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Modelling of changes in Southern Hemisphere weather systems during the 20th century

Frederiksen, J.S. [1], **C.S. Frederiksen** [2] **and S.L. Osbrough** [1]

[1] *Centre for Australian Weather and Climate Research, CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia*
[2] *Centre for Australian Weather and Climate Research, Bureau of Meteorology, Docklands, Victoria, Australia*
Email: jorgen.frederiksen@csiro.au

Abstract: The changes in Southern Hemisphere autumn and winter storms have been studied using a global two-level primitive equation instability model with reanalysed observed May and July basic states during the 20th century. For July, storm track instability modes growing on the subtropical jet show a dramatic reduction in growth rate post-1975. This reduction in the intensity of cyclogenesis has continued to the present time for storm track modes that cross Australia and is associated with the observed decrease in rainfall in southern Australia. For May, the strength of the subtropical storm track crossing Australia has decreased while the polar storm track has increased. This again is associated with a decrease in the strength of the divergence field and rainfall across southern Australia. These effects have become more pronounced with time. We find for both autumn and winter that the rainfall reduction is also associated with a decrease in the vertical mean latitudinal temperature gradient and in the peak upper tropospheric jet-stream zonal winds near 30^{o} south throughout most of the Southern Hemisphere.

We have examined the ability of a number of climate models with anthropogenic forcing including increasing greenhouse gas concentrations to replicate the changes in transient weather systems during the 20th century. Here, we focus on Australian models including the CSIRO Mark 3.0 and 3.5 coupled models and the ACCESS atmospheric model with prescribed SSTs; we also consider the UKMO HadGem1 coupled model that has a similar atmospheric component to the ACCESS model. The coupled models are not able to capture the storm track changes. However, the leading storm track mode crossing Australia from the ACCESS model simulations with prescribed SSTs has a structure that is remarkably similar to those based on July reanalyses and has reasonably good growth rate.

Keywords: *Climate Modelling, Climate Change, Weather Systems, Southern Hemisphere Circulation*

1. INTRODUCTION

During the second half of the 20th century there have been significant reductions in the rainfall across southern Australia and particularly across south west Western Australia (SWWA) (Nicholls 2007; Bates et al. 2008; Cai and Cowan 2008; Ummenhofer et al. 2008). In this paper, the changes in Southern Hemisphere autumn and winter storm track modes during the 20th century have been studied based on May and July reanalysed observations and on data from climate models. Frederiksen and Frederiksen (2005, 2007) showed that there had been a dramatic reduction in the growth rates of storm track modes crossing Australia in the 1975-1994 reanalyses. Here, we examine whether this reduction has continued into the present time. We also study the corresponding changes in autumn, focusing on the month of May.

Finally, we examine the ability of a number of climate models with anthropogenic forcing including increasing greenhouse gas concentrations to replicate the changes in transient weather systems during the 20th century. In this paper we focus on Australian models including the CSIRO Mark 3.0 and 3.5 coupled models and the ACCESS atmospheric model with prescribed sea surface temperatures (SSTs); we also consider the UKMO HadGem1 coupled model that has a similar atmospheric component to the ACCESS model.

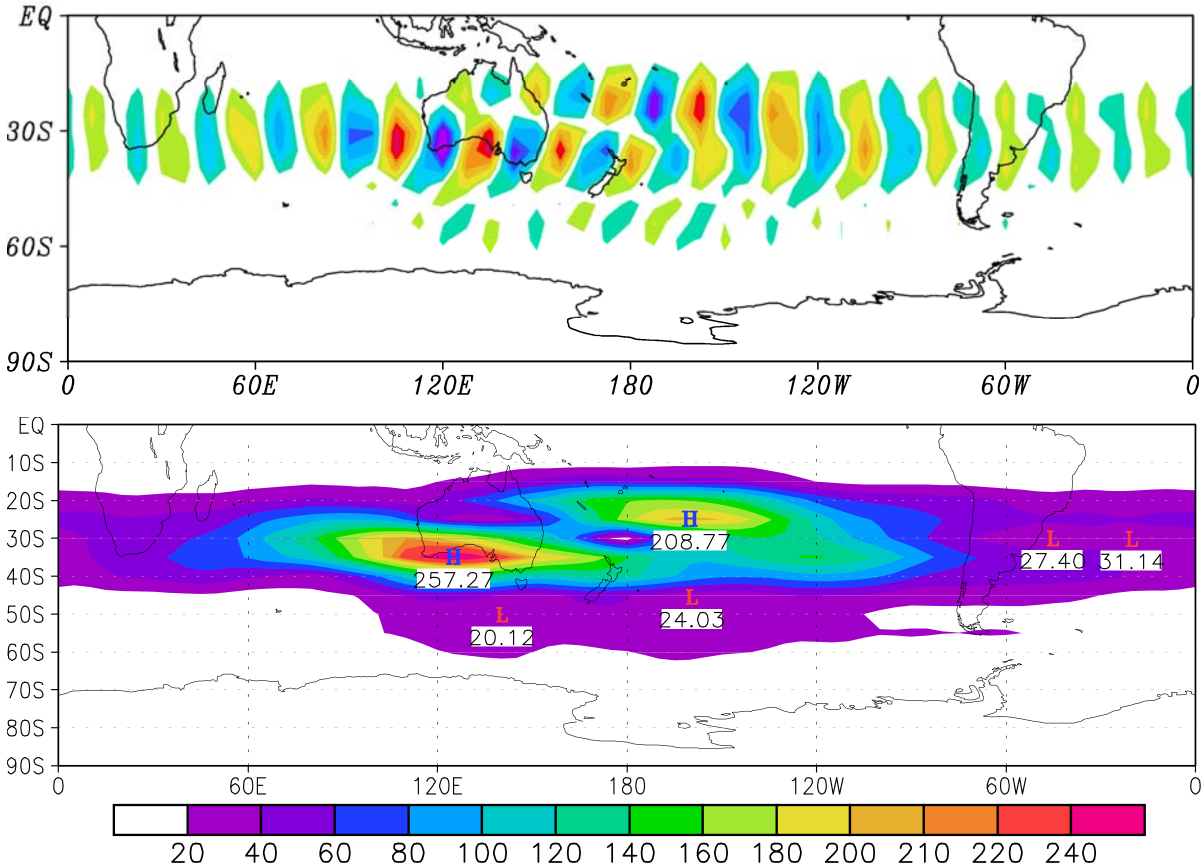

Figure 1. The fastest growing July storm mode, mode 1, for the period 1949-1968. Shown in top panel are the 300 hPa troughs (blue) and ridges (red) of the streamfunction at a particular instance and in bottom panel the corresponding amplitude for the storm track. Units are relative.

2. PRIMITIVE EQUATION INSTABILITY MODEL

The transient instabilities analyzed in this study have been obtained using the two-level linearised primitive equation model that was developed and applied in a series of studies by Frederiksen and Frederiksen (2005, 2007). The current version of the model includes a generalized Kuo-type heating parameterization that incorporates closures for both convection and evaporation-wind feedback as described by Frederiksen (2002). Each of the perturbation fields and basic state fields, entering the linearised equations, is expanded in terms of spherical harmonics with the perturbations also having a time dependence $\exp(-i\omega t)$. Here t is the time and $\omega = \omega_r + i\omega_i$ is the complex angular frequency with ω_r being the frequency and ω_i the growth rate. This then results in a system of eigenvalue-eigenvector equations described in Frederiksen and Frederiksen (1992) for the perturbation field variables of streamfunction, potential temperature and velocity potential. A so-called rhomboidal 15 truncation is used for both the perturbation and basic state fields in which the zonal wave number $m = -15, \ldots, 0, \ldots, 15$ and the total wave number $n = |m|, |m|+1, \ldots, |m|+15$ in the spherical harmonic expansion. In this study we use typical parameters for the strength of the convection, evaporation and dissipation as described in Frederiksen and Frederiksen (2005). A review of instability theory and applications is given by Frederiksen (2007).

Basic State	Mode	Correlation with Mode 1	Growth Rate, ω_i	Change in ω_i
1949-68 NCEP	1	1.0000	0.423 day^{-1}	0.0%
1975-94 NCEP	9	0.9148	0.282 day^{-1}	-33.5%
1997-2006 NCEP	12	0.8960	0.266 day^{-1}	-37.1%
Pre Indust CSIRO 3.0	4	0.5435	0.293 day^{-1}	-30.7%
Pre Indust HadGem1	11	0.5770	0.336 day^{-1}	-20.6%
1980-99 HadGem1	2	0.7995	0.481 day^{-1}	+13.7%
1980-99 ACCESS	2	0.9013	0.367 day^{-1}	-13.3%

Table 1. Properties of leading storm track modes crossing southern Australia.

3. CHANGES IN THE SOUTHERN HEMISPHERE CIRCULATION

The global Southern Hemisphere (SH) July climates for the periods 1949-1968 and 1975-1994, using the National Centres for Environmental Prediction (NCEP) reanalyses, have been compared and there are significant differences between the two periods. Most noticeable is a reduction of about 17% in the peak strength of the SH subtropical jet stream (Figure 1 of Frederiksen and Frederiksen 2007). Similar changes occur in May between 1949-68 and the later periods 1975-94 and 1997-2006 but with the decrease in the strength of the subtropical jet (near 30° S) being slightly less and the increase in the polar jet (near 60° S) slightly more (not shown).

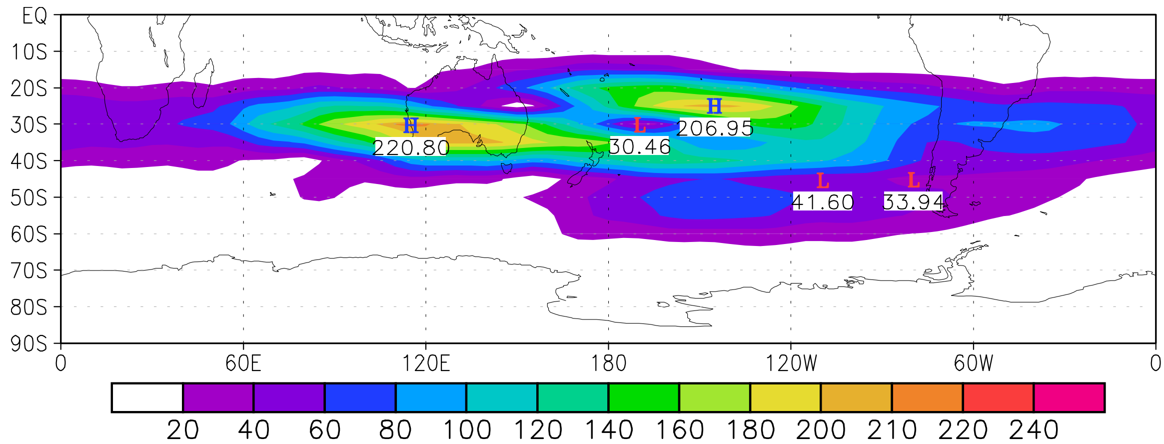

Figure 2. As in bottom panel of Figure 1 for July mode 12 for 1997-2006.

In both periods, there is a maximum in the zonal wind strength in the subtropics (near 30S) at about the 200hPa pressure level. This is directly associated with changes in the Hadley circulation in the Southern Hemisphere. The thermal structure of the SH atmosphere has also changed with a significant warming south of 30S, tending to reduce the equator-pole temperature gradient (not shown). Such changes would be expected to have a significant effect on the stability of the SH circulation and hence on the nature of the SH storms, which have a major impact on southwest Western Australia (SWWA), and other modes of weather variability. In fact, in both July and May (not shown) the SH atmosphere has generally become less unstable in those regions associated with the generation of mid-latitude storms.

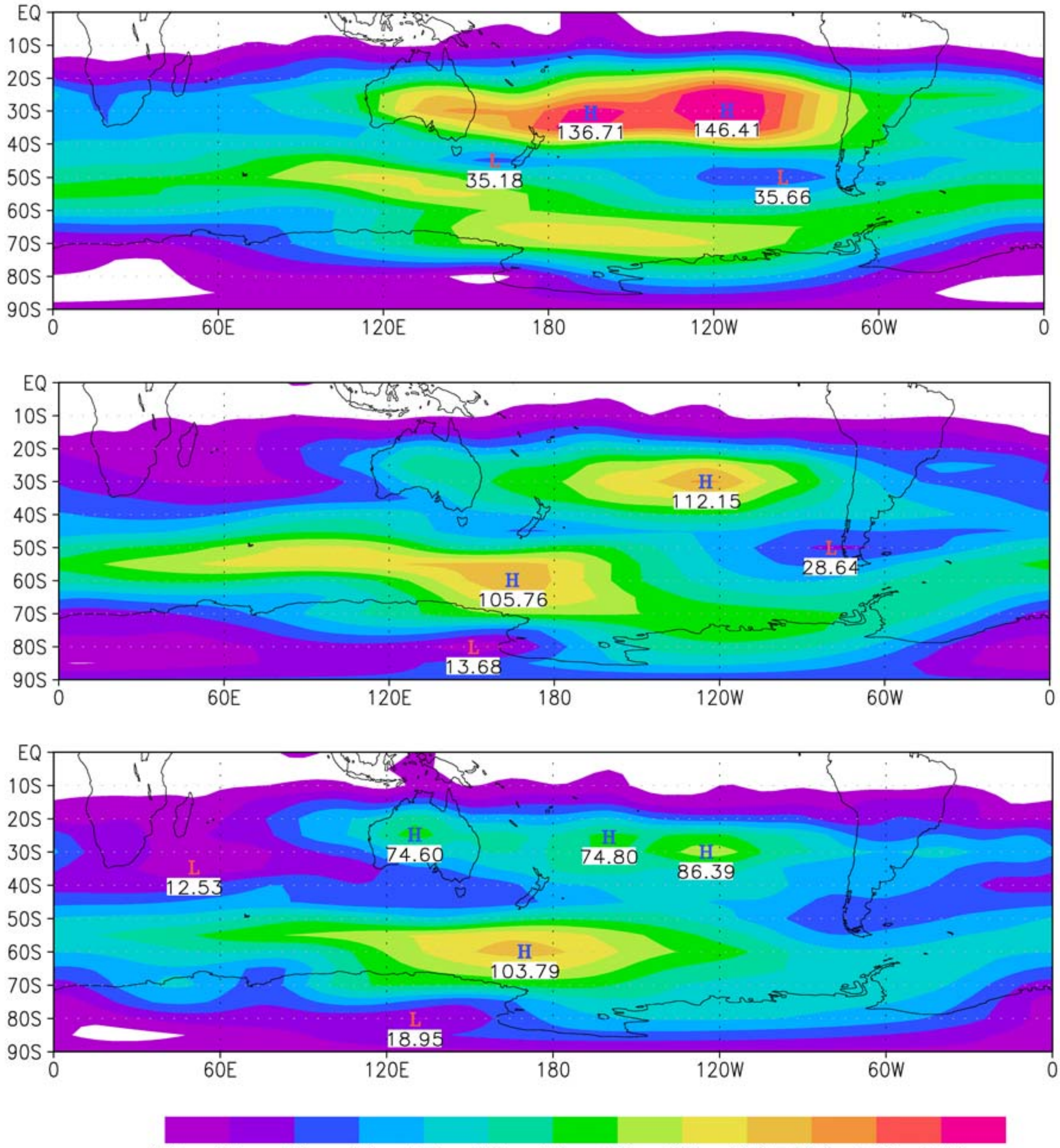

Figure 3. RMS 300 hPa streamfunction averaged over 20 fastest growing May storm track modes for 1949-68 (top panel), 1975-94 (middle panel) and 1997-2006 (bottom panel).

4. CHANGES IN STORM TRACK MODES FROM REANALYSES

An analysis of the impact of these observed SH winter climate changes on the nature of the dominant SH weather modes, was conducted, with particular emphasis on the storm track modes. Here, we have used the primitive equation instability model described in Frederiksen and Frederiksen (2005, 2007) to identify the dominant unstable weather modes in each period. In the earlier period, the fastest growing weather mode is a SH storm mode which affects southern Australia, and has largest impact over SWWA (Figure 1). This mode consists of a series of eastward propagating troughs (blue shading) and ridges (red shading), and is shown in the top panel of Figure 1 at a particular instance. As the troughs and ridges move eastward they amplify to reach a maximum in preferred regions.

The bottom panel of Figure 1 shows the storm track associated with this mode and indicates that its largest impact (red shading) is over south-western Australia. By contrast, in the latter period between 1975 and 1994, the dominant SH storm mode has a different horizontal structure. In particular, this weather mode effectively bypasses SWWA and has maximum impact in the central south Pacific (not shown). There are, however, other subdominant weather modes (mode 9 in Table 1), with a similar structure and frequency to the dominant mode from the earlier period, but their growth rates have been reduced 33% or more, as shown in Table 1. This is consistent with the observed reduction in rainfall over southern Australia, and in particular, SWWA. Figure 2 shows the corresponding storm track mode (mode 12) for the recent period 1997-2006. We note from Table 1 that compared with the results for 1949-1968 there has been a further reduction in the growth rate (by 37%). The reductions in growth rates of the leading storm track modes in later periods, described above, also occurs for averages taken over the leading 10 or 20 modes that cross Australia, indicating that it is a robust result.

For May we have calculated the average root mean square (RMS) amplitude of the 20 fastest growing storm track modes (with each mode normalised to having the same RMS amplitude) for each of the three periods 1949-68, 1975-94 and 1997-2006. The reduction in the average growth rate of the 20 fastest growing storm track modes is only about 10% in the latter periods. However, there are dramatic changes in their structures. The results are shown in Figure 3. We note that for the early period 1949-68 the principal storm track is at the latitudes of the subtropical jet; it crosses Australia and has its maximum downstream. In contrast, for 1975-94, the subtropical storm track is reduced in amplitude and the polar storm track is strengthened. This reduction of the strength of the storm track crossing Australia continues in the period 1997-2006. The RMS associated divergence field across Australia is also reduced correspondingly in the latter periods, as shown in Figure 4, and this explains the observed reduction in rainfall over southern Australia that has occurred in the latter part of the 20th century.

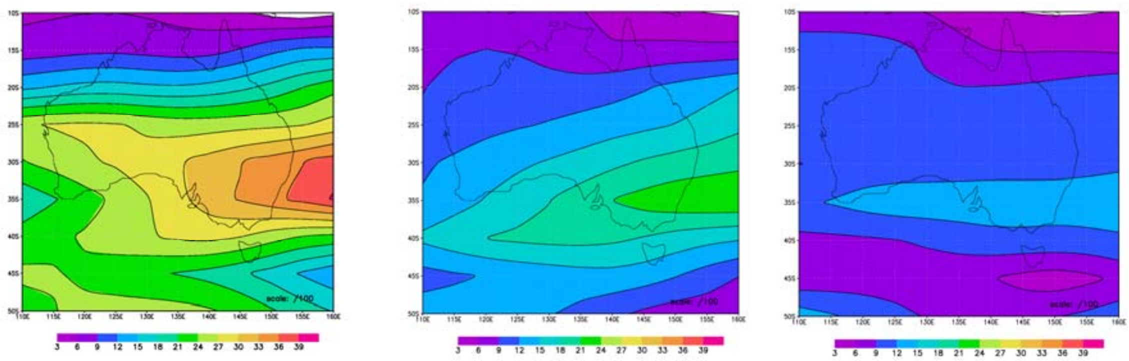

Figure 4. RMS 700hPa divergence averaged over 20 fastest growing May storm track modes for 1949-68 (left panel), 1975-94 (middle panel) and 1997-2006 (right panel).

5. STORM TRACK MODES FROM CLIMATE MODELS

We have examined July storm track modes in Australian climate models including the CSIRO Mark 3.0 and 3.5 coupled ocean-atmosphere models and the ACCESS atmospheric model with prescribed SSTs. We have also considered the HadGem1 coupled model that has a similar atmospheric component to the ACCESS model. The top panel of Figure 5 shows July mode 9, the leading storm track mode crossing southern Australia, using data from the CSIRO Mark 3.0 coupled model run with pre-industrial forcing. We note that the peak of the leading storm track mode occurs over the southern Atlantic rather than over southern Australia; the same failing occurs with other fast growing storm track modes. As seen from Table 1, the correlation with mode 1 for 1949-1968 is poor at 0.54 and its growth rate is too low. These deficiencies also apply to the CSIRO Mark 3.5 model. For the HadGem1 coupled model with pre-industrial forcing the structure of the storm track is again poor with maximum amplitude over the south-west Pacific. Again, correlation with mode 1 for 1949-1968 is low at 0.57 and its growth rate is low.

The bottom panel of Figure 5 shows July mode 2, the fastest growing storm track mode crossing southern Australia in the ACCESS atmospheric model with prescribed SSTs for the period 1980-1999. It has a similar structure to the leading storm track modes during the second half of the twentieth century (Figures 1 and 2). From Table 1 we note that the correlation with mode 1 for 1949-1968 is 0.9, which is similar to the results for the reanalyses for the periods 1975-1994 and 1997-2006. We also see that its growth rate is reduced compared with the period 1949-1968 in the reanalyses but somewhat larger than for the later periods. Table 1 also shows the results for the HadGem1 coupled model for the period 1980-1999. We see that the correlation with mode 1 for 1949-1968 reanalyses is less than for the ACCESS model but still quite reasonable at 0.8. However, the growth rate is much too large compared with the reanalyses for the twentieth century.

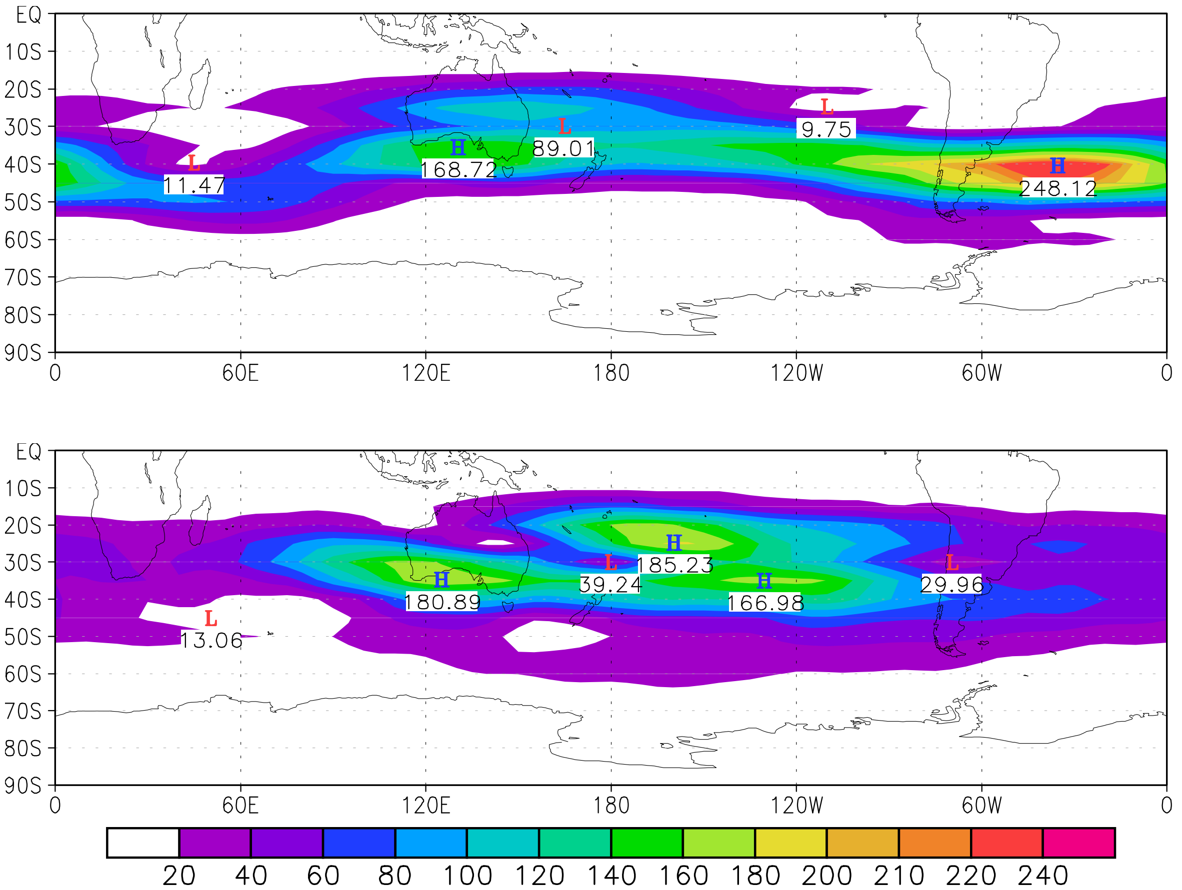

Figure 5. As in bottom panel of Figure 1 for July mode 9 for CSIRO Mark 3.0 model run with pre-industrial forcing (top panel) and July mode 2 for 1980-2000 with ACCESS model (bottom panel).

6. DISCUSSION AND CONCLUSIONS

There has been approximately a 20% reduction in autumn and winter SWWA rainfall, and a 17% reduction in peak July jet stream strength. Similar changes in the circulation have occurred in May. In July there has been about 30% reduction in growth rates of leading SH storm track modes crossing Australia since the mid 1970s. These changes have continued and spread to south-east Australia during the period 1997-2006. The structures of leading July storm track modes crossing Australia are very similar during 20th century. A primary cause of the rainfall reduction over SWWA since 1975 is the reduction in the intensity of cyclogenesis and the southward deflection of some storms. In May the strength of the subtropical storm track crossing Australia has decreased while the polar storm track has increased. Many climate models have difficulty in capturing the detailed structure of the Southern Hemisphere circulation and transient weather systems and their changes during the 20th century. A summary of the performance of the CSIRO, UKMO and ACCESS models has been presented. The structure of the leading SH winter storm track mode crossing Australia, using data from the ACCESS Atmospheric Model Intercomparison Project (AMIP) run, is in very good agreement with results from reanalysed observations and its growth rate is reasonable.

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