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Observed and projected changes in the annual cycle of Southern Hemisphere baroclinicity for storm formation

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Abstract: Recent studies have shown that over the last sixty years, there have been dramatic changes in the properties of mid-latitude winter storms which have impacted on southern Australian winter rainfall. In particular, there have been large reductions and negative trends in rainfall over this period, associated with similar reductions in the growth rates of storm track modes and a preference for some storms to develop further south of the Australian continent. These changes in the properties of mid-latitude storms have been shown to be associated with major shifts in the Southern Hemisphere winter circulation over this period. In particular, there have been significant negative trends in the baroclinic instability of the mid-latitude atmospheric circulation resulting in a reduction in storm formation at these latitudes, while increases in baroclinicity further poleward have led to increased storm development. These effects have become more pronounced with time and are likely to worsen under future climate change scenarios.

In this paper, we consider the observed changes in the baroclinicity of Southern Hemisphere circulation in all months. We employ a useful diagnostic of storm development related to baroclinic instability, and encapsulated in the Phillips criterion. The relationship between changes in the Phillips criterion and the implied changes in storm formation and rainfall in all months during the twentieth century is discussed. We find that there are significant negative trends in baroclinicity at mid-latitudes in all months which imply a reduction in storm formation and rainfall at these latitudes. Further poleward, we find significant positive trends associated with increased cyclogenesis and rainfall, in all months. These trends are shown generally to be statistically significant at the 99% level. Negative trends with values around -0.15 ms^{-1} per year occur upstream of Australia, in regions associated with storm formation. Trends further southwards can reach values of +0.1 ms^{-1} per year. During May to October, significant negative trends occur in the region of the subtropical jetstream; in November to April, negative trends occur about 10 degrees further south. These trends correspond to reductions of up to 7 – 8 ms^{-1} in the mid-latitudes, and increases of about 5 ms^{-1} at high latitudes, by the end of the twentieth century. This tendency for a reduction in storm development in the mid-latitudes, and a greater chance of storm development at higher latitudes, is a consistent feature of each month.

Results from the *miroc3_2* high and medium resolution models, which capture many of these changes during the twentieth century, have also been used to examine the projected changes in baroclinicity in SRESA1B and SRESA2 scenarios for the period 2001 to 2099. During May to October, when mid-latitude storms have the biggest impact on southern Australia, we find similar patterns of negative and positive trends in the mid-latitudes and high latitudes to those observed and simulated in the twentieth century. Consistent with this result, the projections show hemispheric reductions in rainfall in a band between 10S and 40S and increases further south. Differences in rainfall, between the periods 1980-1999 and 2080-2099, vary between -40mm to +40 mm. Over SWWA and southeastern Australia there are reductions in rainfall in all months with differences exceeding -20mm in some months, especially over SWWA.

Keywords: *Baroclinic Instability, Mid-latitude Storms, Climate Modelling, Climate Change, Southern Hemisphere Circulation*

1. INTRODUCTION

Over the last sixty years there has been a steady downward trend in winter rainfall over much of southern Australia, and especially over southwest Western Australia (SWWA) (Nicholls 2007; Bates et al. 2008; Frederiksen et al., 2010, 2011a, b). In a series of papers, these trends have been associated with large-scale changes in the global atmospheric circulation and the resultant impact on Southern Hemisphere (SH) cyclogenesis, with a reduction in the intensity of storm formation and the southward deflection of some storms (Frederiksen and Frederiksen, 2007, 2011c). Frederiksen et al. (2010, 2011a, b) have related these changes in storm formation, and consequently rainfall, to long term trends in the baroclinic instability of the SH circulation, as measured by the Phillips criterion (Phillips, 1954). Significant negative trends in the Phillips criterion in a hemispheric band between 30S - 40S were shown to be consistent with the observed reduction in growth rate of storm development and rainfall decrease in similar latitude bands. Positive trends in instability further southward were shown to be similarly consistent with a tendency for storms to develop in these regions and for increased rainfall. Frederiksen et al. (2010, 2011a, b) also showed, in climate models able to reproduce twentieth century changes, that these trends would continue into the twenty first century with increasing anthropogenic carbon dioxide emissions.

In this paper, we consider the observed changes and trends in the annual cycle of SH baroclinicity and discuss the implications for changes in midlatitude storm formation and SH rainfall. We also examine projections of possible changes in baroclinic instability under some of the Special Report on Emission Scenarios (SRES) (see, for example, Meehl et al., 2007) using simulations from the high and medium resolution *miroc3_2* models. Frederiksen et al. (2010, 2011a, b) examined the response of the Coupled Model Intercomparison Project Three (CMIP3) climate models (Meehl et al., 2007) to observed natural and anthropogenic forcing and found that these two models, in particular, were able to capture many of the large scale winter circulation changes observed over the last sixty years.

2. SOUTHERN HEMISPHERE BAROCLINICITY

2.1. Annual Cycle 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, or storm development (Frederiksen and Frederiksen, 1992). This criterion may be written as

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

Here, $\overline{u}^{(1)}$ and $\overline{u}^{(3)}$ represent the 300hPa and 700hPa zonal velocities, and $\overline{\sigma}$ 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, or mid-latitude, cyclogenesis. The more positive the criterion, the more unstable is the atmosphere and leads to the development of faster growing storms.

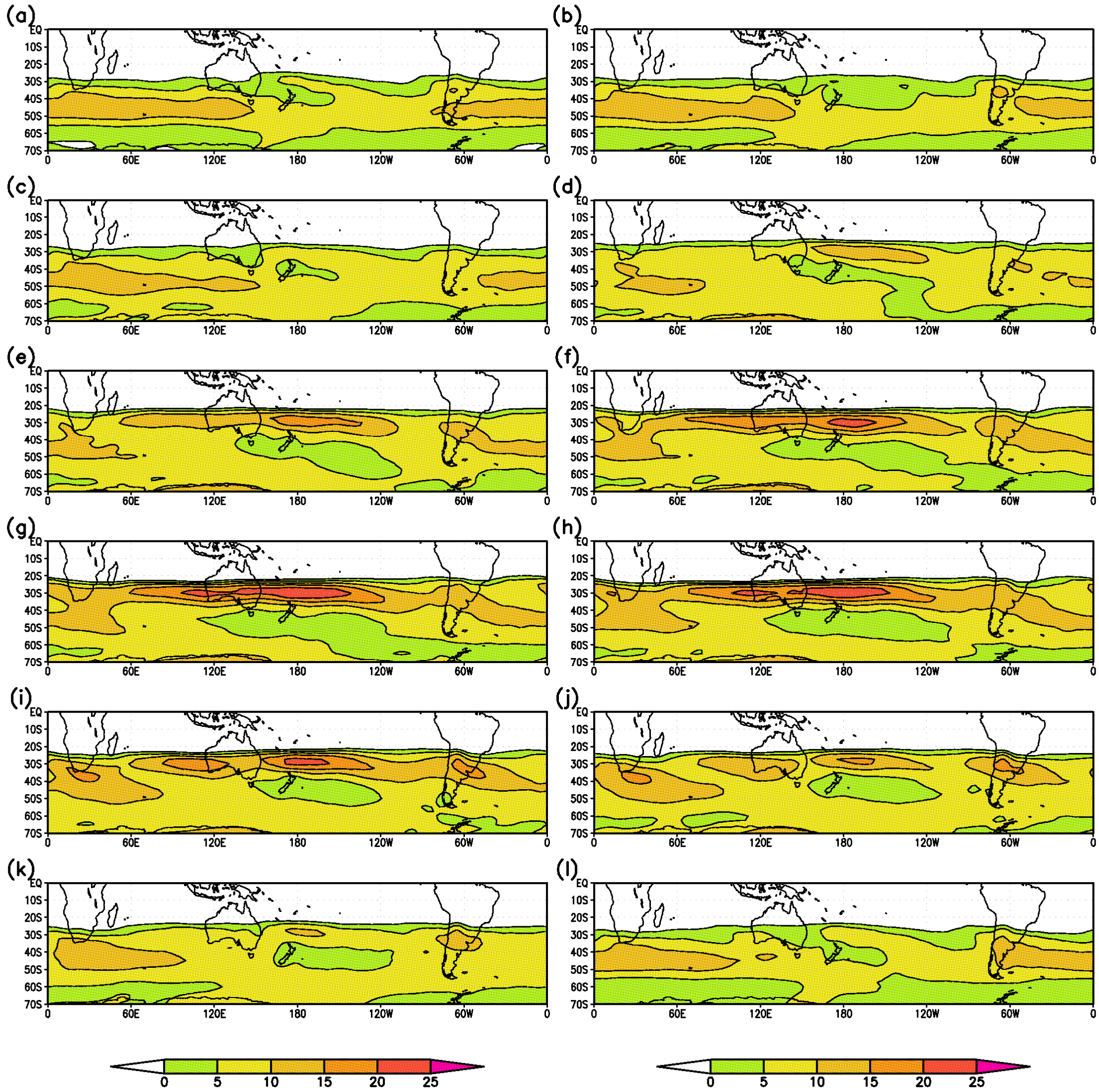

Figure 1. Annual cycle of the Phillips instability criterion (ms^{-1}) from NCEP reanalysis averaged over the years 1949-1968 with (a) – (l) corresponding to months January – December.

Figure 1 shows the climatology of the annual cycle of the monthly Phillips criterion using NCEP reanalysis data averaged over the twenty year period 1949-1968. For the six months May – October, large values in the criterion occur upstream and over Australia, and coincident with the location of the subtropical jet near 30S. In the remaining months, November – April, large values occur upstream of Australia between 40S and 50S at latitudes associated with the polar jet. Thus, storms developing upstream during May – October have trajectories more likely to impact on rainfall over southern Australia than those during November – April whose origin of genesis is further south.

2.2. Observed Trends in Baroclinic Instability

The continual reduction in the growth rates of mid-latitude storm modes, or weather systems, that affected southern Australia, during the latter half of last century, has been shown to be related to the effective stabilization of the atmosphere at these latitudes (Frederiksen and Frederiksen, 2005, 2007, 2011; Frederiksen et al., 2010, 2011b). Consistent with these results, Frederiksen et al. (2011a) recently showed that the dramatic reduction in July rainfall over southern Australia, and especially SWWA, was associated with statistically significant negative trends in the July Phillips criterion in the region of the subtropical jet, upstream of Australia. Here, we examine trends in baroclinic instability in all months for the period 1950 – 1999.

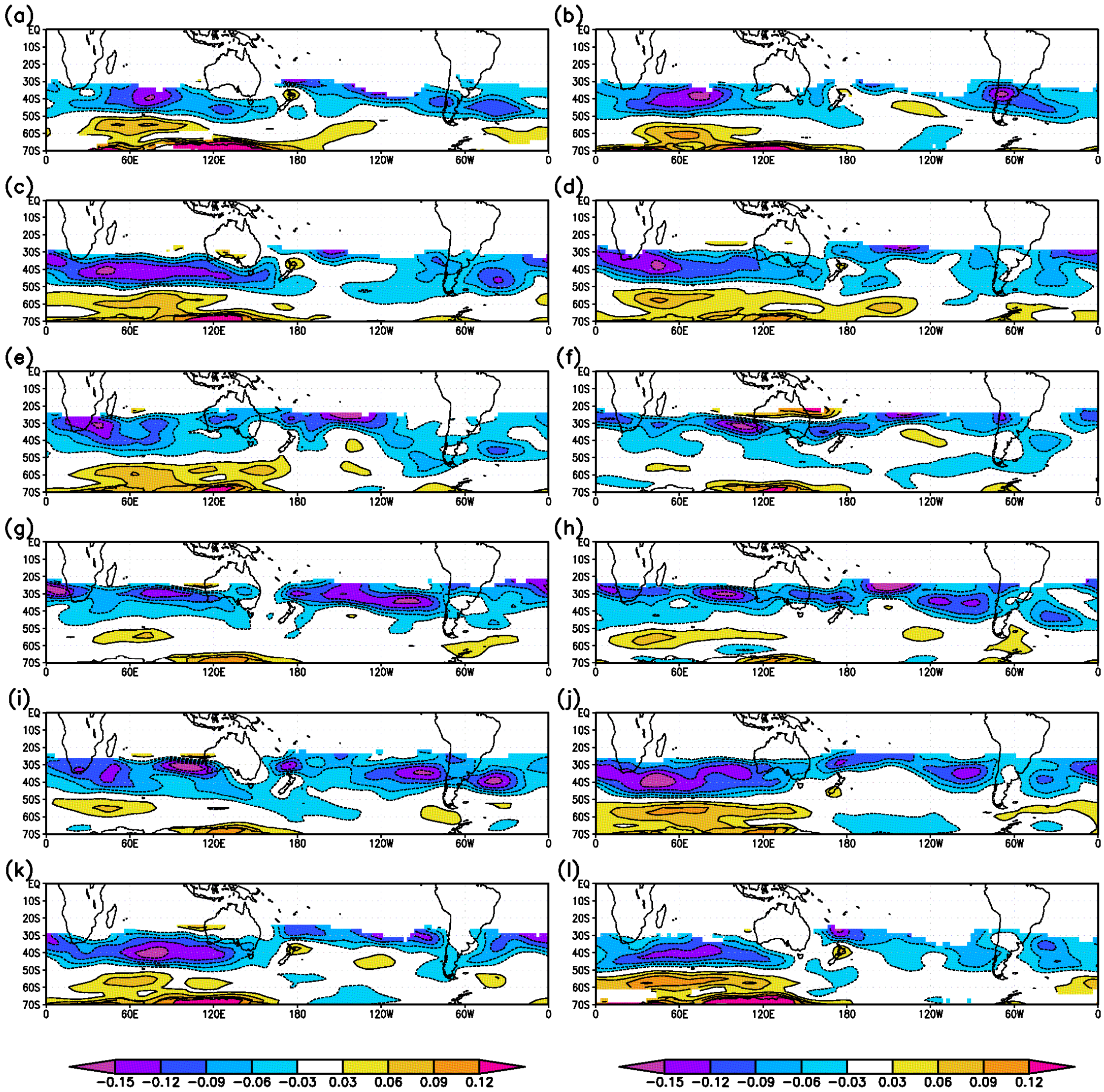

Figure 2. Trends in the Phillips instability criterion (ms^{-1} per year) from NCEP reanalysis for the period 1950 – 1999 with (a) – (l) corresponding to months January – December. Solid lines are positive contours, dotted lines negative contours.

Figure 2 shows the linear trends in the Phillips criterion for each month over this fifty year period. The trends shown in colour are generally statistically significant at the 99% level, and at least at the 95% level. In each month, there are negative trends throughout the mid-latitudes of the Southern Hemisphere. Highly significant negative trends, reaching -0.15 ms^{-1} per year in some months, occur upstream of Australia, in regions associated with storm formation. Further southwards, there are significant positive trends, with maximum values around +0.1 ms^{-1} per year near 60S. There is a clear annual cycle in the position of the greatest negative trends, with these generally located more equatorward (25S – 305S) in May – October, and between 35S – 50S in November – April. Positive trends occur between 50S – 70S in all months. Over the fifty years, these trends correspond to reductions of up to 7 – 8 ms^{-1} in the mid-latitudes, and increases of about 5 ms^{-1} at high latitudes. Thus, in all months, there is a tendency for a reduction in storm development in the mid-latitudes, and a greater chance of storm development at higher latitudes.

Upstream of, and over, the Australian region, inter-annual and decadal variations (not shown) in the Phillips criterion about these trends can have magnitudes of the order of 4 ms^{-1} and 1.4 ms^{-1}, respectively. The largest variations about the trend line generally occur during May – October. These changes are directly associated with changes in the Hadley circulation including a reduction in the strength of the downward branch near the SH jet core. They are also associated with warming trends in the Southern Ocean showing a similar annual cycle.

2.3. Future Projected Trends in Baroclinic Instability

In this section we discuss projections of possible changes in baroclinic instability under some of the Special Report on Emission Scenarios (SRES) (see, for example, Meehl et al., 2007; Randall, D.A., et al. 2007). The largest impact of mid-latitude storms on southern Australian rainfall occurs during May – October, so we will restrict our analysis to this six month period. Frederiksen et al. (2011a, b) evaluated the performance of the CMIP3 models in simulating the large scale shifts in the Southern Hemisphere July circulation and baroclinicity during the second half of the twentieth century. They found that many of the models were not able to capture the sign of these changes. Of the models that were able to, the *miroc3_2_medres* and *miroc3_2_hires* were particularly good. We have also examined the annual cycle of trends in the baroclinicity in these two models. The *miroc3_2_hires* model reproduces the annual cycle reasonably well but has trends that are about half or less of the observed; *miroc3_2_medres* has trends which are much smaller again.

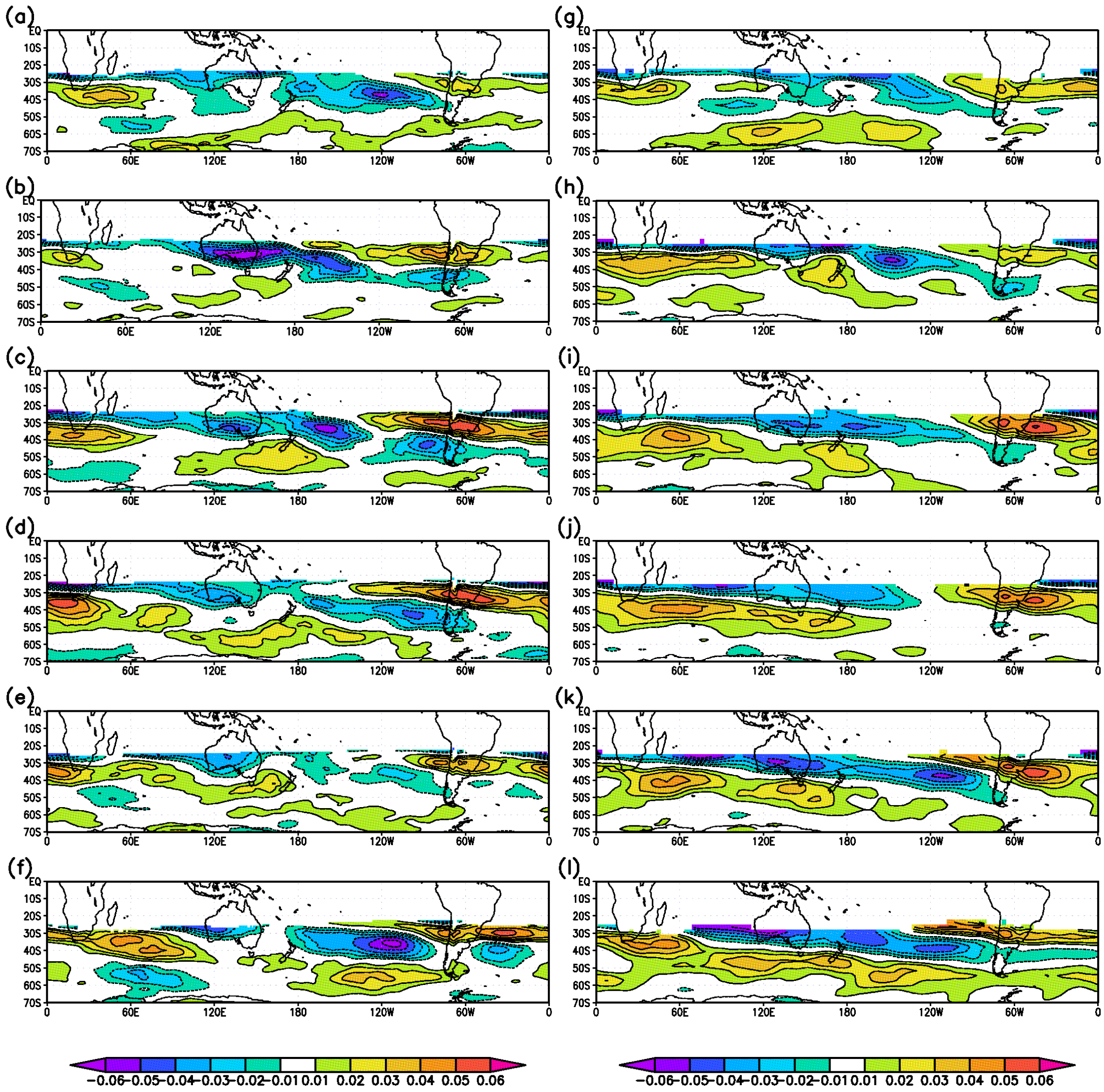

Figure 3. Trends in the May – October Phillips instability criterion (ms^{-1} per year), over the period 2001 – 2100, from the *miroc3_2_hires* model ((a) – (f)) for the SRESA1B scenario, and from the *miroc3_2_medres* model ((g) – (l)) for the SRESA2 scenario.

Figure 3 shows the trends in the Phillips criterion over the period 2001 – 2099 for the months of May – October from the *miroc3_2_hires* model under the SRESA1B scenario (Figure 3(a) – (f)) and from the *miroc3_2_medres* model under the SRESA2 scenario (Figure 3(g) – (l)). The trends shown are generally significant at the 99% level or 95% level. In both cases, the models predict negative trends upstream and over the southern half of Australia at latitudes between 25S – 35S. These negative trends can be as negative as -0.06 ms^{-1} per year. Positive trends approaching 0.06 ms^{-1} per year are seen further poleward. These trends are about half those seen in the reanalysis observations during the twentieth century. During the twentieth century, these models also tend to display trends which are about half those for the reanalyzed observations. This suggests that under both future scenarios the rate of reduction in baroclinic instability near 30S, observed in the twentieth century, will continue into the twenty first century. By implication, we might expect to see similar reductions in the growth rate of storms over the next fifty years as has occurred, over the last fifty years (Frederiksen et al., 2010) over southern Australia. Similar patterns of trends are seen in the SRESB1 scenario for both models, and for the SRESA1B for the *miroc3_2_medres*.

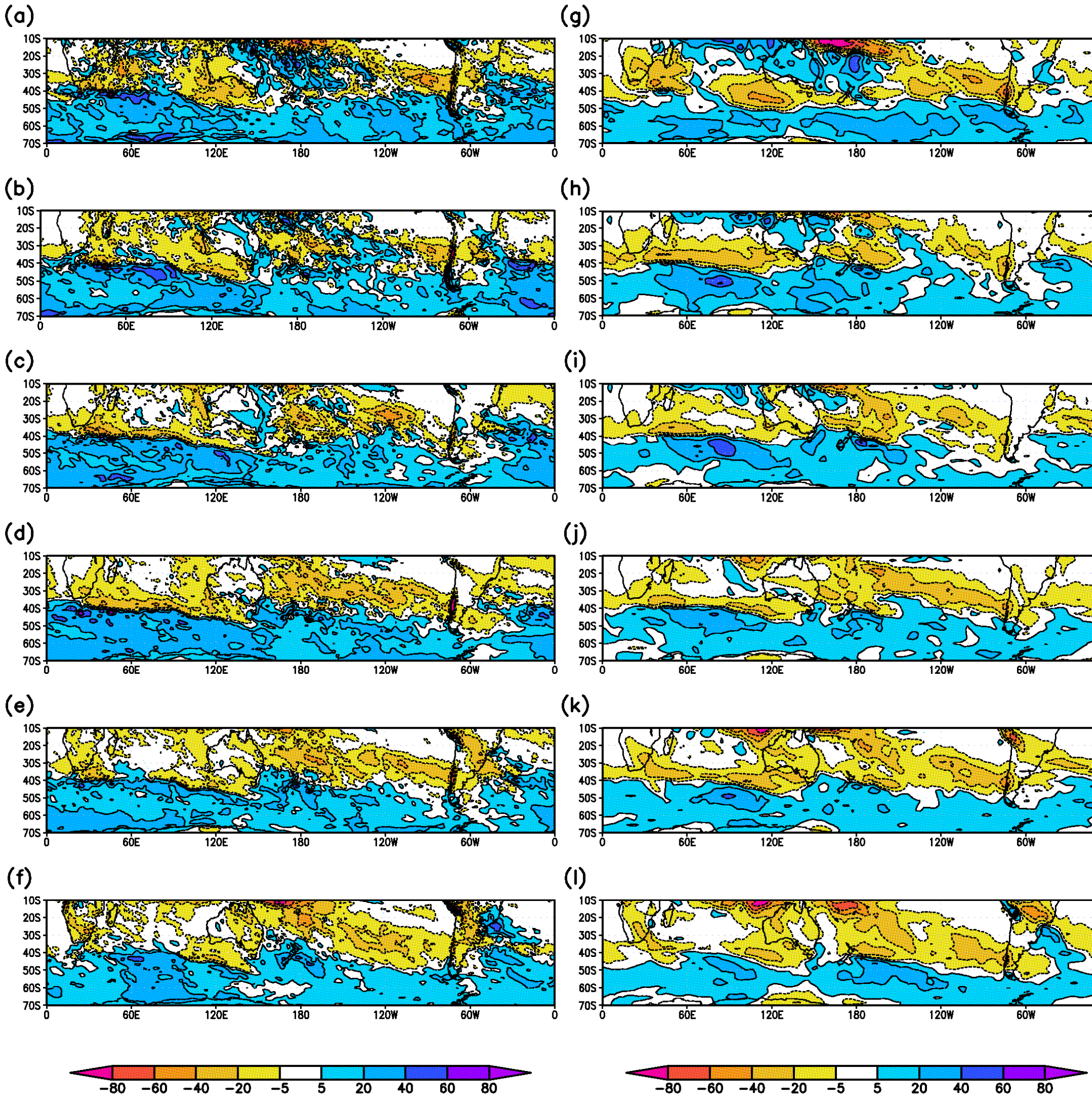

Figure 4. Differences in rainfall (mm per month) for the months May to October, between the periods (2080-2099) and (1980-1999) from the *miroc3_2_hires* model ((a) – (f)) for the SRESA1B scenario, and from the *miroc3_2_medres* model ((g) – (l)) for the SRESA2 scenario.

The impact of these trends in the baroclinic instability on Southern Hemisphere rainfall can be seen in Figure 4. This shows the differences in the average rainfall between the periods (2080-2099) and (1980-1999), for the months May to October, corresponding to the trends shown in Figure 3 for the *miroc3_2_hires* (Figure

4(a) – (f)) and *miroc3_2_medres* (Figure 4(g) – (l)) models. In all months, there are generally reductions in rainfall in a zonal band and north of about 40S; increases in rainfall are generally seen south of 40S. This is consistent with the corresponding negative/positive trends in baroclinic instability seen at these latitudes and the consequent expected decrease/increase in storm development. Differences in rainfall varies between -40mm to +40 mm. Over SWWA and southeastern Australia there are reductions in rainfall in all months with differences exceeding -20mm in some months, especially over SWWA, where the largest declines occur during May, June and July.

3. DISCUSSION AND CONCLUSIONS

We have examined the changes in the annual cycle of SH baroclinic instability for the period 1950-1999, and find that there are significant negative trends in a mid-latitude zonal band in all months; a similar band of significant positive trends occurs further poleward. This decrease/ increase in baroclinic instability would tend to decrease/ increase storm formation at these latitudes over this period. This is consistent with the study of Frederiksen et al. (2011c) where it is shown that there is a reduction of the intensity of the subtropical storm track and an increase in the polar storm track particularly in autumn and spring. Future projections of trends in baroclinicity, during May to October, over the period 2001-2099 show a similar pattern of negative and positive trends. The impact of these trends results in decreased rainfall in a band between 10S and 40S, adversely affecting southern Australia; poleward of 40S, there are generally increases in rainfall.

ACKNOWLEDGMENTS

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