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Tropical Australia and the Australian Monsoon: general assessment and projected changes

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Abstract: The Australian monsoon is a fundamental component of Southern Hemisphere summer circulation, and dominates rainfall distributions over northern Australia and adjacent regions. This paper examines the ability of the current generation of models to simulate the Australian monsoon, including basic temperature, pressure, wind and precipitation patterns and variation. The variability of models on a range of timescales is also assessed, including interannual variability. Monthly time series are used to examine the ability of models to depict timescale variability, as well as issues such as monsoon onset and duration, and intensity of rainfall events. A comparison will be made with aspects of monsoon representation by the previous generation of models. We find that while there are some deficiencies in simulating 20th century monthly climate means (of rainfall in particular) some of the large scale features such as the zonal winds are quite reasonably simulated.

Changes to the Australian monsoon over the coming century could have profound consequences for Northern Australia and adjacent regions, for example affecting rainfall totals, distribution or intensity. This paper examines projected changes in the Australian monsoon as depicted by the coupled climate models. Assessing these changes in the Australian monsoon under enhanced greenhouse conditions is problematic, because the signal (if any) seems to be very weak. The ensemble mean model results indicate a possible later retreat of the monsoon, particular over North-western part of Australia.

Keywords: *Australian monsoon, CMIP3, climate change*

1. INTRODUCTION

Large uncertainties remain in possible climate changes caused by increasing greenhouse gases, particularly at regional levels (IPCC, 2007a; CSIRO, 2007). The Asian-Australian monsoon comprises an important large-scale component of the climate system, as well a being the major source of regional seasonal rainfall variation, and changes in the monsoon may have major impacts. The Australian component of monsoon has, by contrast, been little studied, and although populations are much smaller, regional impacts may also be large particularly on vulnerable indigenous populations and on ecosystems (IPCC, 2007b). This is especially the case since the Australian monsoon is the dominating factor in tropical Australian rainfall (e.g. McBride, 1998), and uncertainties in possible changes to the mean monsoon, or to monsoon variability remain key uncertainties in Australian regional climate change projection (IPCC, 2007a, b). This study will examine how well large scale monsoon features for the current climate are simulated by state-of-the-art Coupled Global Climate Models (CGCMs), as represented by the models that took part in the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) (Meehl et al., 2007). Additionally, we will consider projected monsoon changes for the following century.Although very few studies have focused specifically on evaluation of climate model representation of Australian monsoon circulations, a significant number have considered aspects of the broader Australian climate, particularly relating to temperatures and precipitation (CSIRO, 2007). As part of the Atmospheric Model Intercomparison Project (AMIP2), Zhang et al (2002) analysed 16 atmospheric GCMs, finding significant model deficiencies in rainfall and surface temperature seasonality. Moise et al (2005), examining 18 CGCMs taking part in the Coupled Model Intercomparison Project phase 2 (CMIP2), found agreement with the gross spatial patterns of austral summer rainfall (DJF), but with significant model errors in simulating the intensity and location of heavy monsoonal rainfall in the north and eastern parts of the continent. Seasonal surface temperature variations were reasonably reproduced, but with biases of around 2 to 4°C. Wang et al (2004) found that atmospheric GCMs forced by SST anomalies skilfully simulated northern Australian monsoon related zonal wind variability for the period 1996-98. A much earlier study by Suppiah (1995) showed that one GCM was able to simulate many of the observed large-scale aspects of Australian monsoon circulation, such as the seasonality of rainfall and temperature, and the location of the low level 'monsoon trough', although was much weaker than observations in its representation of the magnitudes of winds and precipitation.

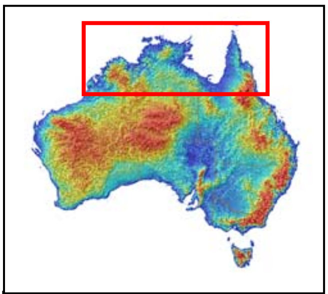


Figure 1. Map showing the tropical area of Australia (10-20°S, 110-150°E) considered in this paper.

2. MODEL AND VALIDATION DATASETS

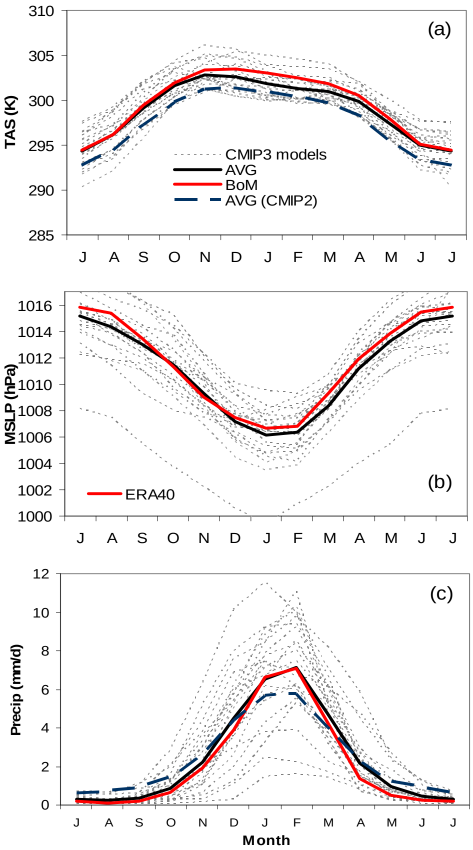
Models considered were those submitted to the WCRP's CMIP3 (Meehl et al., 2007). Monthly results were extracted from the 20th century coupled runs (20C3M) for the period 1980-1999 for analysis of mean fields, and the longer period, 1950-1999, for interannual variability (see AchutaRao et al., 2007 for a summary of model forcing). A single realisation was selected for each model where multiple realisations were available. Variability of climate between different ensemble members for individual models, however, was investigated and is addressed below. Australian daily mean surface temperatures were calculated by averaging maximum and minimum temperatures from the high-quality observational data sets compiled by the National Climate Centre of the Australian Bureau of Meteorology (Jones and Trewin, 2000). Precipitation observations over Australia were taken from the 0.25° monthly high quality gridded data set (based on gauge data) developed by the Australian Bureau of Meteorology (Jones and Weymouth, 1997). For inclusion of surrounding oceans (as in the bias plots below) the Climate Prediction Center Merged Analysis of Precipitation (CMAP) blended gauge/satellite data set was used (Xie and Arkin, 1997). Winds and surface pressure were taken from monthly means from the European Centre for Medium Range Weather Forecasting (ECMWF) 40 year reanalysis (ERA40) (Uppala et al., 2005).

3. THE MODEL SIMULATED MONSOON CLIMATE

3.1. Seasonal cycles over tropical Australia

This section will focus on the seasonal variation of important climate features associated with the monsoon, and their representation by models. Firstly, large-scale averages over northern Australia (120-150°E, 10-20°S, see Figure 1) of surface temperature, mean sea level pressure (MSLP) and precipitation as well as 850hPa and 200hPa zonal winds are shown in Figure 2. Characteristic features of the observed monsoon are a strong seasonal cycle of precipitation, with virtually none falling during winter months, increasing rapidly in October and November, to a peak of around 7 mm per day on average during February. Rapid falloff occurs in March/April. The mean cycle, of course, disguises a large amount of interannual and intra seasonal variability

(Hendon and Liebmann, 1990a,b; Holland 1986; Drosdowsky, 1996), and some of these features are discussed below. The MSLP change from summer to winter is around 7hPa, with minimum climatological values occurring in September, associated with maximum southward extent of the monsoon trough (e.g. McBride, 1998). Note that averaging of MSLP here includes ocean points, so as to reduce the impact on the mean of the (shallow) surface 'heat low', typically located in the northeast of Western Australia, which occurs commonly over summer months (Gunn et al., 1989). Associated with the motion of the monsoon trough, there is seasonal reversal of both lower and upper winds: low level winter trade wind easterlies are replaced by westerlies (peaking at around 2 m/s) in January and February, and extending up to 500hPa. Upper level easterlies also occur for the peak monsoon period. Temperature displays a seasonal variation of around 10°C, with the peak notably occurring early in the wet season -- in November, followed by a slow decline until April, with more rapid decline thereafter. This is consistent with maximum warming occurring under relatively clear skies prior to the main onset of the monsoon (with subsequent increases in cloudiness and precipitation.



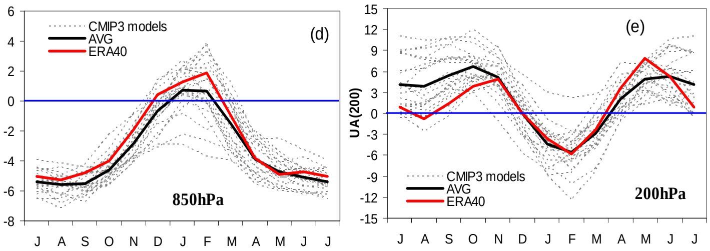


Figure 2. Seasonal variation, averaged over 120-150°E, 10-20°S for (a) daily mean surface air temperature (K), (b) mean sea level pressure (hPa) and (c) precipitation (mm/day), averaged over the period 1980-1999. Individual CMIP3 models are shown as dashed grey lines. Also shown are the multi-model means (black lines) and observational/reanalysis estimates (red). (a) and (c) show averages over land points only. Also shown are the averages calculated over 18 CMIP2 models (dashed black). Parts (d) and (e) show the 850hPa and 200hPa zonal winds averaged over the same region.

3.2. Mean climate and circulation

Firstly, large-scale patterns of surface temperature, MSLP and precipitation for austral summer (DJF) are compared for the average of the 24 CMIP3 models and the observational/reanalysis datasets (not shown here). Particular for rainfall, substantial biases are found across the ensemble of models. Figure 3 shows that the ensemble mean model has a dry bias in tropical Australia and a wet bias further south, i.e. the North-south gradient in summer rainfall is not steep enough.

This is apparent also in the rms error and spatial correlation statistics shown in Figure 4. However, a significant improvement over CMIP2 model performance is found for both statistics in the ensemble mean model during the Australian summer season. Because of the steep North-south gradient in tropical Australian rainfall, relatively small geographical mismatches will result in large underperformances in spatial correlation to the observations, as can be seen in Figure 4 (bottom).

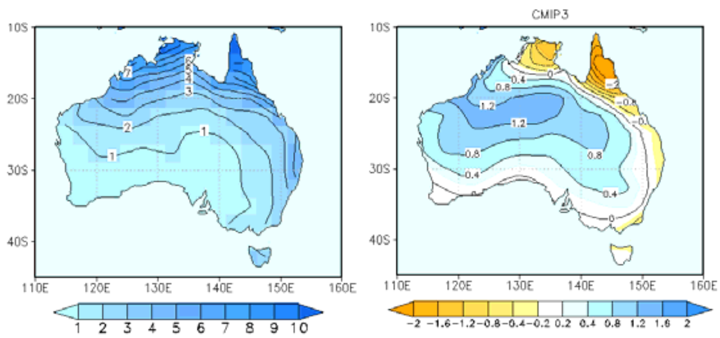


Figure 3. Mean summer (DJF) rainfall for Australia (1980-1999) from observations (left) and the CMIP3 ensemble mean model bias (right). Units are (mm/day).

One of the distinct features of the Australian monsoon season is the reversal in the zonal winds at both low and high altitudes. Figure 5 shows this reversal for the ERA40 reanalysis and CMIP3 ensemble mean model for the period 1980-1999. From the reanalysis, the mean monsoon onset date for the entire tropical region considered

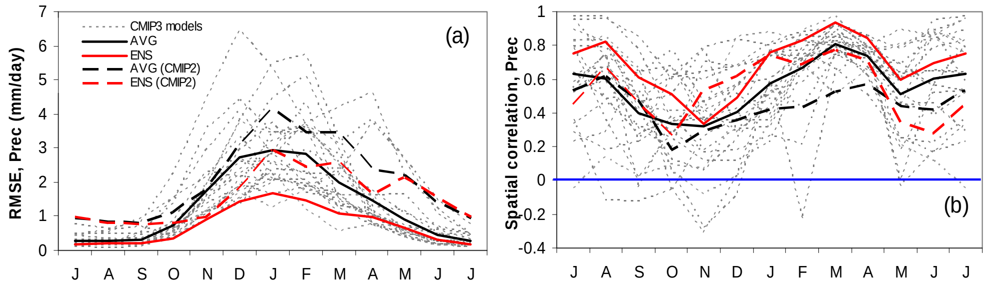


Figure 4. Tropical Australian rainfall rms error (top) and spatial correlation (bottom) for the ensemble mean (red) and average (black) model from CMIP2 (long dashed) and CMIP3 (solid) inter-comparisons. The individual CMIP3 models are depicted in grey.

is around late November and the mean retreat date is in late February. The low level westerlies during the monsoon season extend upward to around 500hPa with easterlies at higher altitudes. While the overall height structure of the zonal wind is captured by the ensemble mean model, there are some deficiencies: the monsoon onset is too late (mid-December) and the retreat somewhat too early (mid-February); the low level westerlies are generally too weak; and they do not extend high enough (only to 700hPa).

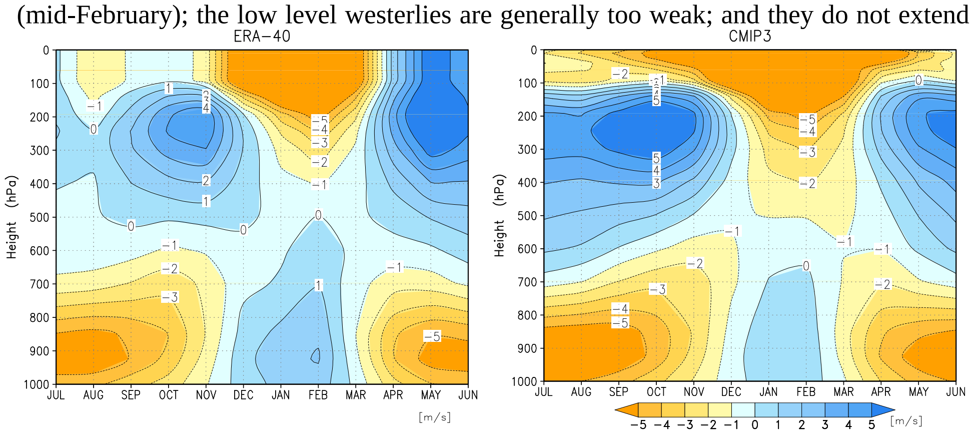
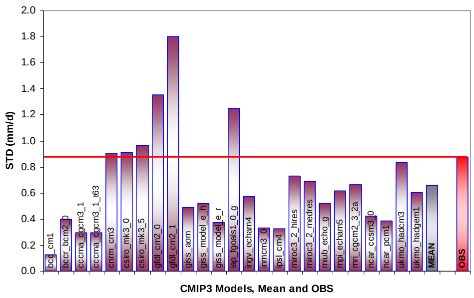


Figure 5. Seasonal change of mean zonal winds (m/s) vs pressure level (hPa) for Australia (1980-1999) from ERA40 (left) and the CMIP3 ensemble mean model (right). Units are (m/s).

3.3. Interannual Variability



The year-to-year variability in rainfall during the wet season is an important feature for the Australian monsoon. Figure 6 shows the ONDJFMA rainfall variability across tropical Australia for the 20 year period 1980-99 in the observed record and all CMIP3 models. Most models have a too low interannual variability, however in 3 models it is comparable to observations and too large in three others.

Figure 6. CMIP3 inter-annual variability of wet season (ONDJFMA) rainfall over tropical Australia (purple), mean (grey) and observations (red). Unites are (mm/d).

4. PROJECTED CHANGES IN TROPICAL AUSTRALIA

4.1. Change in mean climate

Recent results from the Global Carbon Project (2008) indicate that the global CO_2 emission pathway is currently tracking along the A2 scenario, the highest CO_2 emission SRES scenario considered in the IPCC Fourth Assessment report (IPCC, 2007). This was highlighted at the International Scientific Congress on Climate Change (Copenhagen, 10-12 March 2009), where this point was mentioned in the first of the six key messages from the Congress. All results in this section will refer to projected changes for the period 2080-99 as simulated under the A2 scenario compared to the 20 year period 1980-99.

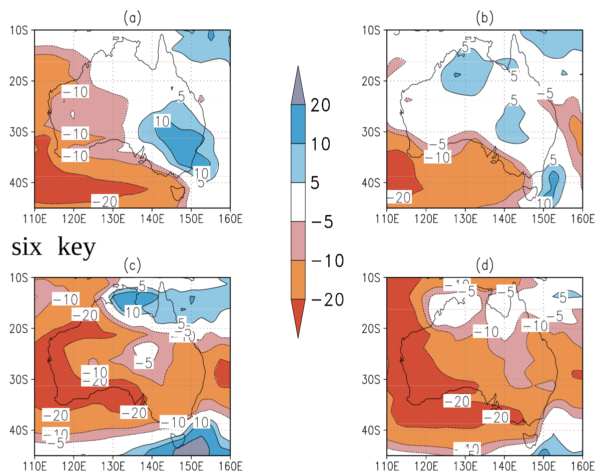


Figure 7. CMIP3 ensemble mean model changes in rainfall (units: %) for DJF, MAM, SON, JJA (clockwise from top left). White areas indicate a change of less than +/- 5%.

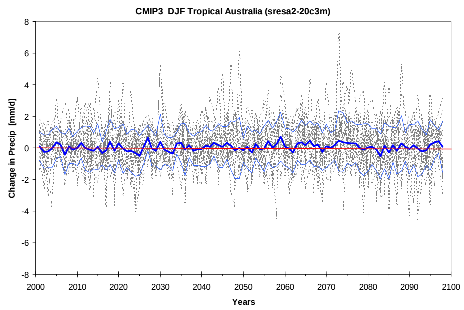


Figure 8. Time series of rainfall changes across tropical Australia (land points only) throughout the 21st century. Shown is the ensemble mean (thick blue line), +/- one STD (thin blue line) and all individual CMIP3 models (grey dashed lines).

Figure 7 shows the seasonal average changes in precipitation (in %) for the ensemble mean model. During the summer season, no significant change across tropical Australia can be seen. This is also the case for the pre-monsoon season (SON), while decreases in rainfall are simulated across southern and western parts of the continent. Some increase in rainfall is seen in autumn (MAM) and winter (JJA) for tropical Australia.

The time series of rainfall shown in figure 8 shows the large spread of model simulations for tropical Australia (land only points). For the entire 21st century, there is no trend for monthly mean rainfall changes in the ensemble mean model as well as the model spread (indicated by the width of the +/- one standard deviation (STD)).

4.2. Change in seasonal cycle of tropical rainfall and interannual variability

The lack of a signal in rainfall changes across tropical Australia does not extend into the deep tropics. Figure 9 shows the seasonal migration of monthly mean rain across the equator for the end of the 20th century (top-left) and 21st century (top-right). While these results are averaged over (100-150E), we have found very similar results for the global tropical belt.

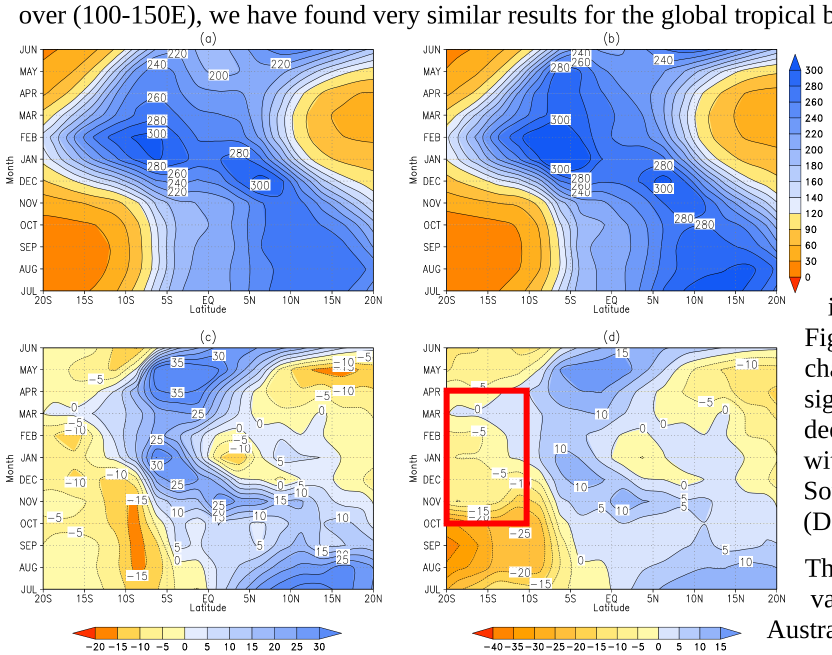


Figure 9. CMIP3 ensemble mean model seasonal migration of rainfall (20c3m-top left; sresA2-top right) and its changes (units: [mm] except bottom right: %). The red box indicates the area marked in Fig 1 during the wet season.

The change in seasonal migration is shown in the two bottom plots in Figure 9 (left-absolute units; right-% change). Clearly visible is the main signal of increased rainfall in the deeper tropics (10% to 15% increase) with only little change south of 10° South during the Australian summer (DJF).

The model simulated inter-annual variability in rainfall over tropical Australia during the late 20th century was found to be too small for most models (figure 6), and there is no coherent signal in how this variability would change under enhanced greenhouse conditions. Figure 10 shows that there are more models pointing toward enhanced variability than not, but the overall average change is only in the order of +0.15 mm/d. Future work will assess the significance of this change.

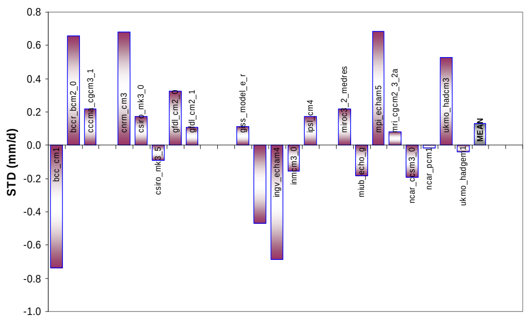


Figure 10. Change in tropical Australia rainfall inter-annual variability (in mm/day) during the wet season (ONDJFMA) of CMIP3 models.

4.3. Change in monsoon onset and duration

With results from the entire ensemble mean model of CMIP3 simulations pointing towards no changes in Australian tropical rainfall during the summer and only slightly enhanced inter-annual variability, we investigated changes in the reversal of the zonal winds during the onset and demise of the monsoon over Australia.

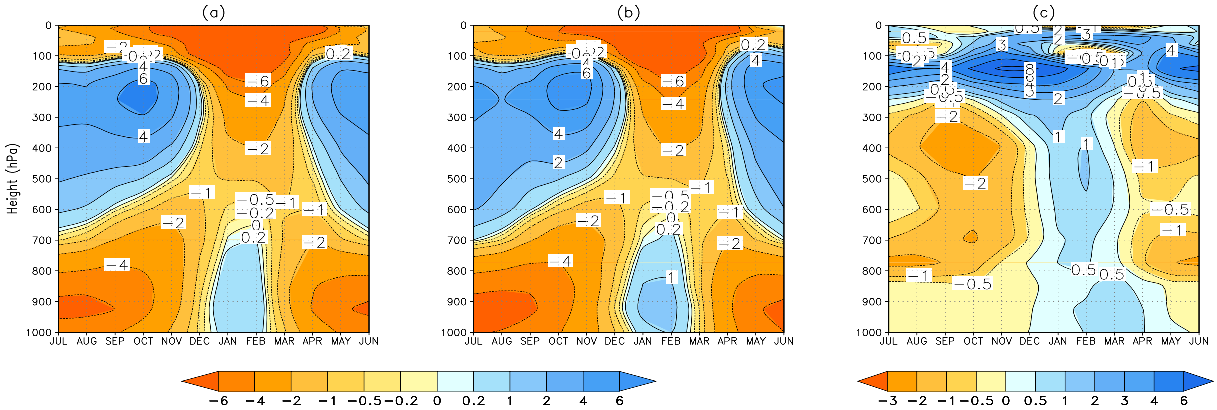


Figure 11. CMIP3 mean zonal winds vs height seasonality for tropical Australia for 20th century (left), 21st century (centre) and the difference (right). Units are (m/s).

There are large differences between models in their depiction of both onset date and monsoon duration. Here we present the ensemble mean model results (Figure 11) for the end of the 20th century (top left), the 21st century (top right) and their difference (bottom right). The overall changes with regard to the monsoon season over Australia are fairly small: a slight intensification of the westerlies at low levels combined with a slight weakening of the upper level easterlies. Furthermore, while the onset date (850hPa wind reversal) seems to stay the same (mid December), the retreat date is somewhat extended towards the end of March by the end of the 21st century.

This is also evident in the analysis of the monsoon shear line. Figure 12 shows the position of the monsoon shear line (defined via the 925hPa zonal winds) for ERA40, simulated 20th century and 21st century for the months January (close to onset) and March (close to retreat). It is a well known fact that a large fraction of tropical cyclones in the Australian region will develop along the shear line within several hundred kilometers of land (see for example McBride, 1982). There is a large spread between the different model simulations (grey lines for the 20th century in figure 12), however the position of the ensemble mean model's shear line (light blue) is quite close to the ERA40 re-analysis data for the same time period. Under enhanced greenhouse gas conditions, the ensemble mean model shear line seem to only move slightly south over North-west Western Australia during the onset period, but more significantly so during the retreat period. This could indicate the later retreat of the Australian monsoon over the tropical North-west region of Australia. Further work is underway to investigate this issue in more detail.

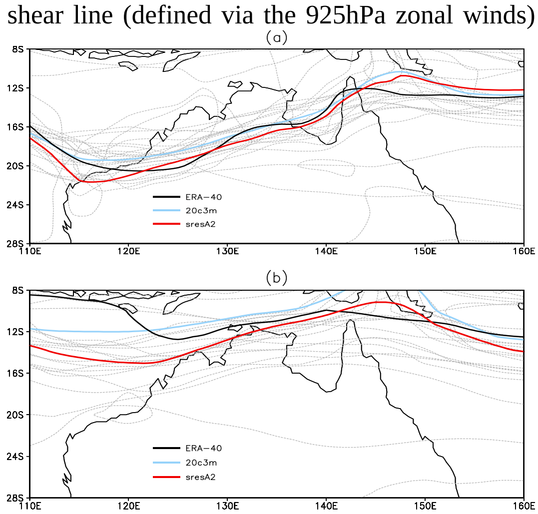


Figure 12. Monsoon shear line for January (a) and March (b) as simulated by CMIP3 models for the end of the 20th century (light blue), 21st century (red) and ERA40 (black). Individual CMIP3 models for the 20th century are shown in grey.

5. DISCUSSION AND CONCLUSIONS

This paper describes some of the basic features of the Australian monsoon as simulated by the recent generation of coupled atmosphere ocean GCM's. We find that while there are some deficiencies in simulating 20th century monthly climate means (of rainfall in particular) some of the larger scale features such as the zonal winds are quite reasonably simulated. Models display an enormous range in skill in depicting the Australian monsoon. Most models reproduce large scale pressure changes (not shown here), and seasonal temperature changes (not shown here). All show strong precipitation seasonality, but range from 20% to almost 200% of peak rainfall. Models vary from almost no penetration of rainfall over the continent to excessive southern and eastern penetration. *Mean model* pattern and seasonal variation of MSLP, TAS and precipitation are close to observed, and improved over CMIP2 model means. RMS error and spatial correlations are also improved. The RMS error and the correlation of the ensemble mean model are generally better than in any individual model over much of the wet season. Low level Monsoonal wind reversals are apparent in most, but not all models. Low level westerlies are too weak on average (despite mean precipitation being close to observations). The 200hPa wind reversal is captured by all models (bar one) and mean model strength is good. Zonal wind seasonality shows additional lack in vertical penetration of westerlies in the ensemble mean model compared to ERA40 (westerlies penetrate up to 500hPa during February). Interannual total wet-season rainfall variability is too low in most models, however is comparable to observations in three and too large in three others. The monsoon shear line agrees well with reanalysis *for ensemble mean model*. It captures the SW/NE orientation of monsoon trough well. Changes in the Australian monsoon under enhanced greenhouse conditions have been assessed, pointing towards only small changes in the mean state. The ensemble mean model results for the change in zonal winds indicate a possible later retreat of the monsoon, particular over North-western parts of the tropical region. Based on these findings we can expect small changes in North Queensland with stronger impact possible across northwestern tropical Australia. Detailed ecosystem modeling using climate model outputs may help to quantify further implications for these impacts.

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REFERENCES

AchutaRao, K.M., M. Ishii, B. D. Santer, P. J. Gleckler, K. E. Taylor, T. P. Barnett, D. W. Pierce, R. J. Stouffer and T. M. L. Wigley (2007): Simulated and observed variability in ocean temperature and heat content. Proc Natl Acad. Sci. USA., 104, 10768–10773.

CSIRO (2007): Climate Change in Australia, Commonwealth Science and Industry Research Organisation Technical Report, 148pp.

Drosdowsky, W. (1996): Variability of the Australian summer monsoon at Darwin: 1957-1992. J. Climate, 9, 85-96.

Gunn, B.W., J.L. McBride, G.J. Holland, T.D. Keenan, N.E. Davidson, and H.H. Hendon (1989): The Australian Summer Monsoon Circulation during AMEX Phase II. Mon. Wea. Rev., 117, 2554–2574.

Global Carbon Project (2008) Carbon budget and trends 2007, [www.globalcarbonproject.org, 26 September 2008].

Hendon, H.H., and B. Liebmann, (1990): The Intraseasonal (30–50 day) Oscillation of the Australian Summer Monsoon. J. Atmos. Sci., 47, 2909–2924.

Hendon, H.H., and B. Liebmann, (1990): A composite study of the Australian Summer Monsoon. J. Atmos. Sci., 47, 2227-2240.

Holland, G.J. (1986): Interannual Variability of the Australian Summer Monsoon at Darwin: 1952–82. Mon. Wea. Rev., 114, 594–604.

IPCC (2007a): Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC [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.

IPCC (2007b): Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp.

Jones, D. A. and B. C. Trewin (2000): The spatial structure of monthly temperature anomalies over Australia. Aust. Met. Mag., 49, 261-276.

Jones, D. A. and G. Weymouth (1997): An Australian monthly rainfall data set. Technical Report No. 70, Bureau of Meteorology, Melbourne, Australia, 19pp.

McBride, J.L. and T.D. Keenan (1982): Climatology of tropical cyclone genesis in the Australian region. *J.Climatol*., 2, 13-33.

McBride, J. (1998): Indonesia, Papua New Guinea, and Tropical Australia: The Southern Hemisphere Monsoon. Chapter 3A of "Meteorology of the Southern Hemisphere, Meteorological Monograph No. 49, American Meteorological Society.

Meehl, G.A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J.F.B. Mitchell, R.J. Stouffer, and K.E. Taylor (2007): The WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. Bull. Amer. Meteor. Soc., 88, 1383–1394.

Moise, A.F., R.A. Colman, H. Zhang and participating CMIP2 modelling groups (2005): Coupled model simulations of current Australian climate and its changes under greenhouse warming: an analysis of 18 CMIP2 models. Aust. Met. Mag., 54, 291-307.

Suppiah, R. (1995): The Australian summer monsoon: CSIRO9 GCM simulations for 1xCO2 and 2xCO2 conditions. Global and Planetary Change, 11, 95-109.

Uppala, S.M. et al. (2005): The ERA-40 Reanalysis. Q. J. R. Meteorol. Soc., 131, 2961-3012, doi:10.1256/qj.04.176.

Wang, B., I.S. Kang and J.Y. Lee (2004): Ensemble Simulations of Asian–Australian Monsoon Variability by 11 AGCMs. J. Climate, 17, 803-818.

Xie, P. and P. A. Arkin (1997): Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull. Amer. Meteor. Soc., 78, 2539-2558.

Zhang, H., A. Henderson-Sellers, P. Irannejad, S. Sharmeen, T. Phillips, and K. McGuffie (2002): Land-surface modelling and climate simulations: Results over the Australian region from sixteen AMIP2 models. Bureau of Meteorology Research Centre Report 89, 18pp.