



**Downscaling the  
climate change for  
oceans around  
Australia**

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# Downscaling the climate change for oceans around Australia

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## Abstract

At present, global climate models used to project changes in climate do not resolve mesoscale ocean features such as boundary currents and eddies. These missing features may be important to realistically project the marine impacts of climate change. Here we present a framework for dynamically downscaling coarse climate change projections utilising a global ocean model that resolves these features in the Australian region.

The downscaling model used here is ocean-only. The ocean feedback on the air-sea fluxes is explored by restoring to surface temperature and salinity, as well as a calculated feedback to wind stress. These feedback approximations do not replace the need for fully coupled models, but they allow us to assess the sensitivity of the ocean in downscaled climate change simulations. Significant differences are found in sea surface temperature, salinity, stratification and transport between the downscaled projections and those of the climate model. While the magnitude of the climate change differences may vary with the feedback parameterisation used, the patterns of the climate change differences are consistent and develop rapidly indicating they are mostly independent of feedback that ocean differences may have on the air-sea fluxes.

Until such a time when it is feasible to regularly run a global climate model with eddy resolution, our framework for ocean climate change downscaling provides an attractive way to explore how climate change may affect the mesoscale ocean environment.

## 1 Introduction

Global-scale Atmosphere-Ocean General Circulation Models (AOGCMs) are used extensively to project the response of climate to increasing concentrations of infrared-absorbing, or “greenhouse”, gases in the atmosphere. However, due to the complexity of these models, at present they are formulated at relatively low spatial resolution (e.g., between 1° and 2°, or 100 to 200 km). This enables AOGCMs to run relatively quickly and to project the climate evolution over time scales of decades and centuries for

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various future scenarios of greenhouse gas concentrations in the atmosphere. While global AOGCMs are valuable for providing global- and basin-scale trends in future climate, they are not designed to resolve all of the important ocean features, such as mesoscale eddies and boundary currents. Marine life in Australian waters is sensitive to the impacts of climate change (Poloczanska et al., 2007) and the distribution of projected impacts are modified when high-resolution models resolve boundary currents and eddies (Hartog et al., 2011; Stock et al., 2011; Hobday and Lough, 2011).

The challenge is to provide climate change projections with more realistic ocean dynamics to improve regional projections for marine climate change impact studies. To achieve this we combine a AOGCM climate change projection with a high-resolution Ocean Downscale Model (ODM) that explicitly resolves boundary currents and eddies. In this way, with limited computing resources, we can increase ocean resolution and produce more realistic projections.

In the atmosphere, Regional Atmospheric Models have a long history of being used to dynamically downscale global weather predictions to provide regional predictions (e.g., Lo et al., 2008; Laprise et al., 2008) and now these dynamical downscaling techniques are being modified and applied to make regional atmospheric climate change projections (e.g., Wang et al., 2004). However, there are few examples of dynamical downscaling of climate change projections for the ocean. The few published studies have focused on small regional seas like the Baltic and North Seas (Ådlandsvik, 2008; Meier, 2006). For these limited-region ODMs, the information from the AOGCM is fed into the regional model through open boundaries and the success of such downscaling is critically dependent on passage of the open boundary information into the ODM. Although the regional models provide an economical way to increase ocean resolution, the limited spatial extent of such models restricts their ability to study basin-scale phenomena like boundary currents.

This present study focuses on the downscaling of ocean climate change around the Australian region. Important boundary currents are found west and east of Australia (Fig. 1). In the west, the Leeuwin Current is a unique, poleward flowing eastern





of which are in the upper 500 m (Fig. 2a). Results presented here use the projected climate from the decade of 2060 to 2069 based on the medium emissions, “A1b” scenario (integrated world, balanced energy sources) of the Special Report on Emission Scenarios (Nakicenovic et al., 2000).

### 2.1.2 Ocean downscaling model

We use the Ocean Forecasting Australia Model (OFAM version 1) to dynamically downscale the projection of climate change. OFAM is chosen because it resolves the boundary currents and mesoscale eddies around Australia.

OFAM is based on the Modular Ocean Model, version 4.0 (MOM4, Griffies et al., 2004). OFAM is configured on a global grid with variable spatial resolution. The vertical resolution in the upper 200 m of the water column is 10 m. The model is eddy-resolving around Australia (0.1° resolution in longitude and latitude between 90° and 180° E, and south of 20° N) with coarser resolution outside this region (Fig. 2b). OFAM is used extensively to model dynamics in the Australian region (e.g., Schiller et al., 2009; Oke and Griffin, 2011). OFAM is the core of the Bluelink Ocean Data Assimilation System, that produces 7-day operational forecasts of the ocean state (Oke et al., 2005; Brassington et al., 2007), and derives the ocean state around Australia over the last decade (Bluelink Reanalysis, Oke et al., 2008), as well as to explore the processes controlling spatial distribution of phytoplankton off both Western (Dietze et al., 2009) and Eastern (Mongin et al., 2011) Australia.

## 2.2 Preparing the ODM

To prepare the ODM there was an initial spin-up where the high-resolution ocean model was forced with reanalysis flux products (ERA-40, Uppala et al., 2005) and relaxed to observed surface temperature and salinity (Reynolds and Smith, 1994; Levitus, 2002); see Oke et al. (2008) for more details. The ODM was spun up for 16 yr, using forcing fields from the 1990s and 2000s, where the time in the model is changed back to the

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1990s when it reaches the end of the 2000s forcing. We use the model at the end of 1994 to be our base ocean state, a time when the ocean was neither in a strong El Niño or La Niña state. The initial condition for some of the experiments came from a previous experiment, as indicated in Table 1. Using a previous experiment reduced the time required for the model to reach a quasi-stable solution in the upper ocean.

Climate change anomaly fields in temperature and salinity are added to the base ocean state to construct initial conditions for the ODM climate projections. The climate change anomaly fields are defined as the change from the decadal averages in the 1990s to the decadal averages in the 2060s. Climate change anomaly fields were used instead of the actual ocean state of the AOGCM in 2060 to remove the potential regional biases in AOGCM-simulated ocean state. This approach assumes the AOGCM can simulate changes in ocean state and atmospheric forcing between the two decades despite these biases.

### 2.3 Forcing fields

The ODM projections are forced by surface fluxes of heat, freshwater and momentum, derived by adding climate change anomalies to present-day fields. Like the anomaly applied to the initial conditions, climate anomalies are applied to the ODM forcing to reduce the effect of bias from the AOGCM. The approach of applying anomalies to forcing fields has been used before to keep models close to expected climatology (e.g., Kirtman et al., 2002).

The ODM surface fluxes applied are the sum of the present-day fluxes, diurnal variability, climate anomaly fluxes derived from the AOGCM simulation, correction flux from the ODM spin-up and an ocean feedback term. ERA-40 fluxes (Uppala et al., 2005) from years 1993–2001 are averaged to produce a monthly climatology for present-day forcing. Diurnal variability in the fluxes is determined from the differences between the daily values and their monthly mean. ERA-40 fluxes from 1995 are used to derive diurnal variability in this experiment. The climate change anomalies are calculated as the change in the monthly averaged fluxes between the decades 2060s and 1990s from

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the AOGCM. The ocean feedbacks parameterise how the ocean in the ODM changes the fluxes as detailed in the next section.

The following equations summarise the fluxes used in the ODMs.

$$HF = SW_{\text{present}} + LW_{\text{present}} + \text{Sens}_{\text{present}} + \text{Lat}_{\text{present}} + \text{HC}_{\text{present}} + H' + H_{\text{feedback}} + H_{\sigma} \quad (1)$$

$$FW = \text{Prec}_{\text{present}} - \text{Evap}_{\text{present}} + \text{FC}_{\text{present}} + \text{FW}' + \text{FW}_{\text{feedback}} + \text{FW}_{\sigma} \quad (2)$$

$$\text{Stress} = \text{Stress}_{\text{present}} + \text{Stress}' + \text{Stress}_{\text{feedback}} + \text{Stress}_{\sigma} \quad (3)$$

The heat flux (HF, Eq. 1) is the sum of: present day shortwave solar radiation (SW); longwave radiation (LW); sensible heat flux (Sens); latent heat due to evaporation (Lat); a correction term (HC) derived from the ODM spin-up by relaxing the simulated sea surface temperature with a time scale of 30 days to observations (Reynolds and Smith, 1994); climate change heat flux anomaly from AOGCM experiments ( $H'$ ); a feedback term ( $H_{\text{feedback}}$ ; discussed below); and diurnal variability ( $H_{\sigma}$ ). Most components of heat flux can be treated as a single flux to the top ocean layer. However, shortwave radiation penetrates into the ocean so it is handled differently and for this component an ERA-40 (Uppala et al., 2005) seasonal climatology (averaged from 1993–2001) is used for the ODM projections. It is assumed that there are no changes in the penetrative heat flux and only changes in the surface flux.

The freshwater flux (FW, Eq. 2) is the sum of: precipitation (Prec); evaporation (Evap); a correction term (FC) derived from the ODM spin-up by relaxing the simulated sea surface salinity with a time scale of 30 days to a monthly climatology (Levitus, 2002); climate change freshwater flux anomaly from AOGCM experiments ( $\text{FW}'$ ); a feedback term ( $\text{FW}_{\text{feedback}}$  discussed below); and diurnal variability ( $\text{FW}_{\sigma}$ ).

Stress (Eq. 3) gives the zonal and meridional components of momentum flux as the sum of: present day stresses (Stress); climate change stress anomalies calculated from the AOGCM simulations ( $\text{Stress}'$ ); a feedback term ( $\text{Stress}_{\text{feedback}}$  discussed below); and the stresses due to diurnal variability ( $\text{Stress}_{\sigma}$ ).

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## 2.4 Control experiment

We run a control experiment (CTRL) for the present climate, with climate change anomalies removed from the initial condition and the forcing fields from the ODM climate simulations. This control experiment is hence like the ODM spinup, except with repeat-year forcing. Output from this control experiment is used in the construction of the guide fields for SST and SSS relaxation, as well as the reference states to calculate the climate change impacts in the ODM projections.

## 2.5 Ocean feedback on air-sea forcing

All climate change simulations in this study are done with an ocean-only model. However, we do expect the changes in the ocean state due to resolving eddies and boundary currents to influence the fluxes of heat, freshwater and momentum between the atmosphere and ocean. We use the term feedback to denote the impact that change in ocean state predicted by ODM may have on these fluxes. Potentially, one could do climate downscaling with a coupled model but at this stage we have taken a simpler and more computational efficient strategy of using an ocean-only model and relying on simple formulations of the feedback terms to account for the coupling. This approach tests the effect of these feedbacks on the ocean state. The following section discusses how we parameterize the heat, freshwater and momentum flux feedbacks in the simulations performed. Table 1 summarises feedbacks used with a list of these experiments.

### 2.5.1 Feedback of heat and freshwater

To represent the ocean feedback on the air-sea heat and freshwater fluxes we include additional heat and freshwater fluxes based on restoring the sea surface temperature (SST) and sea surface salinity (SSS) to guide fields. Guide fields are constructed

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by adding the monthly climate change anomalies from the AOGCM simulation to the monthly surface temperature and salinity climatologies from the control experiment.

There is a clear physical argument for linking the SST anomaly with heat flux, which is quantified in bulk flux formulas (Large, 2005). Heat loss via longwave radiation, evaporation/latent heat and sensible heat are all strong functions of temperature.

It is less clear that SSS anomalies and freshwater fluxes are linked; however, for consistency we also include restoring for SSS. SSS is restored with the same time scale as SST. SSS restoring is applied for two main reasons. Firstly, the freshwater fluxes that control the surface salinity are poorly defined for even the present ocean. Secondly, we wish to ensure that the upper ocean density does not undergo a dramatic transition within the ODM that would be induced by differences in advection and/or vertical mixing between the models. In general, simulations without feedback typically drift away from observed salinity fields and exhibit instabilities in the thermohaline circulation (e.g., Zhang et al., 1993; Cai and Godfrey, 1995). There is also potential for coupling between the restoring freshwater flux with SST and the heat flux through latent heat (evaporation or condensation). However, for typical magnitudes of heat flux feedback, the equivalent freshwater flux is small relative to the applied freshwater feedback. For instance, the typical latent heat flux feedback of  $5 \text{ W m}^{-2}$  would equate to a freshwater flux of  $0.17 \text{ mm day}^{-1}$ , and this is an order of magnitude less than the typical freshwater flux feedback in our experiments.

We compared numerical experiments with and without restoring for SST and SSS to assess the sensitivity of ODM projection to the applied feedback (experiments RELX and FREE; Table 1). The time scale for restoring was 30 days, which gives a heat flux feedback rate with this ODM of  $-16 \text{ W m}^{-2} \text{ K}^{-1}$ . This value is comparable to an analysis of SST anomalies and heat fluxes found in the North Atlantic that suggests an ocean feedback rate of about  $-20 \text{ W m}^{-2} \text{ K}^{-1}$  (Frankignoul et al., 1998). For the freshwater flux, the feedback rate with 30-day restoring with this ODM in water of 35 practical salinity units (psu), is  $+10 \text{ mm day}^{-1} \text{ psu}^{-1}$ .

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## 2.5.2 Feedback of wind stress

To quantify how changes in the ocean state impact the atmospheric circulation we conducted atmosphere-only simulations using the MK3L model (Phipps et al., 2011). This model is a reduced-resolution version of the atmospheric model used in the Mk3.5 AOGCM. Two simulations were conducted to assess the impact of SST change on the wind stress field. Firstly, we used a climatology of the monthly SST fields from the Mk3.5 AOGCM decade of the 2060s. Secondly, we construct a new SST climatology by adding the change in SST from the 1990s to 2060s found with the ODM (RELX experiment) to the Mk3.5 SST in the 1990s. Both simulations were run for 60 yr and we used the average of the last 30 yr to compute the differences in the monthly surface wind stress between the two simulations, which we call the wind stress feedback. The 30-year averaged wind stress feedback (lower right Fig. 3) was added to the wind stress used in the RELX and FREE experiments to assess the impact of wind stress feedback (experiment STRS, Table 1).

The magnitude of the wind stress feedback is much less than the applied stress, and the wind stress with the added feedback term looks very similar to the wind stresses used in the FREE experiment (top panels, Fig. 3). However, the feedback term is comparable to the climate anomaly (lower panels of Fig. 3). The feedback term appears to weaken the westerly winds around 40–60° S in the South Pacific region.

## 3 Climate change projections

In this section we use various ODM experiments (FREE, RELX and STRS from Table 1) to simulate the impact of climate change on the ocean state around Australia, to assess the sensitivity of ocean state impacts to feedback and compare these impacts to changes in AOGCM simulations. To help discuss the results for both the AOGCM and ODM, we define “projected climate change” as the difference in ocean state between the 2060s and 1990s. For the AOGCM, change is calculated from the difference between decadal averages of the 2060s and 1990s. For the ODM, the change is

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calculated from the average of one or more years in the projection minus a decadal average from the CTRL experiment. In some figures, for consistency, we compare results from just one year from each experiment since the FREE experiment only ran for 3 yr from when it branched from RELX.

We then define “difference in climate change” as projected climate change from the ODM minus the projected climate change of the AOGCM. If the projected climate changes were the same between the ODM and AOGCM, the difference in climate change would be zero. In the following discussion, we focus on the difference in climate change by comparing annual or multi-year averages of 4 key fields: (1) SST, (2) SSS, (3) upper ocean currents, and (4) stratification. By identifying differences common in each experiment, results are less sensitive to the bias in any of the model setups. Finally, we present results from extended runs of the CTRL and RELX experiments to demonstrate the temporal stability of the ODM results.

### 3.1 SST

Projected climate change in SST in both the AOGCM and the ODM shows a warming of generally 1 to 2 °C in SST over the Australian region (bottom row, Fig. 4). Both models show somewhat less warming in regions around Indonesia and in the Southern Ocean, though the Southern Ocean in the ODM also has regions of enhanced warming. There is also less warming around New Zealand in both models. The projected change in SST with the AOGCM shows a strong warming feature off the coast of Tasmania (150° E, 40° S), whereas in the ODM this warming is found in the central Tasman Sea. The difference in the projected change in SST from the models (right column, Fig. 4) also highlights other differences in the warming pattern found with the ODM, such as more warming in the Indian Ocean and near Indonesia, and less warming in the Great Australian Bight.

In order to confirm that the features found in the projected changes and the differences in projected change are not sensitive to the setup of the experiments, we compare results from ODM experiments with different parameterisations of air-sea

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feedbacks (Fig. 5). For consistency, annual averages from each experiment are shown since the FREE experiment was not integrated long enough for a multi-year average. The difference in climate change annual SSTs exhibits a similar spatial structure from each experiment (centre column, Fig. 5). The amplitude of the difference in climate change for SST, as measured by the standard deviation over the region shown in Fig. 5, is significantly larger for FREE (0.69 °C) than experiments with SST restoring (i.e. RELX 0.40 °C, and, STRS 0.43 °C). However, despite the different amplitudes, SST differences are well correlated spatially between all experiments:  $R = 0.65$  between FREE and RELX, and,  $R = 0.63$  between STRS and RELX. For comparison, typical  $R$  values found in SST differences between different years of the same experiment are between 0.6 and 0.7.

The retention of the warmer and cooler regions in the three different ODM experiments suggests that the structure of the difference in climate change for SST is largely independent of feedback at the surface. For instance, RELX heat flux feedback ranges from  $-25$  to  $+25 \text{ W m}^{-2}$  over the region (right column of Fig. 5), yet the difference in climate change annual SST (centre column) retains the prominent warmer and cooler regions of the FREE experiment, in which the heat flux feedback is zero. The wind stress feedback (STRS) does not significantly affect the spatial structure of the difference in climate change annual SSTs. But the STRS experiment does show a larger decrease in warming in the Tasman and Coral Seas than the RELX experiment, which is more consistent with the FREE experiment.

Where these spatial differences are independent of the surface fluxes implies that they are driven by differences in the transport and mixing between the AOGCM and ODM. Since the ODM is eddy-resolving, it can calculate eddy-mixing explicitly rather than rely on parameterisations. Also, the resolution of cyclonic and anti-cyclonic eddies allows for a better representation of vertical movement and mixing. It is beyond the scope of this work to attribute the exact role of these processes to the various features identified in the differences found in the projected changes; our objective at this time is to demonstrate these features are robust with surface fluxes.

## 3.2 Salinity

The projected climate change in the annual SSS from the ODM experiments show a prominent decrease in salinity in the Coral Sea and Western Equatorial Pacific, and a prominent increase in salinity in the mid-latitude Indian Ocean off Western Australia and around the island of Java (left column, Fig. 6). The difference in climate change annual SSSs (ODM climate change – AOGCM climate change) shows freshening in the mid-latitudes west of Australia, and saltier conditions in the tropics ~ 10–15° S and most of the Southern Ocean (middle column, Fig. 6).

As found with SST, with the freshwater feedback (restoring to SSS guide fields) the magnitude of the SSS difference declined; the standard deviation of the SSS difference in FREE is 0.19 psu, compared to 0.10 and 0.11 psu for RELX and STRS, respectively. However, the spatial pattern evident in the FREE experiment remained in the RELX and STRS experiments, e.g., the correlation coefficient ( $R$ ) between FREE and RELX is 0.77.

In experiments with SSS restoring, the freshwater flux feedback is greater than the climate anomaly flux (bottom right panel of Fig. 6). However, even with this large freshwater flux feedback the consistency in pattern of the difference in climate change SSSs suggests the SSS difference pattern is not very sensitive to air-sea fluxes.

## 3.3 Upper ocean vertical stratification

To assess projected climate changes in the upper ocean's vertical stratification we calculate the annual averaged difference in water density between a depth of 200 m and the surface (Behrenfeld et al., 2006). The ODM climate change projections show increased stratification almost everywhere in the Australian region (left column, Fig. 7). The largest increases in stratification are equatorward of 20° S. In the experiments with heat and freshwater feedbacks (RELX and STRS) the greatest increases in stratification occur in the tropical Pacific. The FREE experiment shows large increases in stratification occur in the Indian Ocean too.

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For reference, upper ocean vertical stratification of the present-day is shown for the ODM and AOGCM (right column, Fig. 7). The ODM stratification is similar to the observed stratification (not shown, based on Levitus, 2002). In contrast, the AOGCM tends to overestimate the vertical stratification, particularly north of 15° S.

Differences in the climate change in upper ocean stratification in all experiments (centre column, Fig. 7) show a similar pattern of reduced stratification change in the Pacific and increased stratification change in the mid-latitude Indian Ocean relative to the AOGCM projected changes. Like in SST and SSS, the magnitudes of differences in stratification changes are greater in the FREE experiment than RELX or STRS.

The difference in climate change in upper ocean stratification shows a similar pattern to the difference in climate change in SSS. In the Indian Ocean, regions of increased stratification correspond to regions that are fresher, while in the Pacific Ocean, regions of decreased stratification correspond to regions that are saltier (Fig. 6). The correlation coefficient ( $R$ ) of the stratification difference with the SSS difference is  $-0.65$  for the FREE experiment, and  $-0.49$  for RELX. It appears that differences in vertical stratification are closely related to differences in SSS.

### 3.4 Upper ocean transport

To assess changes in the upper ocean circulation we calculate the mean transport averaged over the upper 250 m from each experiment (left column, Fig. 8). In Fig. 8, just the Tasman Sea region is shown, which includes the prominent EAC boundary current, in order demonstrate the consistency between experiments of features that indiscernible at larger scales. To assess the various ODM simulations of climate change we focus on how the transport differs between our three experiments, rather than on making a comparison to the coarse-resolution AOGCM as it is simply unable to resolve the fine structures present in the transport field (bottom right panel).

Projected climate change in transport (centre column) is presented as a scalar field that is calculated as the change in the flow in the direction of transport of the control experiment (i.e.  $(\Delta \mathbf{u} \cdot \mathbf{u})/|\mathbf{u}|$ ). Therefore, positive values represent an increase in transport



in the direction of the control experiment. The projected climate change displays more fine-scale spatial structure due to mesoscale eddies in the FREE experiment which is only a one-year average. In all experiments, in the region where the EAC flows as a single jet (latitudes 25 to 30° S) shows an increase flow relative to the control experiment. The experiments also give the suggestion of a southward shift in the point where a large component of the water turns east along the Tasman front. Also demonstrated is the high spatial variability of transport in the ODM indicating the need for averages over long time or large spatial domains to quantify results. Further analyses of boundary currents in downscaled projections around Australia are presented in Sun et al. (2011).

### 3.5 Temporal stability in ODM output

In addition to the experiments exploring the different feedbacks between the ocean and atmosphere, we extended the experiments CTRL and RELX to assess temporal stability of the ODM. Of particular interest is to determine an appropriate run time for the ODM climate projection to allow sufficient time for the ocean state to adjust to the new forcing conditions.

Given the ocean's inertia and the time it takes the ocean to respond to a change in atmospheric forcing, the ODM projection is not expected to be in a steady state. To assess the temporal evolution of the experiment we compare the annual mean of the difference between simulated SST and the guide fields (like those shown in the centre column of Fig. 5), with the annual mean difference of the subsequent year, for each year of the simulation. To show the temporal evolution of SST we use a Taylor diagram to display the standard deviation of each annual difference and correlation between differences of sequential years on a single plot (Fig. 9). The drift in average SST over the region in the ODM projection is insignificant after the first few years of the simulation (the colour scale in Fig. 9). The correlation of SST between subsequent years also increases significantly over these first few years as the pattern in the difference in climate change for SST becomes established. By the fifth year the changes in SST

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correlations become much smaller. Due to eddy variability in the ODM we do not expect any two years to look identical but we see a convergence to a correlation between years of 0.6 to 0.7, and a standard deviation in the SST field  $\sim 0.4^\circ\text{C}$ .

To gauge the stability of the ocean circulation in the Australian region, we examine a time series of volume transport through a section of the EAC at  $28^\circ\text{S}$  and  $153\text{--}157^\circ\text{E}$  (Fig. 10). We focus on the EAC because it is Australia's strongest boundary current and the change in wind stress in the Eastern Pacific in our future climate change simulations may generate slowly propagating Rossby waves that alter the EAC transport (Hill et al., 2008). The RELX experiment does not appear to have any discernible drift or trend in EAC transport. All ODM climate change simulations have similar EAC transport, with large interannual variability due largely to the eddy variability still influencing the section used to calculate the transport.

#### 4 Discussion and conclusions

We present here a framework to combine a AOGCM projection with an eddy-resolving ODM to downscale the effects of climate change on the marine environment. Ideally, we would like to increase the ocean resolution in a global coupled climate model but the limited computational resources make such an approach unfeasible at present. We integrate a high-resolution ODM with forcing fields computed by adding climate change anomalies in the heat, freshwater and momentum air-sea fluxes from the AOGCM to the present-day (1990s) forcing fields.

In one experiment (FREE), the ocean is forced with the fluxes described above without any feedback. However, changes in ocean state will alter the atmospheric fields, but a fully coupled model would be required to include feedback on air-sea fluxes. Here we use feedback parameterisations in two other experiments to test the sensitivity of the results in ocean projections to potential feedbacks. In one experiment (RELX), we restore the ODM's SST and SSS fields to monthly guide fields derived by adding the SST and SSS climate change anomalies of the AOGCM to the present day SST

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and SSS fields. In another experiment (STRS), we use atmosphere-only simulations with monthly SST fields to determine how differences in climate change for SST fields between the ODM and AOGCM alter atmospheric circulation and use the differences between these atmosphere simulations to estimate a correction to apply to the surface wind stress.

To analyse the ODM climate results, we focus on differences such as the difference between the ODM climate projection and the ODM control experiment, to reduce effects of model bias. We examine the differences in climate change in SST, SSS, upper ocean stratification and transports. From the three ODM projections, persistent patterns emerge in the differences in climate change between the ODM and AOGCM. For example, the magnitude of differences in SST change is  $\sim 0.5^{\circ}\text{C}$ , and SSS change  $\sim 0.1$  psu between the ODM and AOGCM projections.

ODM projections persistently show greater warming in the Southern Ocean and northwest of Australia, and less warming in the Great Australia Bight, and east of Tasmania. In SSS, the ODM projections are fresher at the mid-latitudes west of Australia and generally saltier in the tropics and Southern Ocean. For vertical stratification the differences in climate change generally mirror the SSS differences. In places where the ODM was saltier in the Pacific, the ODM is also less stratified; likewise regions that are fresher in the ODM west of Australia show more stratification. The consistency of volume transport in the ODM projections is demonstrated by the strengthening and similar spatial response of the EAC in each ODM experiment.

We use an extended ODM simulation (RELX) to assess temporal stability of the ODM results. SST fields rapidly adjust in the first years and a consistent pattern emerges, after  $\sim 5$  yr SST fields stabilise and year-to-year differences converge. A time series of EAC transport shows no trend or drift in circulation discernible from the interannual variability.

The persistent and robust differences in climate change between the ODM and AOGCM demonstrate that resolving important boundary currents and eddies does alter the ocean response to climate change. That the spatial differences between ocean

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simulations are consistent with different feedbacks of heat, freshwater and momentum fluxes, implies that the large-scale response is dominated by differences in transport and mixing between the ODM and AOGCM.

The downscaling approach presented here provides an attractive way to explore marine impacts of climate change on regional and local scales. In particular, in those regions where resolving eddies and boundary currents is critical for producing more realistic projections.

*Acknowledgement.* The ODM simulation was run at the High Performance Computing and Communications Centre and Australian National Computational Infrastructure (NCI) supercomputing facility. The FERRET program was used for analysis and graphics (<http://ferret.pmel.noaa.gov/Ferret/>). This work is supported by the WAMSI Node 2 project and with additional support from the Australian Climate Change Science Program and CSIRO Wealth from Oceans Flagship.

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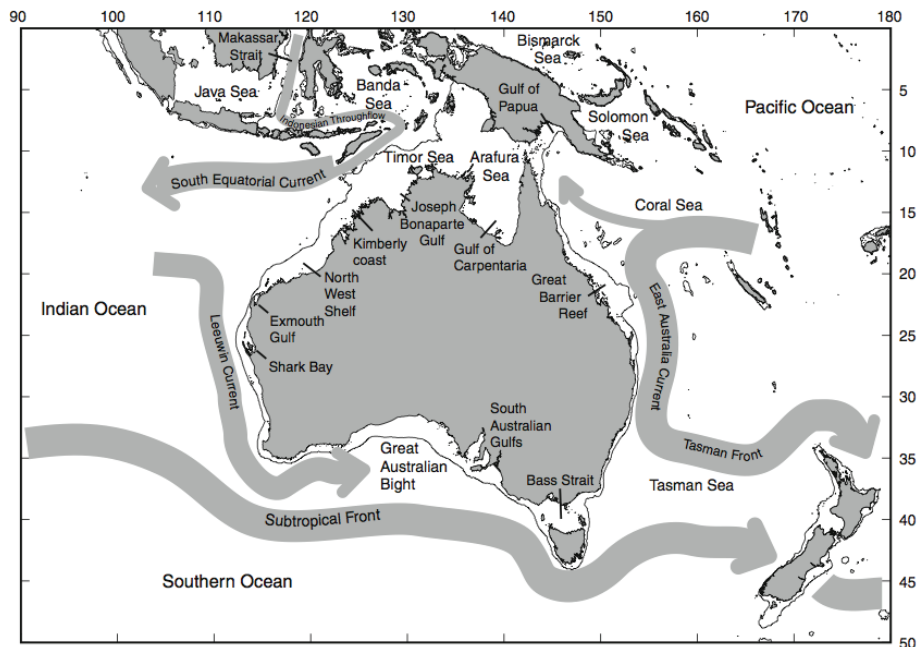


**Table 1.** Details of experiments presented.

Experiment name	Initial conditions	Run length	Comments
CTRL	OFAM spinup	26	Present climatology, no feedback
RELX	OFAM spinup plus climate anomaly	14	Future climatology, feedback on heat and freshwater
FREE	End of year 3, RELX	3	Future climatology, no feedback
STRS	End of year 3, RELX	7	As for RELX with stress feedback

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**Fig. 1.** Boundary currents around Australia, based on Poloczanska et al. (2007).

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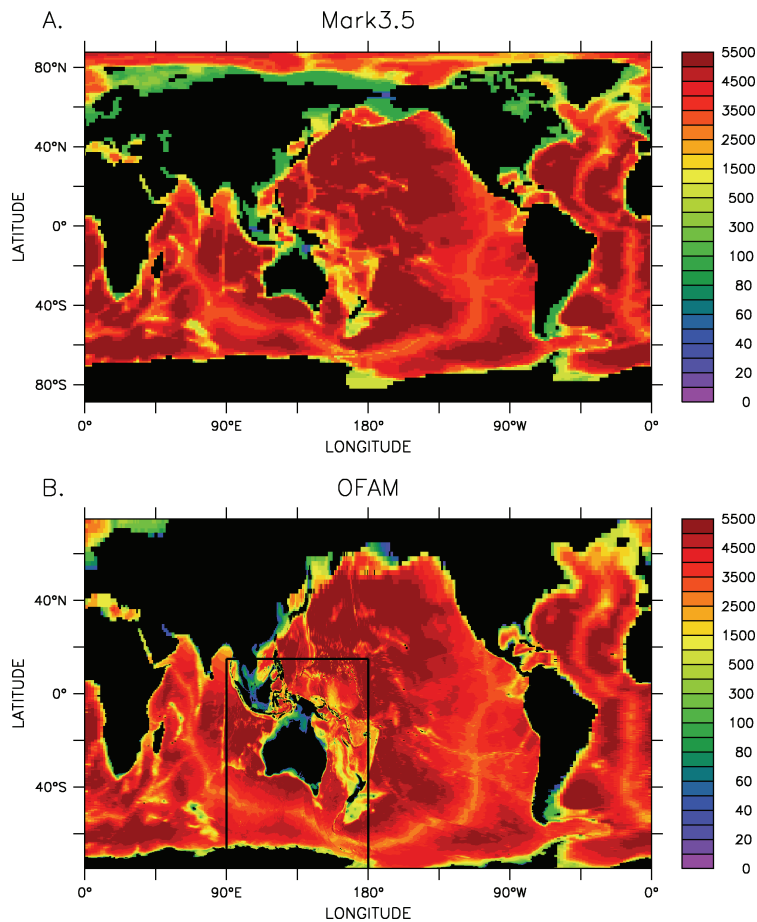
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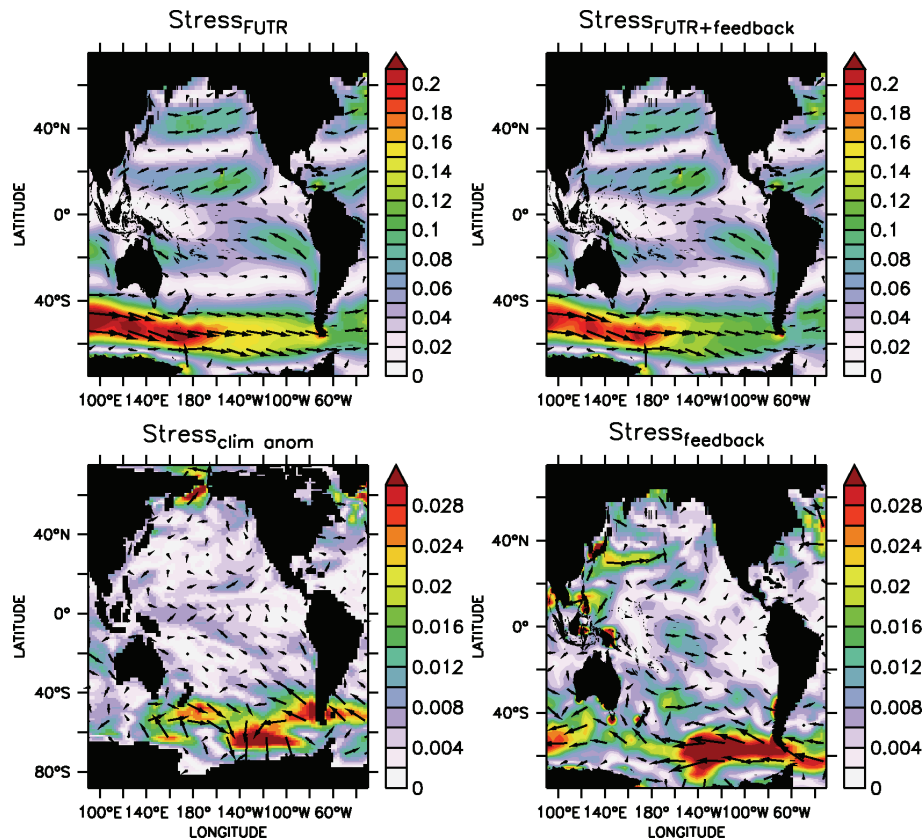
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**Fig. 2.** Model grids of the (a) AOGCM (Mk3.5) and (b) ODM (OFAM). In panel (b), the box area around Australia indicates the region where OFAM has a resolution of  $0.1^\circ$ .

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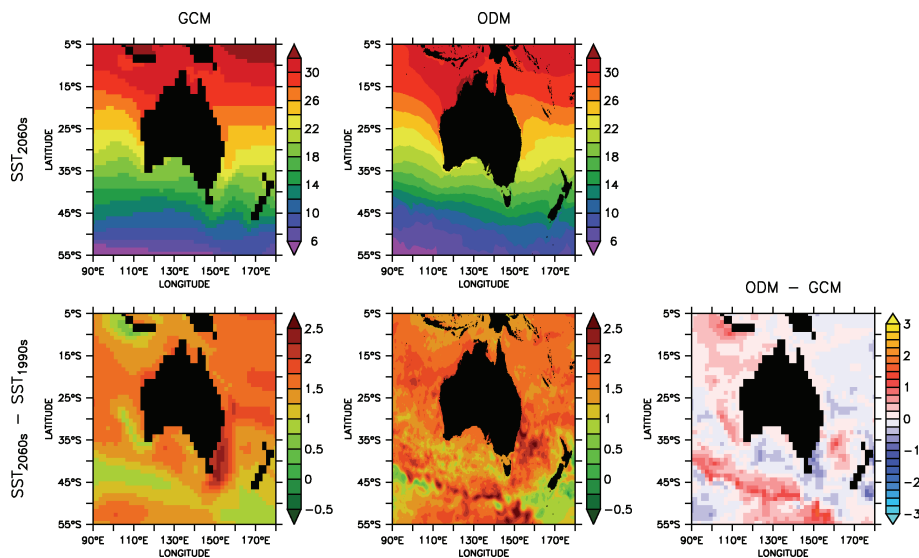
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**Fig. 3.** The top row shows the annual averaged windstresses (shades show magnitude in  $\text{N m}^{-2}$ , arrows give direction) used by FREE (left) and STRS (right) experiments. The bottom row shows annual averaged windstresses for the climate anomaly (left) and feedback (right), see Sect. 2.5.2 for details about windstress feedback.

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**Fig. 4.** 10-yr averages of: projected SST (top row, in °C) and the projected climate change in SST (bottom, °C). The AOGCM experiment is shown in the left column, the RELX ODM is in the centre, and the difference between this ODM and AOGCM is on the right.

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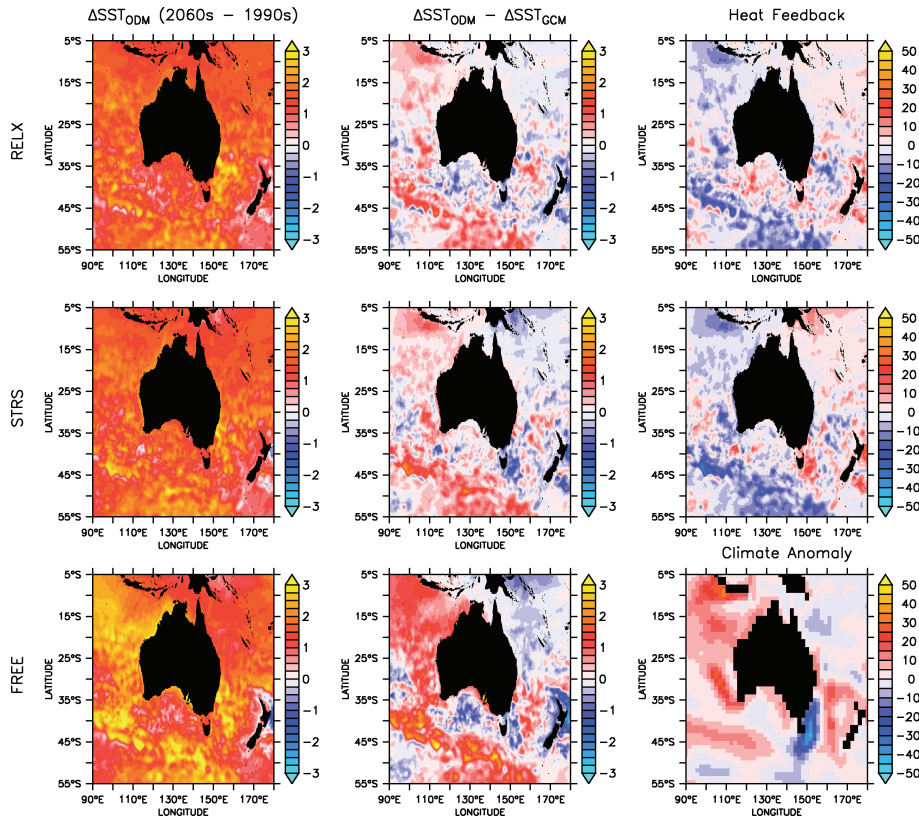
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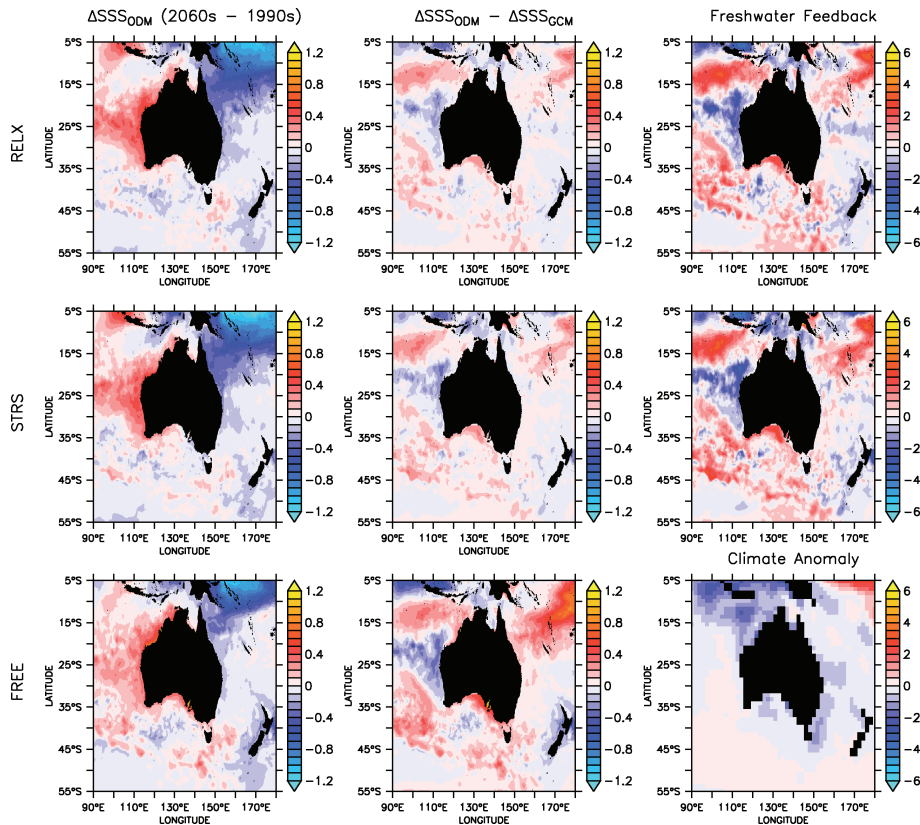


**Fig. 5.** Annual averages of: projected climate change in SST from the ODM (left column, in °C), differences in climate change for SST (centre, °C), and, heat flux feedback (right,  $\text{W m}^{-2}$ ). For comparison, the average climate change heat flux anomaly is shown in the bottom right panel. The RELX experiment is shown along the top, STRS is in the middle, and, FREE is on the bottom.



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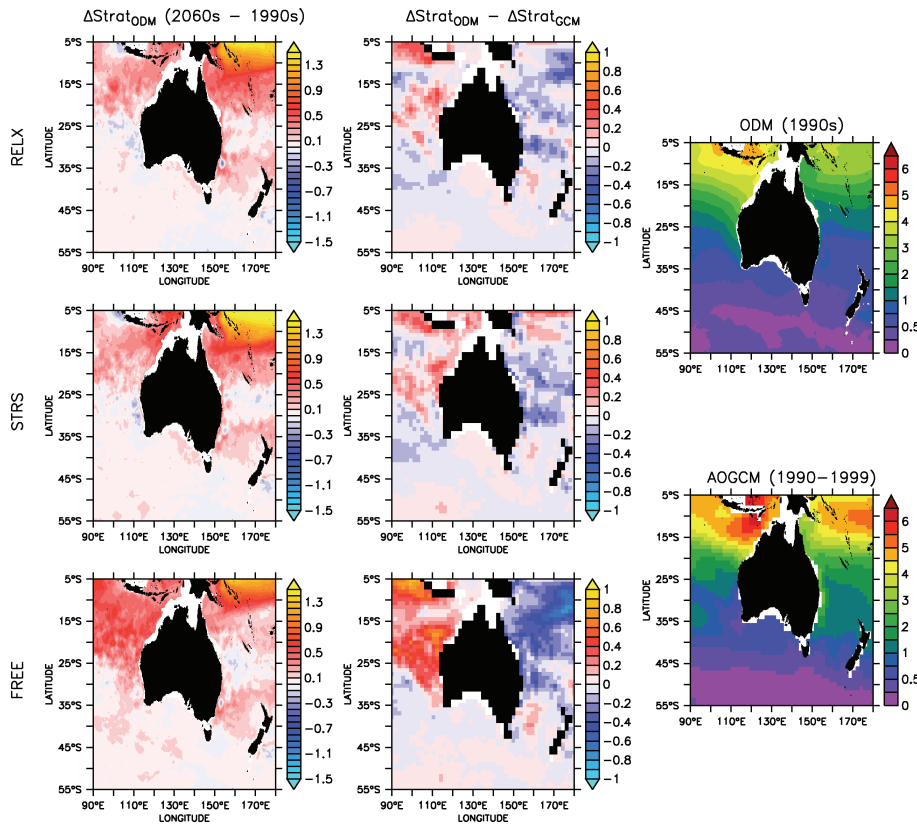
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**Fig. 6.** Annual averages of: projected climate change in SSS from the ODM (left column, in practical salinity units – psu), differences in climate change for SSS (centre, psu), and, freshwater flux feedback (right,  $\text{mm day}^{-1}$ ). For comparison, the average climate change freshwater flux anomaly is shown in the bottom right panel. The RELX experiment is shown along the top, STRS is in the middle, and, FREE is on the bottom.

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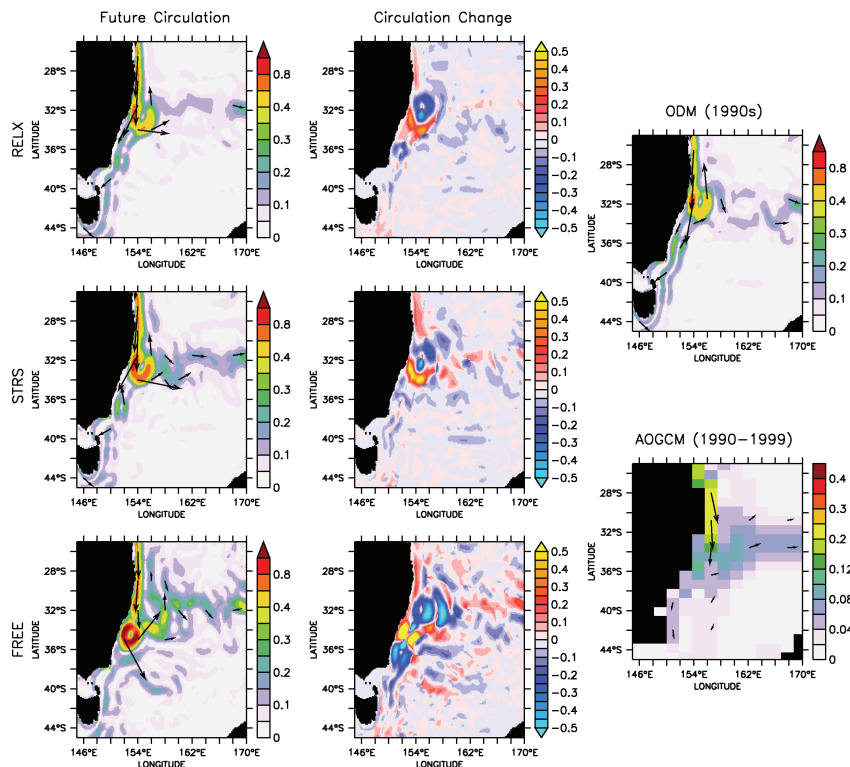
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**Fig. 7.** Annual averages of: projected climate change in stratification from the ODM (left column, in  $\text{kg m}^{-3}$ ), and, differences in climate change for stratification (centre,  $\text{kg m}^{-3}$ ). In these columns, the RELX experiment is shown along the top, STRS is in the middle, and, FREE is on the bottom. The right column shows stratification for the 1990s in the ODM and AOGCM. Stratification is shown here as the difference in density in water at 200 m and the surface.

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**Fig. 8.** Multi-year averages of: transport in the upper ocean from the ODM (left column), and, projected climate change in transport (centre). The RELX experiment is shown along the top (average of 10 yr), STRS is in the middle (5 yr), and, FREE is on the bottom (1 yr). For reference, the transport fields for the 1990s in the ODM and AOGCM are shown in the right column. Transports are calculated as the average current over the top 250 m, in  $\text{m s}^{-1}$ ; colours indicate magnitudes, arrows show direction. Transport changes are calculated in the direction of the present day transport.

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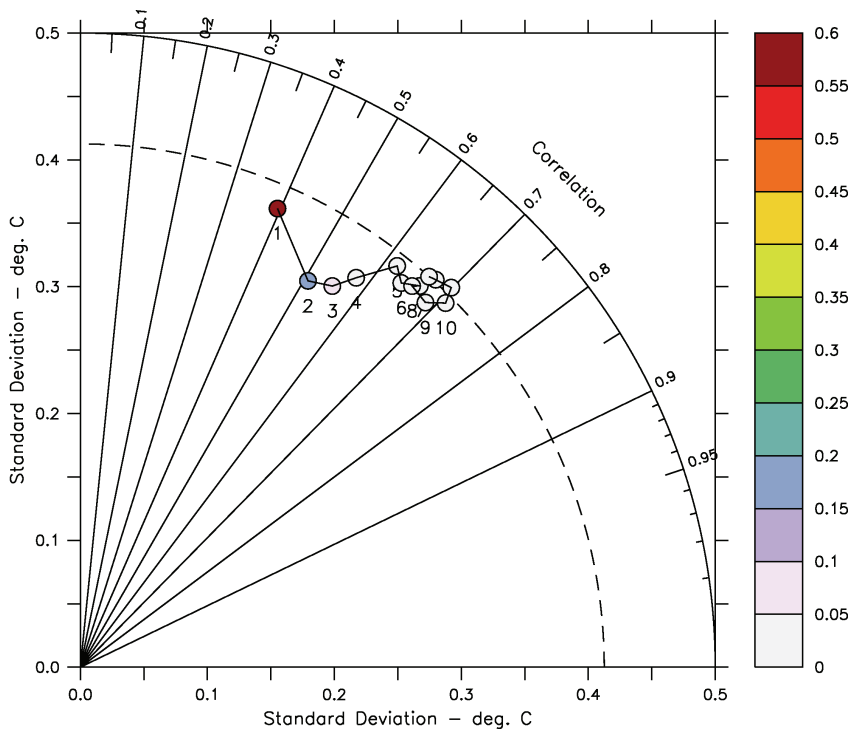
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**Fig. 9.** Taylor diagram of the convergence of SST in the RELX experiment. The standard deviation shown is of the difference between the annual SST and the guide field for each year of the experiment (in degrees Celsius). These SST difference fields are correlated to the difference of the following year, so point “5” is the correlation of SST from years 5 and 6. A perfectly correlated (or anti-correlated) field would appear somewhere on the x-axis on the Taylor diagram, a completely uncorrelated field would be on the y-axis. The value of the difference in the average for the Australian region to the average of the final year (in degrees Celsius) is represented by the colour of each point.

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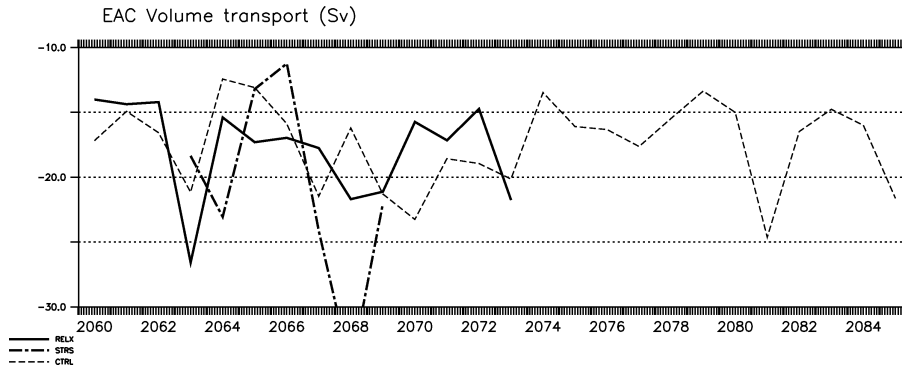
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## Downscaling the climate change for oceans around Australia

M. A. Chamberlain et al.



**Fig. 10.** EAC volume transport ( $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ) in ODM experiments through a section at  $28^\circ \text{ S}$ . Volume transports shown are annual averages of the integrated north-south flow over  $153\text{--}157^\circ \text{ E}$  and  $0\text{--}600 \text{ m}$  depth, values are negative since the flow is to the south. Transport in CTRL is a thin dashed line, which is shifted in time, RELX is a solid line, STRS is dash-dot line. Note that all these experiments use repeat-year forcing so the year values only indicate the year into each simulation, not calendar year.

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