and by temperature changes at lower latitudes (Fig. 2). This results in a large scale shoaling of the deep mixed layers at mid-latitudes over the 21st century (Fig. 3). The total volume of the mid-latitude mixed layer reduces by between 5 and 20% across the models.

2.4 Circulation changes

Fig. 2 also shows the projected southward shift of isopycnal surfaces that is more pronounced at lower latitudes. This increases the meridional density gradient at mid-latitudes, causing a southward intensification of the ACC, driven ultimately by the modified wind-stress over the Southern Ocean. There is also a clear southward shift of the subtropical gyres, driven by the southward intensification of the wind-stress curl (Fig. 4). The shift in the circulation along with some spin-up of the gyres sets the pattern of depth integrated warming (fig. 4), which is largest between the core of the ACC and the southern limbs of the gyres. This can be understood as a simple poleward displacement in the temperature distribution in a region where the meridional temperature gradients are large. The strongest warming occurs in the Atlantic region where the simulations also project a strong spin-up of the gyre, with an associated increase in the southward advection of warm water.

The surface freshening and surface intensified warming is consistent with a weakening of bottom water formation. This is seen in a spin-down of the Antarctic overturning cell from ~6Sv to ~4Sv (in the multi-model mean). In contrast, the poleward intensified winds drive more vigorous surface divergence at high latitudes, that intensifies the upwelling of deep water, and convergence at lower latitudes, feeding the intermediate depth interior circulation. This can be seen as an increase of ~4Sv in the Deacon cell overturning from a multi-model mean of ~26Sv.

2.5 Sea Ice

Around the Antarctic margin enhanced heating from above and below (as a result of enhanced wind-driven upwelling of relatively warm deep water) helps to cause a melt back of the summer and winter sea-ice (Fig. 5). Over the period, in the multi-model mean, there is a ~30% reduction in total wintertime ice volume, and over 50% reduction during the summer. This acts to diminish the magnitude of the seasonal cycle in ice volume.

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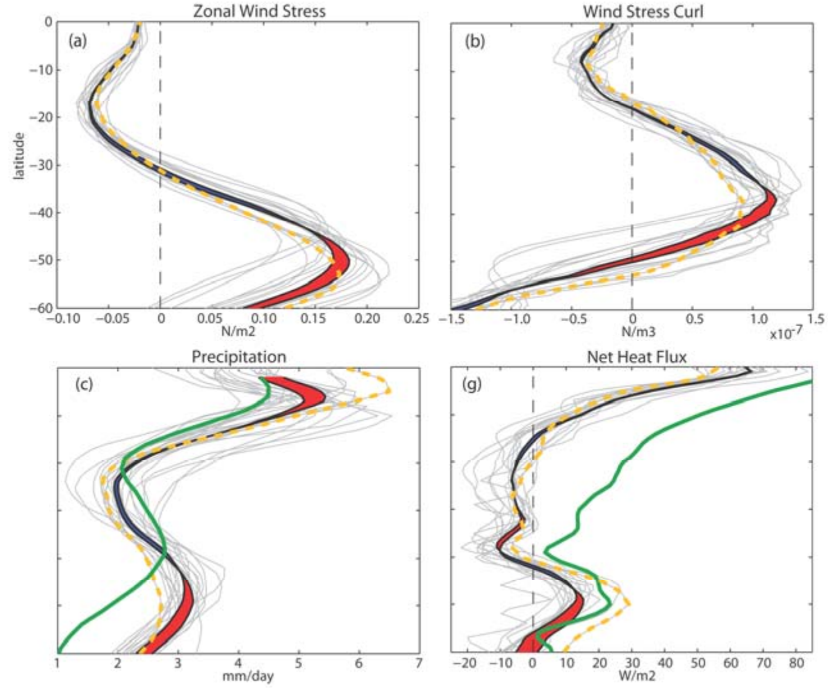

Figure 1. Zonally-averaged wind-stress [$\mathrm{Nm^{-2}}$] (a), wind-stress curl [$\mathrm{Nm^{-1}}$] (b), precipitation [$\mathrm{mmd^{-1}}$] (c), and net heatflux [$\mathrm{Wm^{-2}}$] (g) from the multi-model ensemble for 20C and 21C. Red (blue) areas represent a strengthening (weakening) of the variable from **20C** to **21C**. Yellow line represents ERA40 reanalysis. Green line: (c) CMAP and (d) SOC observations. Grey lines indicate **20C** zonal averages for the individual models.

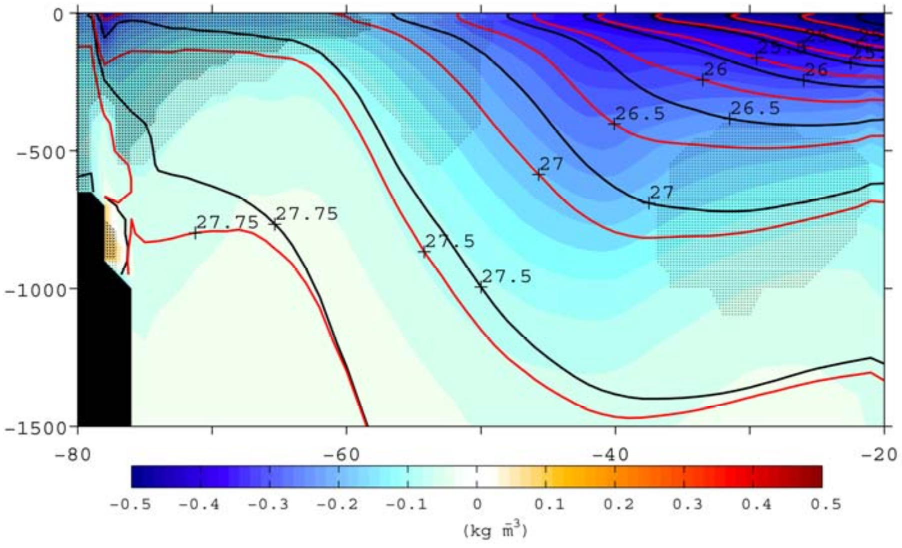

Fig. 2 Projected change in potential density over the 21st century (colour contours). Superimposed are 20C (black) and 21C (red) isopycnals. Mottling indicates regions where salinity is playing a large role (>50% heavy mottling, >25% light mottling) in controlling the density change.

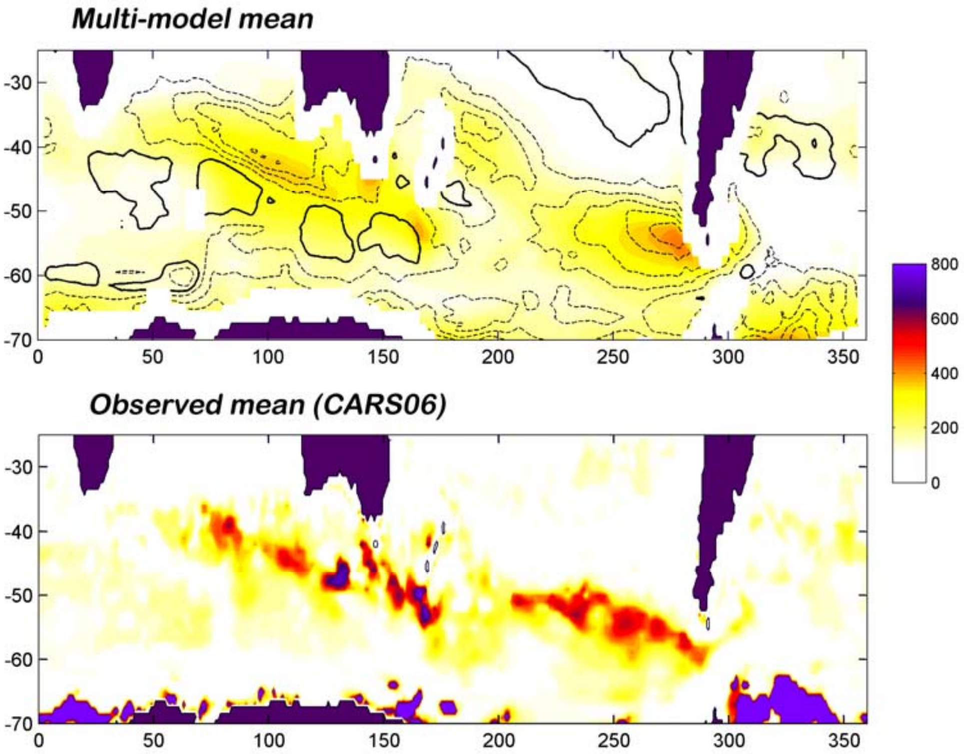

Fig. 3 Maximum mixed layer depth [m] for **20C** milti-model mean (top), and observations (bottom). Superimposed is the change in MLD over the 21st century change (contour interval 50m, dashed lines indicate shoaling).

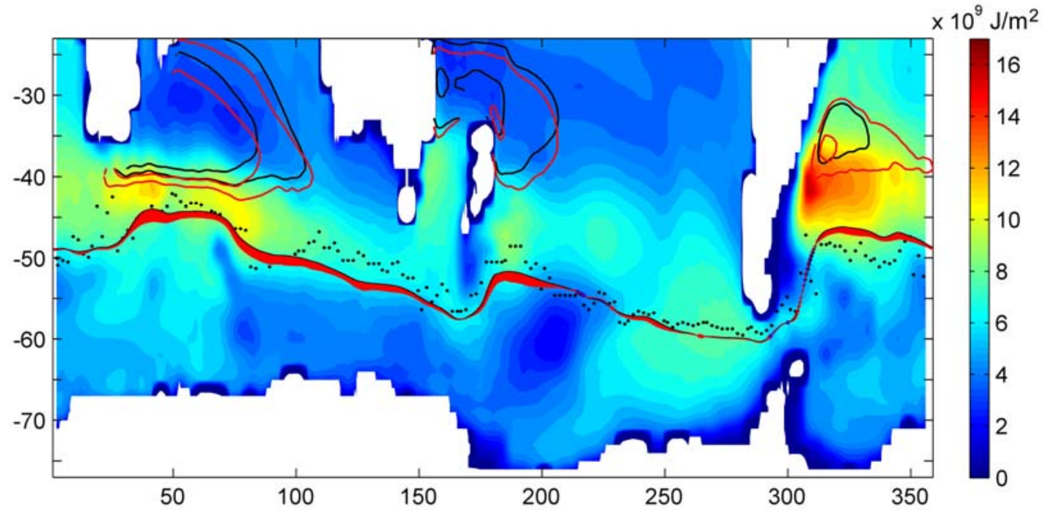

Fig. 4 Lateral, depth averaged circulation and heat content changes for the multi-model mean. Colour contours show the projected change in the depth integrated heat content (21C-20C ; J/m^2). Superimposed are (i) Mean barotropic stream function for 20C (black) and 21C (green, only streamlines indicative of subtropical gyre positions are shown) and (ii) position of ACC maximum for 20C and 21C (red/blue shading between lines indicates poleward/equatorward movement of ACC axis over the period). Dotted line indicates mean position of the observed ACC.

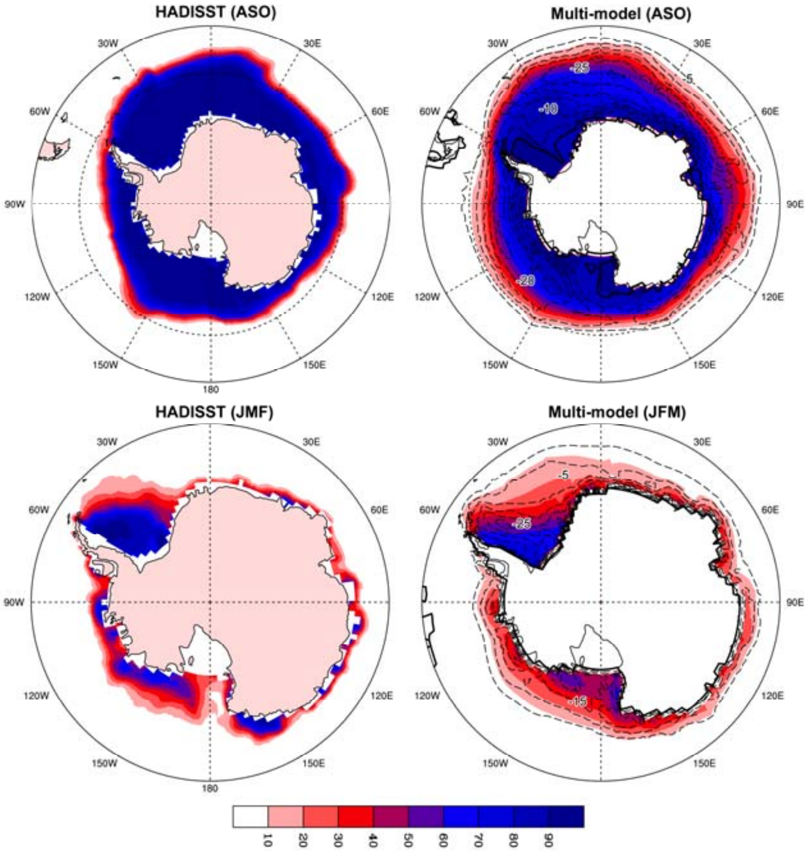

Fig. 5 Winter (top) and summer (bottom) **20C** sea-ice concentration (% cover) for observation (left) and multi-model mean (right). Superimposed contours show the percentage change in sea-ice concentration between 20C and 21C (contour interval 5%, dashed contours denote reduction in sea-ice).