The effect of windstress change on future sea level change in the Southern Ocean

Article

Published Version

Bouttes, N., Gregory, J. M. ORCID: https://orcid.org/0000-0003-1296-8644, Kuhlbrodt, T. ORCID: https://orcid.org/0000-0003-2328-6729 and Suzuki, T. (2012) The effect of windstress change on future sea level change in the Southern Ocean. Geophysical Research Letters, 39 (23). L23602. ISSN 0094-8276 doi: https://doi.org/10.1029/2012GL054207 Available at https://centaur.reading.ac.uk/34190/

To link to this article DOI: http://dx.doi.org/10.1029/2012GL054207

Publisher: American Geophysical Union

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L23602, doi:10.1029/2012GL054207, 2012

The effect of windstress change on future sea level change in the Southern Ocean

N. Bouttes,[1] J. M. Gregory,[1,2] T. Kuhlbrodt,[1] and T. Suzuki[3]

Received 11 October 2012; accepted 30 October 2012; published 1 December 2012.

[1] AOGCMs of the two latest phases (CMIP3 and CMIP5) of the Coupled Model Intercomparison Project, like earlier AOGCMs, predict large regional variations in future sea level change. The model-mean pattern of change in CMIP3 and CMIP5 is very similar, and its most prominent feature is a zonal dipole in the Southern Ocean: sea level rise is larger than the global mean north of 50°S and smaller than the global mean south of 50°S in most models. The individual models show widely varying patterns, although the inter-model spread in local sea level change is smaller in CMIP5 than in CMIP3. Here we investigate whether changes in windstress can explain the different patterns of projected sea level change, especially the Southern Ocean feature, using two AOGCMs forced by the changes in windstress from the CMIP3 and CMIP5 AOGCMs. We show that the strengthening and poleward shift of westerly windstress accounts for the most of the large spread among models in magnitude of this feature. In the Indian, North Pacific and Arctic Oceans, the windstress change is influential, but does not completely account for the projected sea level change.
Citation: Boutttes, N., J. M. Gregory, T. Kuhlbrodt, and T. Suzuki (2012), The effect of windstress change on future sea level change in the Southern Ocean, *Geophys. Res. Lett.*, *39*, L23602, doi:10.1029/2012GL054207.

1. Introduction

[2] Global mean sea level is expected to rise during the 21st century; atmosphere-ocean general circulation models (AOGCMs) predict global mean thermal expansion ranging within 0.1–0.4 m in 2090 to 2099 relative to 1980 to 1999 depending on the model and emissions scenario [*Meehl et al.*, 2007]. Regional change in sea level (with respect to the geoid) depends mainly on changes in ocean density and circulation. AOGCMs predict that future regional sea level change will not be spatially uniform [*Gregory et al.*, 2001; *Yin et al.*, 2010; *Pardaens et al.*, 2011]. In the mean of 21st-century projections made using the AOGCMs of CMIP3 (Coupled Model Intercomparison Project Phase 3), regional sea level rise ranges from almost zero to twice the global mean thermal expansion in 2080 to 2099 relative to 1980 to 1999 [*Meehl et al.*, 2007]. In particular, the pattern of sea level change displays a meridional dipole in the Southern Ocean: sea level rise is relatively lower south of around 50°S and relatively higher north of 50°S. In addition, sea level rise is relatively higher in the north-western part of the Pacific Ocean and in the Arctic.

[3] All the models show that sea level change will be non-uniform, but they do not show the same patterns. The features mentioned are present in most models, but their magnitude is model-dependent, and the models exhibit a great diversity of local detail (Figure S1 in the auxiliary material).[1] Thus, there is a large inter-model spread in local sea level change, which we quantify as twice the ensemble standard deviation, among CMIP3 models [*Pardaens et al.*, 2011] (Figure 2a). The spread is largest where sea level change differs most from the global mean, namely in the Southern Ocean, Arctic Ocean, North Atlantic and western North Pacific. It is important to understand why such differences exist between models in order to identify which aspects of the model formulation and behavior should receive most attention if the reliability of predictions is to be improved.

[4] In general terms, the differences in patterns among models could arise because they predict different sea-level changes in response to given changes in surface fluxes (of heat, freshwater and momentum, i.e., windstress), or because they predict different changes in surface fluxes. Although both may be true, and both are linked to the climate state, it is useful to distinguish them because the first would depend more on the ocean model, the second on the atmosphere model.

[5] Because the windstress change has been identified as a key driver of past and future sea level change in previous studies [*Thompson and Solomon*, 2002; *Merrifield and Maltrud*, 2011; *Han et al.*, 2010; *Timmermann et al.*, 2010; *Sueyoshi and Yasuda*, 2012], we focus on the role of surface windstress change on future sea level change, and test whether it can explain the differences among model results.

2. CMIP5 Results Compared to CMIP3

[6] The sea level change is remarkably similar in the ensemble-means of CMIP3 AOGCMs (Figures 1a and 1c) and of the newer CMIP5 AOGCMs (Figures 1b and 1c). For CMIP3, we have chosen the SRESA1B scenario because the sea level change data were available for the largest number of models, few of which offered them for 1%CO_2. The 14 CMIP3 models and 13 CMIP5 models used in this study are listed in Table S1. The SRES scenarios are not used in CMIP5, and we have chosen 1%CO_2 because it minimizes differences among models in the forcing, which could

---

[1] NCAS-Climate, Meteorology Department, University of Reading, Reading, UK.

[2] Met Office Hadley Center, Exeter, UK.

[3] Research Institute for Global Change, Japan Agency for Marine Earth Science and Technology, Yokohama, Japan.

Corresponding author: N. Bouttes, NCAS-Climate, Meteorology Department, University of Reading, Reading RG6 6BB, UK. (n.bouttes@reading.ac.uk)

0094-8276/12/2012GL054207

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL054207.

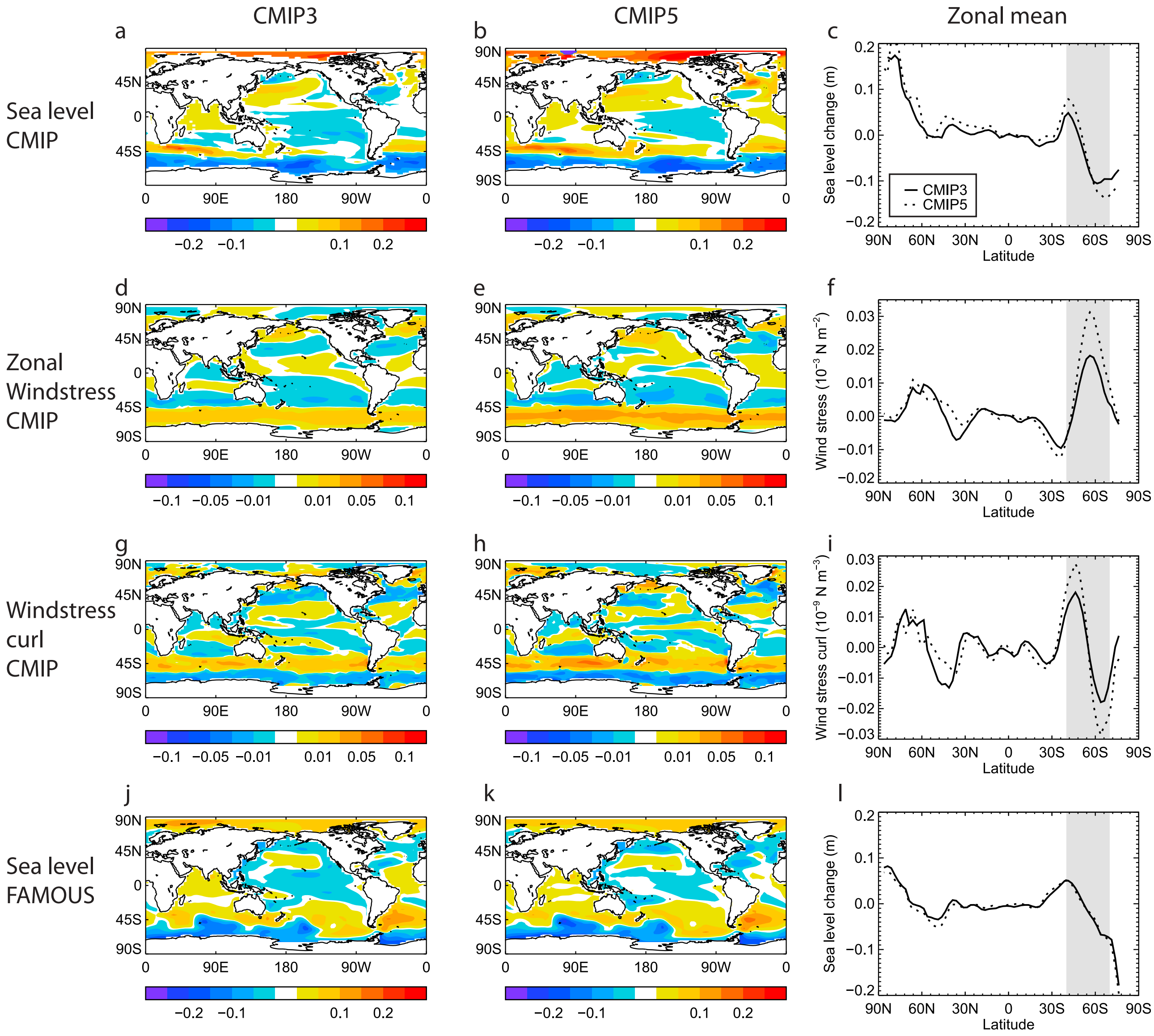

Figure 1. Sea level (m), zonal windstress (10^{-3} Nm^{-2}) and windstress curl (10^{-9} Nm^{-3}) change for (left) CMIP3 models and (middle) CMIP5 models and (right) zonal mean. (a–c) Mean CMIP3+5 sea level change, (d–f) mean CMIP3+5 zonal windstress change, (g–i) mean CMIP3+5 windstress curl change, (j–l) mean sea level change with FAMOUS forced by the windstress anomalies. The change is given by the difference between the mean of the tenth decade and the mean of the first decade of the simulations. The sea level change is relative to the global mean. The sea level and windstress change have been interpolated on a common grid of 3.75° longitude by 2.5° latitude (FAMOUS grid) prior to calculating the mean and the sea level change in inland seas has been masked. The shaded area indicates the zone considered in Figure 3. The CMIP3 models are forced by the SRESA1B emissions scenario and the CMIP5 models by the 1%CO_2 scenario, i.e., an increase of CO_2 by 1% per year.

complicate the interpretation. Similar patterns of sea level change are also observed in CMIP5 simulations run under the RCPs scenarios [*Yin*, 2012]. We study changes in sea level between the first decade and the tenth decade of the simulations in both scenarios; for SRESA1B this means the first and last decade of the 21st century. Though different in time-profile and forcing agents, these two scenarios produce comparable magnitude of climate change; for example, the global mean surface air temperature change after 100 years is 2.32 ± 0.48 K in CMIP3 SRESA1B and 2.74 ± 0.40 K in CMIP5 1%CO_2. The spatial standard deviation of sea level change lies within 0.02–0.29 m; this range is reduced to 0.05–0.11 m for the CMIP5 models except MIROC5 (Table S1). The inter-model spread is somewhat smaller in CMIP5 than CMIP3 (Figures 2a and 2b), and the signal to noise ratio (taken as the ratio of the absolute value of the mean sea level change to the standard deviation) is higher for CMIP5 than CMIP3 (Figures 2c and 2d). This difference in the multi-model spread of the CMIP3 SRESA1B and CMIP5 1%CO_2 ensembles is due mainly to the models and not the forcing (auxiliary material).

[7] For most CMIP3 and CMIP5 models (collectively, "CMIP3+5"), the most striking feature of projected windstress change is a decrease centred around 40°S and an

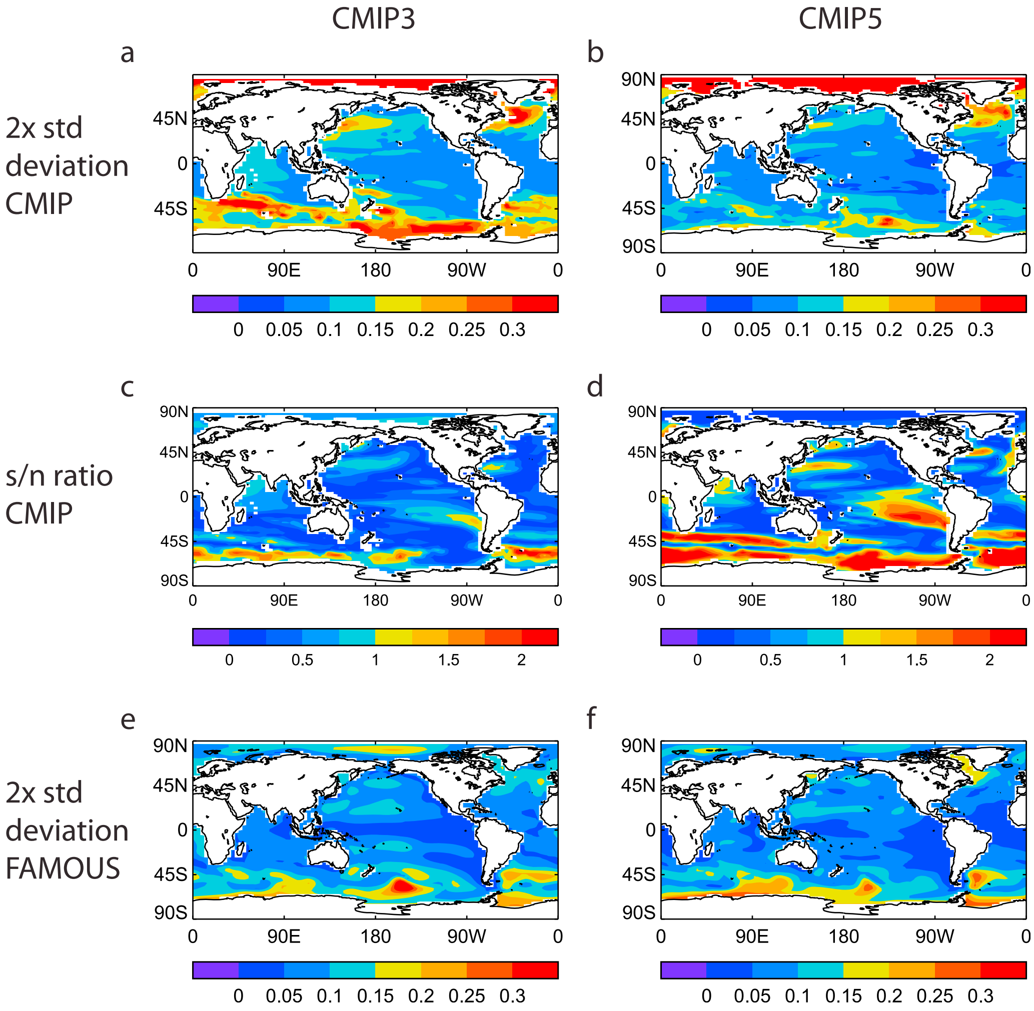

Figure 2. (a, b) Twice the standard deviation of the sea level change (m) in the CMIP3+5 models, (c, d) signal to noise ratio and (e, f) twice the standard deviation of the sea level change (m) in the FAMOUS simulations forced by the windstress anomalies for (left) CMIP3 models and (right) CMIP5 models. The signal to noise ratio is taken as the ratio of the absolute value of the mean sea level change to the standard deviation.

increase around 60°S of the zonal component in the Southern Ocean, which is interpreted as a strengthening and a poleward shift [*Fyfe and Saenko*, 2006] (Figures 1d–1f). The change in windstress curl in this region consequently displays a meridional dipole with lower values south of 50°S and higher values between 50°S and 35°S (Figures 1g–1i). Similar windstress trends are observed and simulated for the recent past [*Cai and Cowan*, 2007]. The windstress change is similar in CMIP3 and CMIP5, but the initial bias in the Southern Ocean (the zonal windstress position is too equatorward in the control simulations) is slightly reduced in CMIP5 [*Swart and Fyfe*, 2012].

3. Simulations Forced by Windstress Changes

[8] Windstress changes can affect sea level by modifying the barotropic circulation through Sverdrup balance, and by altering the baroclinic density structure through Ekman pumping and suction; for decadal changes, the latter is dominant [*Lowe and Gregory*, 2006]. To test the impact of the windstress change on sea level projections, we therefore require a 3D model with interactive surface buoyancy fluxes. We use the FAMOUS AOGCM [*Jones*, 2003; *Smith et al.*, 2008], which is a low resolution version of HadCM3 [*Gordon et al.*, 2000]. Its ocean component has a resolution of 3.75° longitude by 2.5° latitude with 20 levels. It is structurally very similar to HadCM3, and produces climate and climate-change simulations which are in good agreement with the corresponding simulations from HadCM3 [*Smith et al.*, 2008], yet it runs about twenty times faster than HadCM3. However, like all models, FAMOUS has biases in its simulated climatology, which will unavoidably affect the results, as discussed below. For comparison with an AOGCM of higher resolution, we have run similar experiments with MIROC3.2 (medres) [*K-1 Model Developers*, 2004], whose ocean grid is 1.4° in longitude, varies in latitude (from 0.56° at the equator to 1.4° at high latitudes) and has 44 vertical levels. Because it is more time-consuming we run only two simulations with this model.

[9] We calculate the monthly zonal and meridional windstress difference between the scenario simulations and the corresponding controls. These windstress anomalies, interpolated in time between months, are added to the daily mean windstress fields as calculated in the FAMOUS

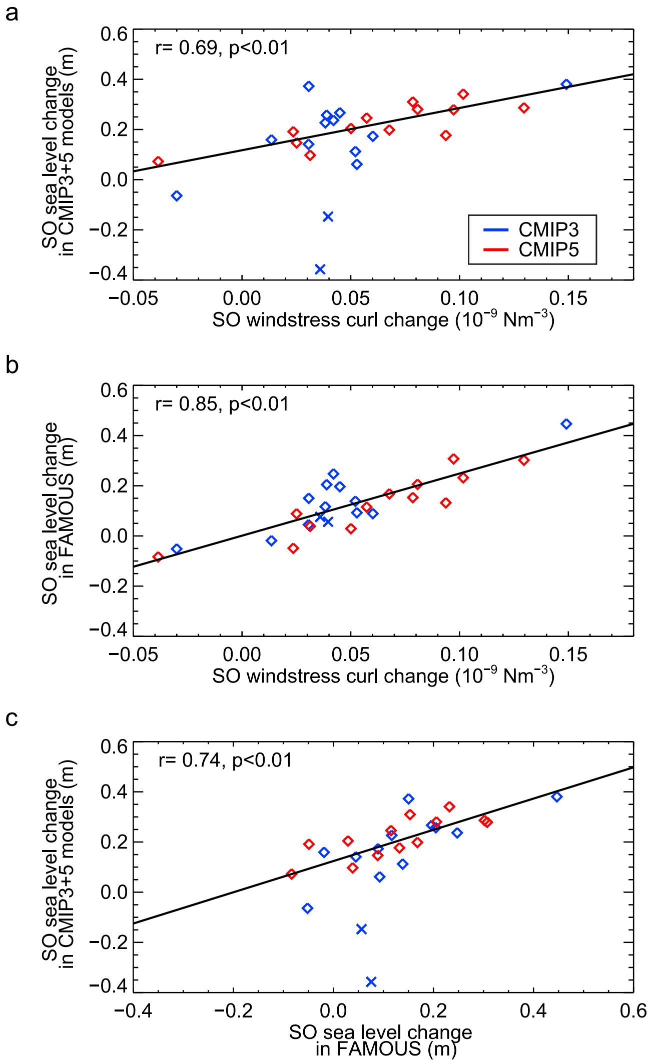

Figure 3. Relation between the strength of the sea level change (m) and the strength of the windstress curl change (10^{-9} Nm^{-3}) in the Southern Ocean: (a) for the CMIP3+5 simulations and (b) for the FAMOUS simulations forced by the windstress anomalies. (c) Relation between the sea level change in FAMOUS and in the CMIP3+5 simulations. The strength of the change is taken as the difference between the maximum and minimum of the zonal mean between 40°S and 70°S (shaded zone of Figures 1c, 1f, 1i, and 1j). The difference is positive if the maximum is northward of the minimum, negative in the opposite case. The crosses are excluded for the correlation coefficients (see section 4).

atmosphere model before applying them to the ocean model. Hence, in the simulations run with FAMOUS and MIROC 3.2, the CMIP3+5 zonal and meridional windstress anomalies are an external momentum forcing of the ocean, and there is no other forcing. We compare the simulated sea level change in our two models in response to CMIP3+5 windstress forcing with that projected by the CMIP3+5 models, in which all surface fluxes evolve in response to changing atmospheric composition.

[10] FAMOUS forced by the CMIP3+5 windstress simulates sea level changes with ensemble mean (Figures 1j–1l) and standard deviation (Figures 2e and 2f) that are of the same order of magnitude as those from CMIP3+5 AOGCMs. The FAMOUS CMIP3+5 ensemble-mean fields are remarkably similar to each other (Figures 1j and 1k) but less similar to CMIP3+5 (Figures 1a and 1b), although there is a correspondence of some large-scale features, notably the zonal-mean dipole in the Southern Ocean. The latter is more zonal in character in CMIP3+5, which is partly due to the averaging of models which have different longitudinal patterns. Among the FAMOUS experiments, the pattern of sea level change in the Southern Ocean is relatively similar, but its amplitude differs; among the CMIP3+5 models, the pattern of sea level change shows greater diversity (Figures S1 and S2).

4. Role of Windstress Change in the Southern Ocean

[11] To quantify the role of the windstress change in the Southern Ocean, for each CMIP3+5 model we compute the difference between the maximum and minimum of the zonal mean change within 40–70°S in windstress curl, in sea level, and in sea level simulated by FAMOUS forced by the windstress change. Like the model mean, most individual models display a meridional dipole in the sea level change with lower values poleward. However, two CMIP3 models (marked with crosses in Figure 3) behave differently from the majority: CSIRO-Mk3.0 and GISS-AOM have a reversed dipole despite showing the meridional dipole for the windstress curl; thus they are not included in the correlation calculations. There is a strong correlation between the strength of the sea level change and the windstress change (Figure 3a, $r = 0.69$ and $p < 0.01$; $r = 0.5$ if the two models are not excluded), indicating a possible link between the windstress change and the sea level change.

[12] The FAMOUS experiments forced only by windstress change show a very strong correlation between the sea level change produced and the windstress change applied (Figure 3b, $r = 0.85$ and $p < 0.01$). The correlation between the sea level change in the CMIP3+5 models, and sea level change in FAMOUS forced only by the windstress change from corresponding CMIP3+5 models, is strong and significant (Figure 3c, $r = 0.74$ and $p < 0.01$). From this we conclude that windstress change is the dominant cause of the sea level change pattern in the Southern Ocean in the CMIP3+5 models [cf. *Landerer et al.*, 2007; *Yin et al.*, 2010].

[13] On the other hand, the relatively low sea level change in the Southern Ocean in UKMO-HadCM3 was found by *Lowe and Gregory* [2006] to be caused by heat flux forcing, and not by windstress forcing. Experiments with both FAMOUS (Figures S3e and S3f) and MIROC3.2 (Figures S3g and S3h) demonstrate that the windstress change simulated by the MIROC3.2 AOGCM produces the dipole of sea level change in the Southern Ocean [*Suzuki and Ishii*, 2011], as for most CMIP3+5 models, whereas the UKMO-HadCM3 windstress change does not (as found by *Lowe and Gregory* [2006]). This qualitative agreement in response by the two models we have run in this work gives confidence in the method we have used.

[14] A zonal-mean cross-section of the ensemble-mean temperature change in FAMOUS (Figure S4c) shows that in the Southern Ocean the windstress forcing produces warming, most pronounced at the surface, above an interface which slants downwards from a shallow depth near Antarctica to

4000 m at 45°S, and cooling below this interface (note that the cross-section of temperature change in the CMIP3+5 simulations differs from this because they are not forced by windstress change only, and in particular show a general warming). The relative sea level rise north of 50°S is due to the warming, and the relative sea level fall south of 50°S due to the cooling (in the depth-mean).

[15] We can attribute the pattern of temperature change to the processes which affect temperature using diagnostics in FAMOUS [*Gregory*, 2000]. The increased zonal windstress changes the advection of heat (the net result of resolved velocities and parameterized eddy-induced transport), shifting the subsurface temperature gradient southward, steepening the isopycnals and causing the water below the surface to warm. Near Antarctica this is outweighed by the effects of increased convection, due to reduced sea ice cover, which warms the surface and cools the subsurface, including the Antarctic Bottom Water. The change of temperature in MIROC3.2 forced by the windstress anomalies is similar (Figures S4c and S4d). The cooling penetrates less deeply, due to the greater stratification in MIROC3.2 than in FAMOUS (Figures S4a and S4b).

5. Conclusions and Discussion

[16] The CMIP5 models show a large model spread in projections of regional sea level change, particularly in high latitudes, although the model spread is somewhat smaller than in CMIP3. The model mean pattern is similar to CMIP3. In both CMIP3 and CMIP5, the most prominent feature is a zonal dipole in the Southern Ocean, comprising a band of sea level rise larger than the global mean north of 50°S, a band of sea level rise less than the global mean south of 50°S, and a consequently intensified meridional sea level gradient. Our simulations indicate that, through its effect on the distribution of ocean heat content, the change of windstress is the dominant factor explaining this feature, and that most of the differences among the models in the magnitude of this feature arise from their different windstress changes. This highlights the need for reliable projections of windstress changes to reduce uncertainty in prediction of regional sea level change, especially in the Southern Ocean.

[17] In some other regions, the different windstress changes are partially responsible for the different patterns of regional sea level change. In the Indian Ocean, FAMOUS forced by the windstress change shows a similar change to CMIP3+5 with higher sea level relative to the global mean. In the Arctic Ocean, FAMOUS forced by windstress change shows a sea level rise of about half the size of CMIP3+5. The remaining part of the sea level increase in this region is probably related to freshening due to increased freshwater input [*Russell et al.*, 2000; *Gregory et al.*, 2001; *Landerer et al.*, 2007]. In the North Pacific, FAMOUS forced by windstress change has a smaller signal than CMIP3+5. The rise in sea level is due to the poleward shift of the subtropical gyre because of the change of winds. The small sea level change in FAMOUS is corroborated by the two simulations with MIROC3.2, indicating that other processes are also playing a role. In other regions, either the local sea level rise does not differ significantly from the mean or the windstress does not account for the sea level changes.

[18] The representation of the stratosphere and of ozone evolution is particularly relevant, because of their strong influence on the windstress simulation in this region [*Son et al.*, 2010]. An ozone-induced reduction of the windstress trend would directly impact the Southern Ocean by reducing the meridional sea level change dipole.

[19] Most ocean models that are currently used for climate projections do not resolve mesoscale eddies explicitly. Resolving them in higher resolution models could modify the sea level change in the Southern Ocean due to the eddy-saturation effect which counteracts the isopycnal changes induced by increased Ekman transport, as suggested by recent observations [*Böning et al.*, 2008]. However, *Suzuki et al.* [2005] showed similar sea level changes in an eddy-permitting model and a lower-resolution version of the same model; further work is required on this aspect.

[20] **Acknowledgments.** We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table S1) for producing and making available their model output. This research has received funding from the ERC under the European Community's Seventh Framework Programme (FP7/2007-2013), ERC grant agreement number 247220, project "Seachange". We thank John Fasullo and an anonymous reviewer for their comments which helped improve this manuscript.

[21] The Editor thanks John Fasullo and an anonymous reviewer for their assistance in evaluating this paper.

References

Böning, C. W., A. Dispert, M. Visbeck, S. R. Rintoul, and F. U. Schwarzkopf (2008), The response of the Antarctic Circumpolar Current to recent climate change, *Nat. Geosci.*, *1*, 864–869, doi:10.1038/ngeo362.

Cai, W., and T. Cowan (2007), Trends in Southern Hemisphere circulation in IPCC AR4 models over 1950–99: Ozone depletion versus greenhouse forcing, *J. Clim.*, *20*, 681–693, doi:10.1175/JCLI4028.1.

Fyfe, J. C., and O. A. Saenko (2006), Simulated changes in the extratropical Southern Hemisphere winds and currents, *Geophys. Res. Lett.*, *33*, L06701, doi:10.1029/2005GL025332.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood (2000), The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Clim. Dyn.*, *16*(2–3), 147–168, doi:10.1007/s003820050010.

Gregory, J. M. (2000), Vertical heat transports in the ocean and their effect on time-dependent climate change, *Clim. Dyn.*, *16*(7), 501–515, doi:10.1007/s003820000059.

Gregory, J. M., et al. (2001), Comparison of results from several AOGCMs for global and regional sea-level change 1900–2100, *Clim. Dyn.*, *18*, 225–240, doi:10.1007/s003820100180.

Han, W., et al. (2010), Patterns of Indian Ocean sea-level change in a warming climate, *Nat. Geosci.*, *3*, 546–550, doi:10.1038/ngeo901.

Jones, C. (2003), A fast ocean GCM without flux adjustments, *J. Atmos. Oceanic Technol.*, *20*, 1857–1868, doi:10.1175/1520-0426(2003)020<1857:AFOGWF>2.0.CO;2.

K-1 Model Developers (2004), K-1 coupled model (MIROC) description, *K-1 Tech. Rep. 1*, edited by H. Hasumi and S. Emori, 34 pp., Cent. for Clim. Syst. Res., Univ. of Tokyo, Tokyo.

Landerer, F. W., J. H. Jungclaus, and J. Marotzke (2007), Regional dynamic and steric sea level change in response to the IPCC-A1B scenario, *J. Phys. Oceanogr.*, *37*, 296–312, doi:10.1175/JPO3013.1.

Lowe, J. A., and J. M. Gregory (2006), Understanding projections of sea level rise in a Hadley Centre coupled climate model, *J. Geophys. Res.*, *111*, C11014, doi:10.1029/2005JC003421.

Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, Cambridge, U. K.

Merrifield, M. A., and M. E. Maltrud (2011), Regional sea level trends due to a Pacific trade wind intensification, *Geophys. Res. Lett.*, *38*, L21605, doi:10.1029/2011GL049576.

Pardaens, A. K., J. M. Gregory, and J. A. Lowe (2011), A model study of factors influencing projected changes in regional sea level over the twenty-first century, *Clim. Dyn.*, *36*(9–10), 2015–2033, doi:10.1007/s00382-009-0738-x.

Russell, G. L., V. Gornitz, and J. R. Miller (2000), Regional sea-level changes projected by the NASA/GISS Atmosphere-Ocean Model, *Clim. Dyn.*, *16*, 789–797, doi:10.1007/s003820000090.

Smith, R. S., J. M. Gregory, and A. Osprey (2008), A description of the FAMOUS (version XDBUA) climate model and control run, *Geosci. Model Dev.*, *1*, 53–68, doi:10.5194/gmd-1-53-2008.

Son, S.-W., et al. (2010), Impact of stratospheric ozone on Southern Hemisphere circulation change: A multimodel assessment, *J. Geophys. Res.*, *115*, D00M07, doi:10.1029/2010JD014271.

Sueyoshi, M., and T. Yasuda (2012), Inter-model variability of projected sea level changes in the western North Pacific in CMIP3 coupled climate models, *J. Oceanogr.*, *68*(4), 533–543, doi:10.1007/s10872-012-0117-9.

Suzuki, T., and M. Ishii (2011), Regional distribution of sea level changes resulting from enhanced greenhouse warming in the Model for Interdisciplinary Research on Climate version 3.2, *Geophys. Res. Lett.*, *38*, L02601, doi:10.1029/2010GL045693.

Suzuki, T., H. Hasumi, T. T. Sakamoto, T. Nishimura, A. Abe-Ouchi, T. Segawa, N. Okada, A. Oka, and S. Emori (2005), Projection of future sea level and its variability in a high-resolution climate model: Ocean processes and Greenland and Antarctic ice-melt contributions, *Geophys. Res. Lett.*, *32*, L19706, doi:10.1029/2005GL023677.

Swart, N. C., and J. C. Fyfe (2012), Observed and simulated changes in the Southern Hemisphere surface westerly wind-stress, *Geophys. Res. Lett.*, *39*, L16711, doi:10.1029/2012GL052810.

Thompson, D. W. J., and S. Solomon (2002), Interpretation of recent Southern Hemisphere climate change, *Science*, *296*(5569), 895–899, doi:10.1126/science.1069270.

Timmermann, A., S. McGregor, and F.-F. Jin (2010), Wind effects on past and future regional sea level trends in the southern Indo-Pacific, *J. Clim.*, *23*, 4429–4437, doi:10.1175/2010JCLI3519.1.

Yin, J. (2012), Century to multi-century sea level rise projections from CMIP5 models, *Geophys. Res. Lett.*, *39*, L17709, doi:10.1029/2012GL052947.

Yin, J., S. M. Griffies, and R. J. Stouffer (2010), Spatial variability of sea level rise in twenty-first century projections, *J. Clim.*, *23*, 4585–4607, doi:10.1175/2010JCLI3533.1.