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Simulations of twentieth century atmospheric circulation changes over Australia

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Abstract: We examine the performance of coupled models to simulate twentieth century winter circulation changes throughout the southern hemisphere, and particularly over Australia. A number of studies have recently shown that the early to mid-1970s was a time of major shifts in the structure of the large-scale circulation of both the northern and southern hemispheres. Over southern Australia there was a concurrent, dramatic and continuing reduction in the winter rainfall. In a recent study, the authors, using reanalyzed observations, have suggested that the rainfall reduction is associated with a decrease in the vertical mean meridional temperature gradient and in the peak upper tropospheric jet-stream zonal winds throughout most of the southern hemisphere, but in particular upstream and over Australia. These and other circulation changes, including changes in the Hadley circulation, and trends in the Southern Annular Mode, were shown to affect winter rainfall over southern Australia. Here, we examine the response of many of the CMIP3 IPCC climate models to observed anthropogenic forcing, including increasing greenhouse gases, from pre-industrial to the end of the twentieth century.

Our interest here is on changes in the atmospheric circulation that affect wintertime cyclogenesis, and for that reason we focus on two diagnostics that can be used to evaluate the climate models in this regard. Thus, our focus is on the ability to simulate (a) the reduction in the strength of the wintertime subtropical 300hPa zonal wind upstream and over southern Australia, and a strengthening in the zonal wind further south, and (b) a reduction in the baroclinic instability of the subtropical SH circulation. We have considered these diagnostics in four cases; one involving the changes in the latter half of the twentieth century, and three involving changes between the end of the twentieth century and different base periods in pre-industrial simulations.

The CMIP3 models display quite disparate abilities to simulate these two diagnostics. While the majority is able to simulate the former ((a)), especially when using the pre-industrial simulations, only about a third of the models capture the changes in the latter ((b)). Our analysis also suggests that there is a component of decadal variability in the model results that is dependent on the base period chosen in the pre-industrial runs.

There are a number of models that consistently simulate changes in the two diagnostics that are in general agreement with results from the NCEP reanalysis. Projected changes in baroclinic instability from these models suggest that further large reductions in baroclinic instability are possible under SRESB1, SRESA1B and SRESA2 scenarios, especially over the Australian region. By implication, this suggests further reductions in the growth rates of SH cyclogenesis modes and further reductions in rainfall, over southern Australia.

Keywords: *Climate Modelling, Climate Change, Southern Hemisphere Circulation, Baroclinic Instability*

1. INTRODUCTION

A number of studies have recently shown that the early to mid-1970s was a time of major shift in the structure of the large-scale circulation of both the northern and southern hemispheres (see for example Frederiksen and Frederiksen, 2005, 2007, for overview). Over southern Australia there was a concurrent, dramatic and continuing reduction in the winter rainfall (see for example Nicholls, 2007, and Bates et al. 2008, for overview). Very large reductions (~20%) in winter rainfall occurred first in the southwest of Western Australia (SWWA).

In trying to explain this reduction in SWWA, Frederiksen and Frederiksen (2007) studied the interdecadal changes in southern hemisphere (SH) winter cyclogenesis by focusing on the leading instability modes for July three-dimensional basic states averaged over the periods 1949-1968 and 1975-1994, as well as other shorter periods, using reanalyzed National Centers for Environmental Prediction (NCEP) and the European Centre for Medium Range Weather Forecasting Reanalysis (ERA40) data. They found that there was a 30% reduction in the growth rate of the cyclogenesis modes in the latter period compared with the earlier. In addition, the leading mode in each period has a different three-dimensional structure. For the 1949-68 basic state the leading mode is a wavenumber 12 disturbance with large amplitude over southern Australia (their Figure7); for the 1975-1994 basic state the leading SH cyclogenesis mode is a wavenumber 8 disturbance with maximum amplitude in the central South Pacific ocean, and only small amplitude south of southern Australia (their Figure 8). These differences were explained in terms of the differences in the mean climate of the two periods. The results were also insensitive to the reanalysis dataset used. They concluded that a primary cause of the rainfall reduction over SWWA was due to these changes in the cyclogenesis modes that affect this region.

Here, we examine the response of the Coupled Model Intercomparison Project Three (CMIP3) climate models (Meehl et al., 2007) to observed natural and anthropogenic forcing, including increasing greenhouse gases, from pre-industrial to the end of the twentieth century. The extent, to which the models show similar atmospheric winter circulation changes, as seen in Frederiksen and Frederiksen (2007) for the reanalysis data, is discussed, as well as the implications of these results for climate change projections and attribution studies.

2. CHANGES IN SOUTHERN HEMISPHERE WINTERTIME CIRCULATION

Frederiksen and Frederiksen (2007) found that there were quite large changes in the thermal structure and circulation in the Southern Hemisphere (SH) circulation between the periods 1949-1968 and 1975-1994. In particular, there was reduction in the strength of the subtropical 300hPa zonal wind upstream and over southern Australia, and extending over much of the hemisphere. Near 45-50^{o}S, there was an increase in zonal wind. Also, they found a reduction in the baroclinic instability, as measured by a generalization of the Phillips (1954) criterion, of between 25-30% upstream and over SWWA. Because our interest here is on changes in the atmospheric circulation that affect cyclogenesis, these are two good diagnostics to use to evaluate the climate models. They are also very much related to other changes discussed by Frederiksen and Frederiksen (2007), including a reduction in the mean atmospheric meridional temperature gradient, changes in the Hadley circulation, and trends in the Southern Annular Mode. Here, we will compare the model results with the NCEP reanalysis.

2.1. Changes in 300hPa Zonal Winds

Figure 1 shows the NCEP 300hPa zonal velocity averaged over the periods 1949-1968 and 1975-1994, and their differences. The difference plot shows quite dramatic reductions near 30^{o}S in the latter period of up to 7ms^{-1}, and increases between 5-6ms^{-1} further south near 50^{o}S. This difference in the zonal wind structure is clearly hemispheric and unlikely to be the response to some local phenomenon. Of particular interest is the region 60^{o}E - 150^{o}E, 60^{o}S - 15^{o}S. Frederiksen and Frederiksen (2007) showed that this area is very much related to the genesis of the storms that affect southern Australia. In this area, there are reductions in the sub-tropical zonal velocity of up to 4.7ms^{-1} with increases up to 5.6ms^{-1} further south.

In Figure 2, we show for twenty two of the CMIP3 models (see Randall et al., 2007 and Meehl et al., 2007, for model nomenclature and description) the anomaly pattern correlation (APC), calculated over the domain (60^{o} S to 15^{o} S, 60^{o}E - 150^{o}E) between the NCEP difference in 300hPa zonal winds (Figure 1c) and similar differences calculated with model data in four different ways. The black bars in Figure 2 are the APCs with zonal wind differences calculated for models using the same two twenty year periods (1949-68 and 1975-94) as for the NCEP reanalysis (i.e. the 20C3M simulations, Meehl et al., 2007). However, because the timing of simulated changes in coupled models may not necessarily synchronize with the reanalyzed observations, we have also included APCs with model differences between pre-industrial control runs (i.e. the PICNTRL simulations, Meehl et al., 2007) and the (1980-1999) period of the 20C3M runs. This will give an indication of the impact of all the twentieth century greenhouse gas forcing. Also, we are interested in the sensitivity of our results to the base period chosen in the PICNTRL runs, and the possible influence of decadal variability on our results. For this reason, we have used three adjoining twenty year periods at the end of the PICNTRL runs, separated by twenty years. These are designated PICNTRL (green bar), PICNTRL_20 (blue bar) and PICNTRL_40 (red bar).

Figure 2 shows that the ability of models to reproduce the reanalysis changes during the same two twenty year periods is quite variable, with some models showing opposite sign in the zonal wind differences. When changes from pre-industrial simulations are taken into account, there is clear evidence of a component of decadal variability with the APCs showing some dependence on the base period. For some models, this is seen in the changing sign of the APC (e.g. *gfdl_cm2_1*), and for others in changes in the magnitude of the APC (e.g. *mk3.0*). Some models show quite large APC with the reanalysis results (e.g. *miroc3_2_medres*, *miroc3_2_hires* and *giss_model_e_r*). A number of models show consistently positive APC in all four cases (e.g. *miroc3_2_medres*, *miroc3_2_hires* and *mk3.0*). Overall the majority of the models do simulate the changes in the zonal wind upstream and over southern Australia, especially in differences between the pre-industrial and end of the twentieth century simulations. The *miroc3_2_medres*, in particular, simulates the SH changes seen in Figure 1(c) remarkably well (not shown).

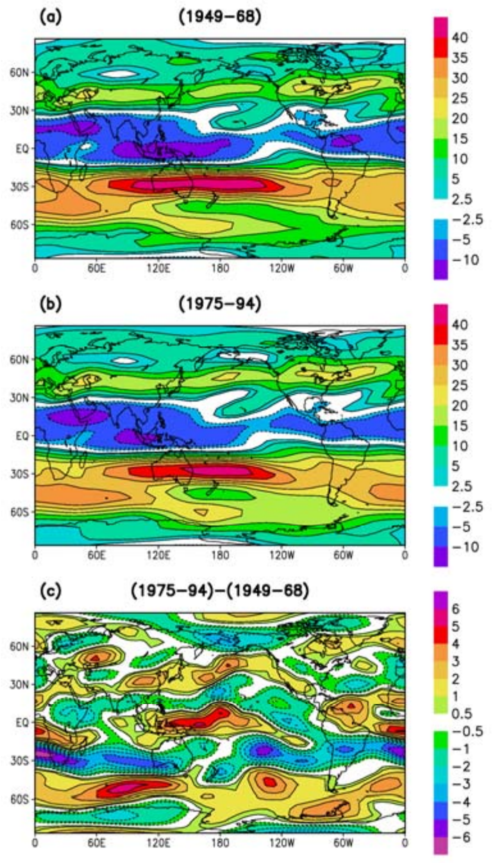

Figure 1. 300hPa zonal velocity (ms^{-1}) from NCEP reanalysis for July (a) 1949-68, (b) 1975-1994 and (c) the difference (b)-(a).

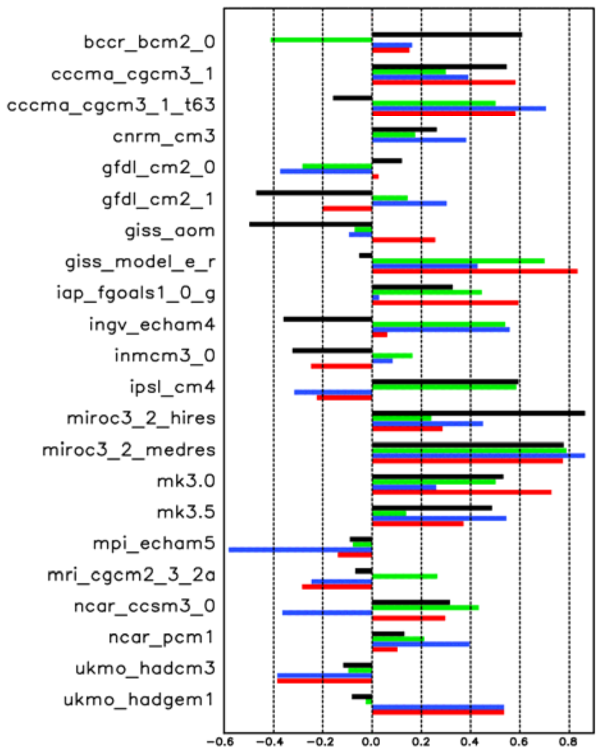

Figure 2. Anomaly pattern correlation between the NCEP 300hPa zonal velocity difference (Figure 1 (c)) and model difference for (i) (1975-94)-(1949-68) (black bar), (ii) (1980-99) – PICNTRL (green bar), (iii) (1980-99) – PICNTRL_20 (blue bar) and (iv) (1980-99) – PICNTRL_40 (red bar).

2.2. Changes in Baroclinic Instability

The Phillips (1954) criterion, generalized for spherical geometry, is a simple diagnostic that provides a measure of incipient baroclinic instability and can be used to identify geographical regions of likely cyclogenesis (Frederiksen and Frederiksen, 1992). This criterion may be written as

$$\bar{u}^{(1)} - \bar{u}^{(3)} - \frac{b_\kappa c_p \bar{\sigma}}{a\Omega} \frac{(1-\mu^2)^{1/2}}{\mu^2} \geq 0. \qquad (1)$$

Here, $\bar{u}^{(1)}$ and $\bar{u}^{(3)}$ represent the 300hPa and 700hPa zonal velocities, and $\bar{\sigma}$ the static stability for a given basic state, calculated here as half the difference between the potential temperature at 300hPa and 700hPa. Also c_p = 1004 J deg^{-1} kg^{-1}, is the specific heat of air at constant pressure, Ω =7,292×10^{-5} rad s^{-1}, is the earth's angular speed of rotation, $b_\kappa = 0.124$ is a dimensionless constant, a = 6.371×10^{6}m, is the radius of the earth and μ is the sine of latitude. Near the equator, the criterion is always negative and is therefore mostly relevant for the development of extra-tropical cyclogenesis.

In Figure 3, we show, for the NCEP reanalysis, regions where this baroclinic instability criterion is positive for the 1949-68 and 1975-94 basic states, and their difference respectively. For both July climates, these regions coincide with the sub-tropical jet and a maximum in the criterion occurs in the South Pacific near 30^{o} S. The difference plot (Figure 1c) shows a reduction in the criterion in the latter period that extends across the whole hemisphere in a band centered near 30^{o}S. As discussed in Frederiksen and Frederiksen (2007), this is associated with a reduction of cyclogenesis throughout this band and the reduction in growth rate of the SH

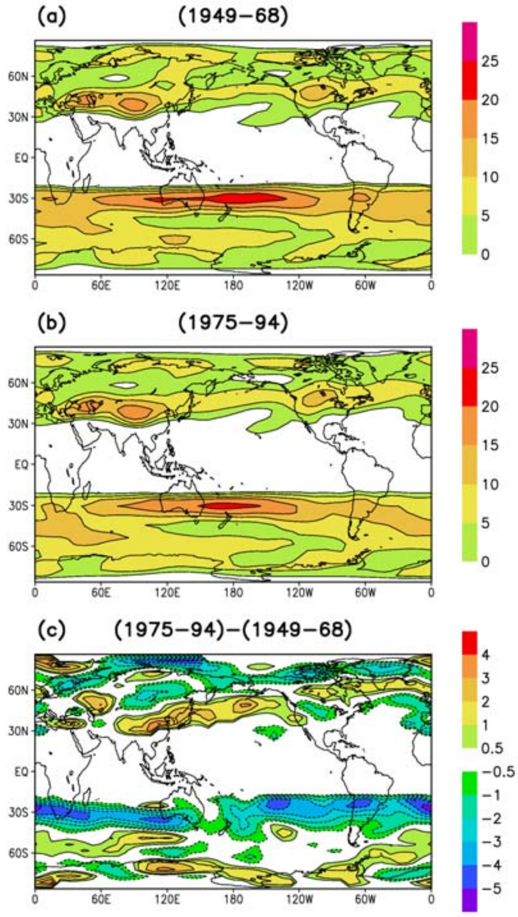

Figure 3. Phillips instability criterion (ms^{-1}) from NCEP reanalysis for July (a) 1949-68, (b) 1975-1994 and (c) the difference (b)-(a).

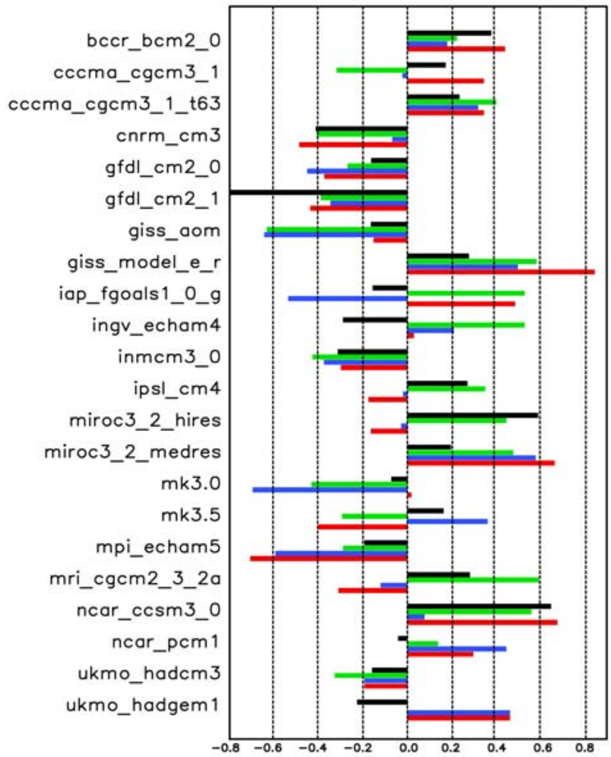

Figure 4. Anomaly pattern correlation between the NCEP Phillips criterion difference (Figure 3 (c)) and model Phillips criterion difference for (i) (1975-94)-(1949-68) (black bar), (ii) (1980-99) – PICNTRL (green bar), (iii) (1980-99) – PICNTRL_20 (blue bar) and (iv) (1980-99) – PICNTRL_40 (red bar).

climatological cyclogenesis modes. Essentially, the SH has become less baroclinically unstable near 30^o S in the latter period compared with the former. In contrast, poleward of about 45^o S there is an increase in baroclinic instability, especially south and upstream of Australia. Importantly, there is a reduction of about 4.5ms^{-1} situated over SWWA.

Figure 4 shows the APCs, calculated for the region 60^{o}E - 150^{o}E, 45^{o}S - 15^{o}S, between the NCEP Phillips criterion difference (Figure 3(c)) and the model differences for the same four cases discussed in the previous section. For this diagnostic, there is much more variability in the models to simulate the reanalysis results. About a third of the models show a consistently negative APC in all four cases (e.g. *gfdl_cm2_1*, *giss_aom*, *mpi_echam5* etc.). For these models, there is an increase in baroclinic instability that would lead to an increase in growth of the cyclogenesis modes. However, about a third of the models show a consistently positive APC (e.g. *miroc3_2_medres*, *giss_model_e_r*, *ncar_ccsm3_0* etc.). Again, as for the zonal velocity, there is evidence of a component of decadal variability in the model results.

For the remaining part of this paper, we are going to concentrate on the results from the *miroc3_2_medres* model. This model agrees fairly consistently with the NCEP reanalysis changes seen in both diagnostics. For example, Figure 5 shows the Phillips criterion differences for this model in all four cases. The difference between the (1980-1999) period and the last 20 years of the PICNTRL run is remarkably similar to the NCEP changes (Figure 3(c)) throughout the subtropical SH.

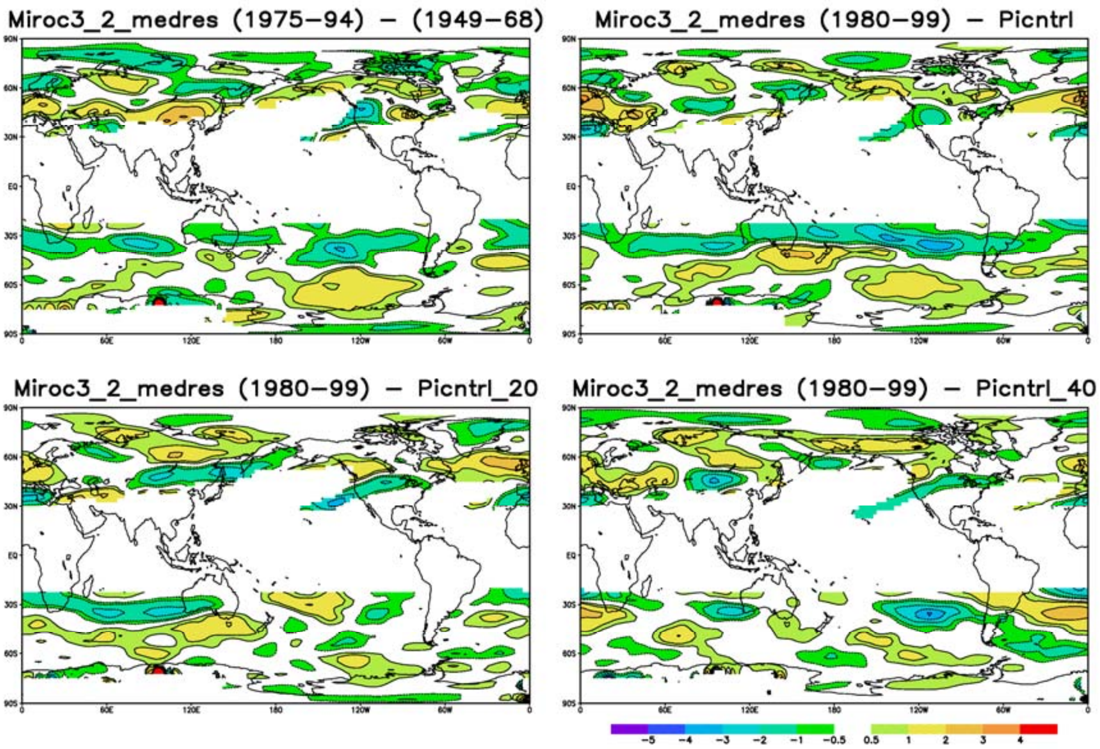

Figure 5. Differences in Phillips criterion (ms^{-1}) for (i) (1975-94) – (1949-68), (ii) (1980-99) – PICNTRL, (iii) (1980-99) - PICNTRL_20 and (iv) (1980-99) – PICNTRL_40, for *miroc3_2_medres*.

2.3. Future Projected Changes in Baroclinic Instability

In this section we shall discuss projections of possible changes in baroclinic instability under three different climate change scenarios using the *miroc3_2_medres* model. The three scenarios we will consider are the Special Report on Emission Scenarios (SRES) B1, A1B and A2 (see, for example, Meehl et al., 2007). These involve low, medium and high CO_2 concentrations of 550ppm, 700ppm and 820ppm, respectively, by 2100. Figure 6 shows the changes in Phillips criterion for (1980-1999) – PICNTRL, SRESB1 – PICNTRL, SRESA1B – PICNTRL and SRESA2 – PICNTRL, using this model. As the CO_2 concentrations increases, there are progressively larger reductions in the subtropical baroclinic instability, especially over the

Australian region. In the SRESA1B and SRESA2 scenarios, these differences are about twice those seen in the model for the twentieth century run. This suggests further reductions in the growth rate of the SH cyclogenesis modes and a worsening of drought conditions over southern Australian. However, the exact nature of the changes in growth rates and three-dimensional structures of the cyclogenesis modes requires a full three dimensional instability analysis to be conducted, and we have plans to do this in a future paper.

We have also looked at projected changes in other models that show good correspondence with the reanalysis results (e.g. the *giss_model_e_r* and *ncar_ccsm3_0* models) and they confirm the results from the *miroc3_2_medres* model.

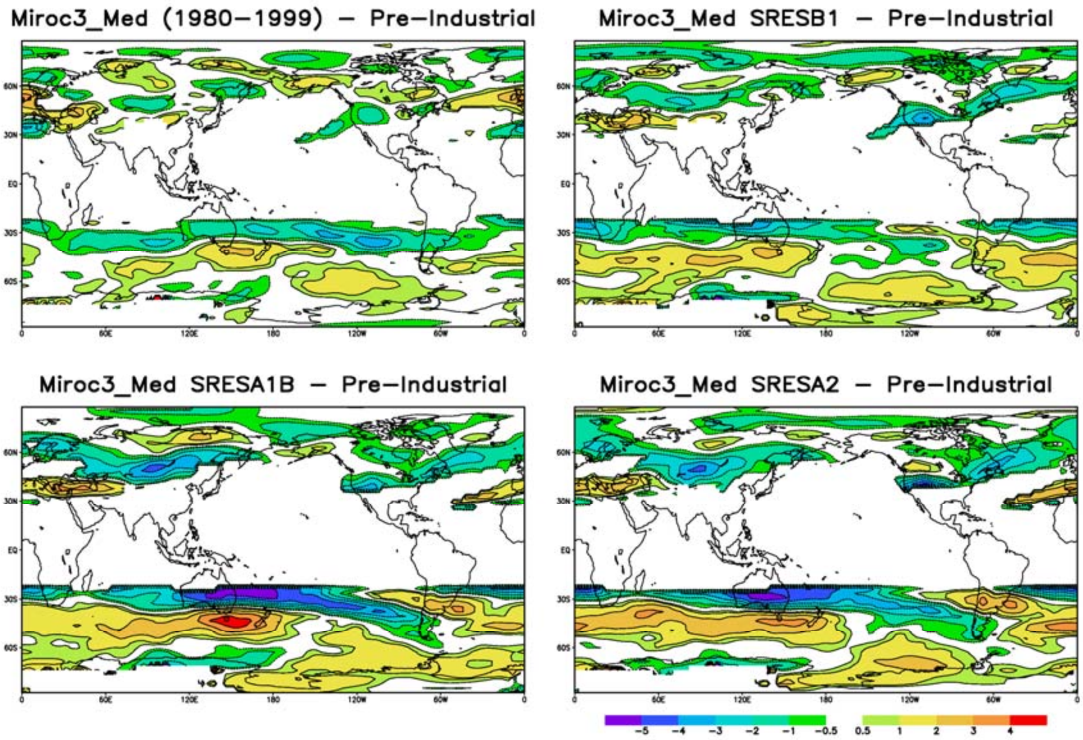

Figure 6. Differences in Phillips criterion (ms^{-1}) for (1980-99) – PICNTRL and projected changes for (i) SRESB1 – PICNTRL, (ii) SRESA1B – PICNTRL and (iii) SRESA2 – PICNTRL, for *miroc3_2_medres*.

3. DISCUSSION AND CONCLUSIONS

The ability of the CMIP3 models to simulate a wintertime reduction in the baroclinic instability of the SH subtropics and the 300hPa zonal winds near 30^o S, is quite variable. About a third of the models are able to simulate the former, and the majority the latter, especially when compared with pre-industrial conditions. It is clear from the results presented here that there is a component of decadal variability in the model results that is dependent on the base period chosen in the pre-industrial runs. This means that attribution and projection of atmospheric circulation changes will involve the disentanglement of decadal variability and anthropogenic climate change.

There are a number of models that consistently, in all the four cases considered here, simulate changes in our two diagnostics that are in good general agreement with results from the NCEP reanalysis. Projected changes in baroclinic instability from these models suggest that further large reductions in baroclinic instability are possible under SRESB1, SRESA1B and SRESA2 scenarios, especially over the Australian region. By implication, this suggests further reductions in the growth rates of SH cyclogenesis modes, and further reductions in rainfall over southern Australia.

The analysis conducted here provides a convenient means of evaluating the CMIP3 models as far as their ability to simulate changes in the atmospheric circulation that are relevant for studying changes in the climatological storm tracks. In future studies, we plan to conduct much more comprehensive three-dimensional studies with the “better” models to determine projected changes in the actual growth rates and three-dimensional structure of the storm track modes. From this we hope to describe the expected impact on southern Australian rainfall.

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