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Dynamical downscaling techniques: Impacts on regional climate change signals

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Abstract: There are many different techniques for dynamical downscaling of global climate change projections to study regional climate change, including high-resolution global atmospheric models, stretched-grid models, and the most popular technique, limited-area models. All these methods require some information from fully-coupled atmospheric-oceanic-ice global coupled models (GCMs), ranging from ocean temperatures through to full atmospheric data every six hours as forcing. A systematic study of these various techniques and their impact on the simulated regional climate is required in order to assess the validity and assumptions that influence the results of the simulations. In this preliminary study, the impact on the precipitation when downscaling with and without atmospheric forcing (in the form of a digital filter) and with and without bias-corrected sea surface temperatures (SSTs) is investigated using the CSIRO Conformal Cubic Atmospheric Model (CCAM). The CCAM is a variable-resolution global atmospheric model with enhanced resolution over a selected region and does not require lateral boundary conditions.

Significant improvement in the distribution of precipitation in the current climate is obtained when bias-corrected sea surface temperatures from global coupled models are used as lower boundary conditions. Using uncorrected SSTs and atmospheric forcing from the GCMs to drive CCAM, the basic large-scale features of the GCMs are preserved in the downscaled run. The results demonstrate the flexibility of using the variable-resolution CCAM for dynamical downscaling.

Keywords: *dynamical downscaling, regional climate, climate change*

1. INTRODUCTION

There are many different approaches to dynamical downscaling, ranging from time-slice experiments with high-resolution global climate models (GCMs), to using stretched-grid climate models with higher resolution over a portion of the globe, to nesting limited-area models within GCM output. Most downscaled simulations provide a very limited sample of the full climate uncertainty, as they typically use only one GCM as forcing. The main reason for this is the limited access to suitable GCM output (outputs more frequent than daily to drive the downscaled model) and the lack of computational resources (the computational time to run multiple, long downscaled simulations). Use of a computationally efficient, variable-resolution, global atmospheric model in conjunction with alternative downscaling techniques can provide new opportunities to downscale more GCMs and provide a better sample of regional climate change uncertainty at higher resolutions.

For more than a decade, CSIRO Marine and Atmospheric Research (CMAR) has carried out extensive regional climate modelling research. The underpinning dynamical downscaling model has been the CSIRO Conformal Cubic Atmospheric Model, CCAM (McGregor, 2005; McGregor and Dix, 2001, 2008). The CCAM is a full atmospheric global general circulation model, formulated using a conformal-cubic grid which covers the globe but can be stretched to provide higher resolution in areas of interest. This gives more flexibility to downscaling experiments, allowing forcing of CCAM by sea surface temperatures (SSTs) as well as forcing by atmospheric fields from the host GCM (somewhat akin to the limited-area model style). In addition, it is possible to downscale from many of the Intergovernmental Panel on Climate Change Forth Assessment Report climate models (Meehl et al., 2007). It is formulated using semi-Lagrangian advection and semi-implicit time step, so it can run long simulations efficiently.

Initial results obtained from CCAM using several downscaling techniques for a sensitivity analysis using simulations for 10 Julys (1970-1979) for a single GCM (CSIRO Mk3.5) are presented here. Results are compared to observations, a continuous 140-year (1961-2100) CCAM simulation within same GCM and to the CSIRO Mk3.5 GCM. The downscaling techniques used include downscaling using just the SSTs (both as specified by GCM and bias-corrected GCM values) and sea ice from the GCM as lower-boundary forcing, as well as using a digital filter to force atmospheric fields (details specified below). A key aspect of this presentation is the impact on the precipitation using the various techniques for the current climate and the climate change signal.

2. MODEL DESCRIPTION AND EXPERIMENTAL DESIGN

The CCAM includes a fairly complete set of physical parameterizations. The GFDL parameterization for long-wave and short-wave radiation is used (Schwarzkopf and Fels, 1991; Lacis and Hansen, 1973), with interactive cloud distributions determined by the liquid and ice-water scheme of Rotstayn (1997). The model employs a stability-dependent boundary layer scheme based on Monin-Obukhov similarity theory (McGregor et al., 1993). The canopy scheme described by Kowalczyk et al. (1994) is used, with six layers for soil temperatures, six layers for soil moisture (solving Richard's equation), and three layers for snow. The cumulus convection scheme uses mass-flux closure, as described by McGregor (2003), and includes both downdrafts and detrainment. The CCAM may be employed in quasi-uniform mode, or in stretched mode by utilising the Schmidt (1977) transformation.

The experiments performed in this study are summarized in Figure 1. The first step is picking a suitable GCM to downscale (sometimes referred to as host GCM). The main criterion chosen here is that the GCM have credible interannual variability and suitable seasonality over Australia. Suppiah et al. (2007) and Smith and Chandler (2009) carried out analyses of the GCMs included in the IPCC Fourth Assessment Report (Meehl et al., 2007). Both assessments involved a comparison of the GCMs performance in reproducing a range of metrics over the Australian continent. Based on these comparisons, demerit points (Suppiah) and a weighted failure rate (Smith) were developed. In these studies, the CSIRO Mk3.5 GCM performed well, and is used in this study. Runs with other GCMs are planned for the future.

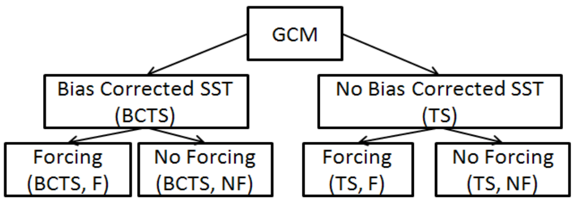

Figure 1. Schematic of various options used in this experiment for dynamical downscaling a GCM. In addition, there are numerous options for forcing (F) the downscaled results with fields from the GCM.

The next choice is the grid spacing and resolution of the downscaling model (CCAM). For these simulations, CCAM is run with a stretched grid with the grid resolution shown in Figure 2. Over Australia, the resolution is about 60 km, which degrades to around 400 km over the North Atlantic Ocean.

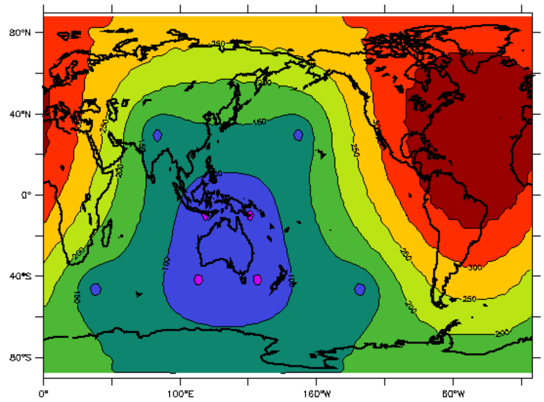

Figure 2. CCAM model grid resolution (km).

All simulations use interpolated monthly SSTs and sea-ice cover as provided by the GCMs. Since the GCMs tend to have biases in SSTs relative to observed climate (Reynolds, 1988), the next step is to decide whether or not to correct these SST biases. The monthly climatology of the GCM SSTs is computed for the current climate (1961-2000). For each month, the GCM SST bias relative to the Reynolds (1988) SST is computed and subtracted from the GCM SST field before using in the downscaled simulation. Using this technique, the climatology of the SSTs in the downscaled simulation is the same as specified by Reynolds (1988). However, the inter- and intra-annual variability is same as that of the host GCM. Since the monthly bias correction is unchanged throughout the run, both the interannual variability and climate change signal of the GCM SSTs are also not altered.

Finally, the variables and amount of atmospheric forcing from the GCM in the downscaled simulation needs to be decided. If a SST bias-correction is applied, there potentially can be some inconsistencies if atmospheric forcing is also applied, since there is no apparent way to make the atmospheric forcing consistent with the bias-corrected SSTs. The inconsistency arises because the atmospheric wind, temperature and moisture fields in the GCM are influenced by the unbias-corrected (GCM) SSTs. Regardless of this potential inconsistency, simulations with bias-corrected SSTs and atmospheric forcing are completed as part of the sensitivity study.

There are several options available for atmospheric forcing within CCAM. In the past, the model was run with far-field (grid-point nudging away from high-resolution area) or global nudging (nudging everywhere, typically just winds above 500 hPa). More recently, digital filter forcing has been developed (Thatcher and McGregor, 2009), where selected fields are replaced at the larger scales. This allows the fine-scale detail in the downscaled simulation to develop, while preserving the large-scale structure from host GCM. In the simulations presented here, those features with length scales greater than the width of Australia are replaced by equivalent data from the host GCM. In all cases, there is also a choice of what variables and levels to force as well as what strength of forcing to use. In the runs presented here, a digital filtered forcing of surface pressure and winds, temperatures and moistures above 850 hPa is used.

In the present runs, all four cases shown at the bottom of Figure 1 are completed using the CSIRO Mk3.5 GCM as host GCM. Precipitation is used to evaluate the various techniques in this study. The various downscaled results are evaluated against observed climatologies (Xie and Arkin, 1996) and with the driving GCM, both for the current climate and climate change signal. Finally, comparison is made to a continuous run downscaled CCAM run using bias-corrected SSTs and no atmospheric forcing which started January 1961. In this run, the land surface temperatures and moistures are equilibrated to the CCAM climatology.

3. RESULTS OF SENSITIVITY STUDY

In this preliminary study, averages from running CCAM for 10 individual Julys (1970-1979) using the four downscaling choices of methodology indicated in Figure 1 are presented. The July SST biases for the CSIRO Mk 3.5 GCM are shown in Figure 3. Note the significant biases, especially in tropical regions. The magnitude and pattern of SST biases in the tropical region has a significant effect on the rainfall, as will be shown next.

Comparison of observed July precipitation climatology (Figure 4a; Xie and Arkin, 1996) with that from the CSIRO Mk 3.5 GCM (Figure 4b) and CCAM run with bias-corrected SSTs and no atmospheric forcing (Figure 4c, BCTS,NF) and without bias-corrected SSTs and a digital filtered atmospheric forcing (Figure 4d, TS,F) shows significant improvement in the rainfall climatology when bias-corrected SSTs are used (especially in the tropics). In particular, a dual inter-tropical convergence zone (ITCZ) is evident in the GCM precipitation and in the CCAM simulation with same SSTs and atmospheric forcing. The rainfall pattern over the Pacific is more realistic in the bias-corrected, unforced CCAM simulation. A more credible current climate simulation gives more confidence in the climate change signal.

Statistics of the rainfall, computed over the Australian region, are presented in Table 1. Note that since only 10 years of data are used here, these statistics should only be used as general indicators, not as robust measure of model performance. Although the CCAM simulations tend to overpredict precipitation more than the GCM does, and have slightly higher root-mean-square errors, the pattern correlations are slightly better, especially for the bias-corrected SST runs. Also note that the results from the 10 Julys from the continuous run are better than from the equivalent run with similar setup, but run only for 10 individual Julys (BCTS,NF run). This suggests that soil properties, such as temperature and moistures, are better equilibrated in the continuous run, as well as possibly some influence of the initial state, taken directly from the GCM for the 10 July simulations, as it would take some time for global climate to equilibrate to CCAM's configuration. More than 30 years of data could provide more robust statistics. Longer runs are planned for the future.

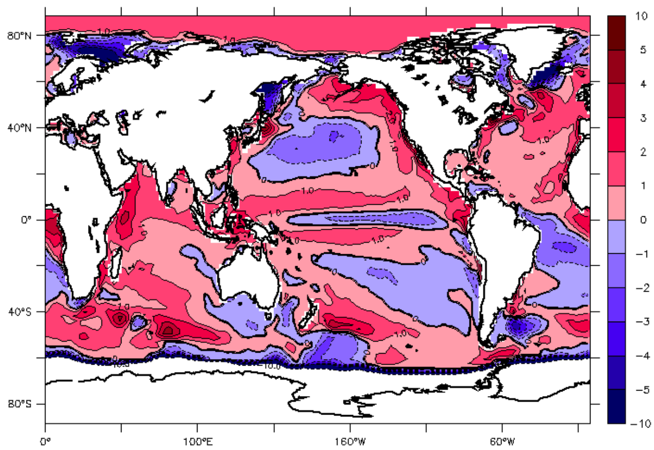

Figure 3. CSIRO Mk 3.5 SST bias (°C, contour interval of 1) for July.

Table 1. Statistics computed for rainfall versus observed climatology for Australian region (110 to 160 E longitudes, -10 to -45 S latitudes).

July Rainfall 110-160 E 10-45 S	GCM	Cont.	BCTS,NF	BCTS,F	TS,NF	TS,F
Bias	0.05	1.06	1.26	0.74	0.91	0.71
RMSE	0.79	1.34	1.53	1.18	1.23	1.20
Pat.Cor	0.76	0.86	0.80	0.82	0.77	0.79

Results for the rainfall change for 10 Julys (2080-89 versus 1970-79) from downscaling one GCM (CSIRO Mk 3.5) are presented in Figure 5. Overall, the pattern of precipitation change is generally similar in all runs. All show increases in tropical Pacific and decreases over Indonesia. Similarities exist over midlatitude regions as well. As expected, the rainfall change in the TS,F run (using unbias-corrected SSTs and with atmospheric forcing from the GCM) is most similar to the GCM, since this run uses the same SSTs and is forced to the atmospheric fields of the GCM. The equivalent run without atmospheric forcing (TS,NF) has some differences, especially in the South Pacific, likely due to the fact that CCAM has different dynamics and physics than the GCM. The two bias-corrected SST runs have broad similarities to each other, indicating the significant impact of SSTs in these simulations. However, differences still exist between these two runs. As noted earlier, there is some question about the validity of using bias-corrected SSTs along with atmospheric forcing from the GCM which uses the original (unbias-corrected) SSTs. Also note the differences in results between the continuous run and the 10 July runs, suggesting insufficient spin-up time in the later runs.

4. CONCLUSION

Various techniques are available to determine regional climate by dynamical downscaling. In this study, several techniques are evaluated using the CCAM model. Using raw SSTs from a GCM and some atmospheric forcing produces current and climate-change signals similar to the GCM. However, these results show that with bias-corrected SSTs from a GCM, a better current climatology of rainfall is produced. It is believed that a better current climatology will also produce a more plausible climate-change signal. This work is preliminary, and more research is needed in order to assess other implications of using the various downscaling techniques. These results show the utility of using CCAM, a stretched grid model, to study various techniques for dynamical downscaling GCMs.

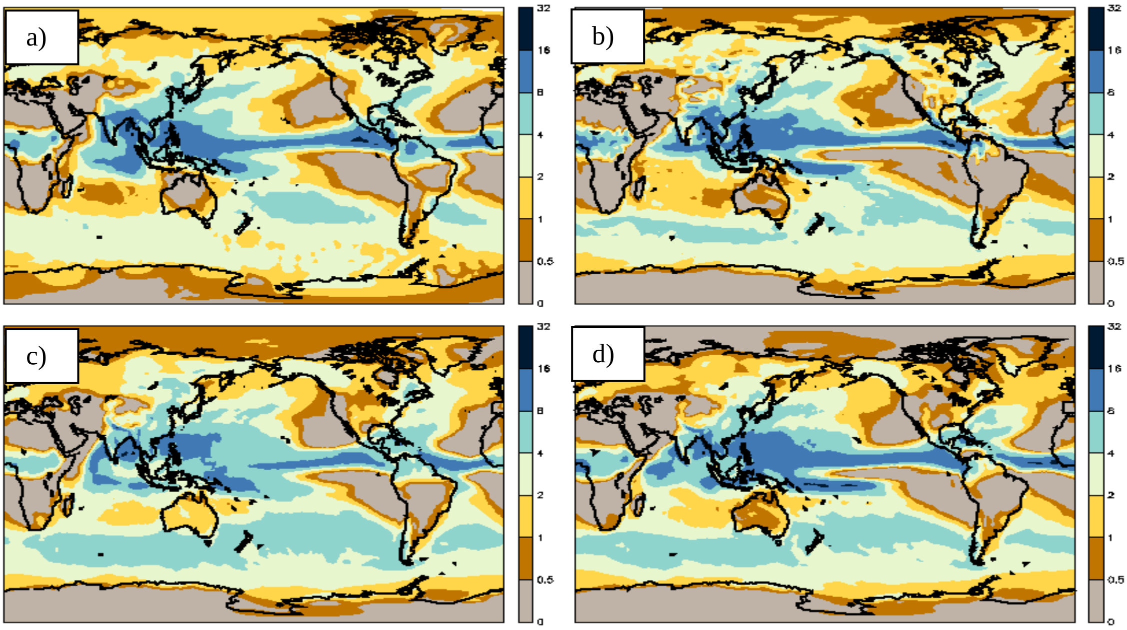

Figure 4. July precipitation distribution (mm/d) a) CPC climatology, b) CSIRO Mk 3.5 GCM, c) CCAM using bias-corrected SSTs and no atmospheric forcing from Mk 3.5 GCM, d) CCAM using raw SSTs and atmospheric forcing from Mk 3.5 GCM.

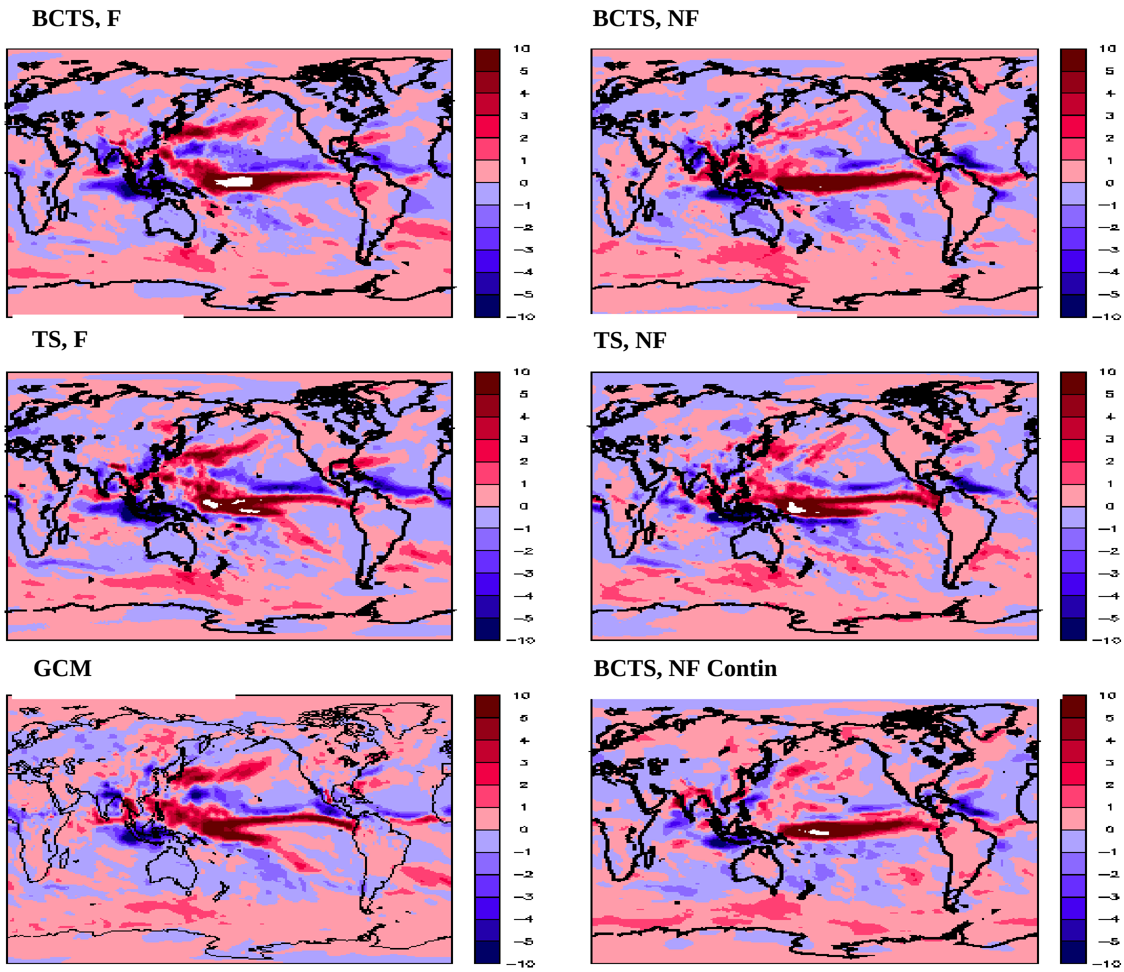

Figure 5. Rainfall change (mm/d) from 2080-2089 minus 1970-1979 for July using CSIRO Mk 3.5 GCM A2 scenario. BCTS = bias corrected SST, F = atmospheric forcing applied via digital filter, GCM from CSIRO Mk 3.5, Contin = results from continuous, 140-year CCAM run.

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REFERENCES

Kowalczyk, E., Garratt, J.R., and Krummel, P.B. (1994), Implementation of a soil-canopy scheme into the CSIRO GCM - regional aspects of the model response, (1994) *CSIRO Div. Atmospheric Research Tech Paper No. 32*, 59 pp.

Lacis, A. and Hansen, J. (1974), A parameterization of the absorption of solar radiation in the Earth's atmosphere. *J. Atmos. Sci*., 31, 118-133.

McGregor, J.L., Gordon, H.B., Watterson, I.G., Dix, M.R. and. Rotstayn, L.D (1993), The CSIRO 9-level atmospheric general circulation model, *CSIRO Div. Atmospheric Research Tech. Paper No. 26*, 89 pp.

McGregor, J.L. (2003), A new convection scheme using a simple closure. In "Current issues in the parameterization of convection", *BMRC Research Report 9*3, 33-36.

McGregor, J.L. (2005), C-CAM: Geometric aspects and dynamical formulation [electronic publication]. *CSIRO Atmospheric Research Tech. Paper No. 70*, 43 pp.

McGregor, J.L., and Dix, M.R. (2001), The CSIRO conformal-cubic atmospheric GCM. In *IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics*, P. F. Hodnett (Ed.), Kluwer, Dordrecht, 197-202.

McGregor, J.L., and Dix, M.R. (2008), An updated description of the Conformal-Cubic Atmospheric Model. In *High Resolution Simulation of the Atmosphere and Ocean*, eds. K. Hamilton and W. Ohfuchi, Springer, 51-76.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J. and Zhao, Z.-C. (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* [Solomon, S.,D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Reynolds, R. W. (1988), A real-time global sea surface temperature analysis. *J. Climate*, 1, 75-86.

Rotstayn, L.D. (1997), A physically based scheme for the treatment of stratiform clouds and precipitation in large-scale models. I: Description and evaluation of the microphysical processes. *Q. J. R. Meteorol. Soc.*, 123, 1227-1282.

Schmidt, F. (1977), Variable fine mesh in spectral global model. *Beitr. Phys. Atmos.*, 50, 211-217.

Schwarzkopf, M.D. and Fels, S.B. (1991), The simplified exchange method revisited: An accurate, rapid method for computation of infrared cooling rates and fluxes. *J. Geophys. Res.*, 96, 9075-9096.

Smith, I. and Chandler, E. (2009), Refining rainfall projections for the Murray Darling Basin of south-east Australia – the effect of sampling model results based on performance. In preparation.

Suppiah, R, Hennessy, K.J., Whetton, P.H., McInnes, K., Macadam, I., Bathols, J., Ricketts, J. and Page, C.M. (2007), Australian climate change projections derived from simulations performed for the IPCC 4th assessment report. Australian Meteorological Magazine, 56, 131–152.

Thatcher, M., and McGregor, J.L. (2009), Using a scale-selective filter for dynamical downscaling with the conformal cubic atmospheric model. Accepted by *Mon. Wea. Rev.*

Xie P., and P. A. Arkin, P. (1996) Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull. Amer. Meteor. Soc., 78, 2539-2558.