An Assessment of Future Southern Hemisphere Blocking Using CMIP5 Projections from Four GCMs

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ABSTRACT

This study is concerned with blocking events (BEs) in the Southern Hemisphere (SH), their past variability, and future projections. ERA-Interim (ERA-I) is used to compare the historical output from four general circulation models (GCMs) from phase 5 of the Coupled Model Intercomparison Project (CMIP5); the output of the representative concentration pathway 4.5 and 8.5 (RCP4.5 and RCP8.5) projections are also examined. ERA-I shows that the higher latitudes of the South Pacific Ocean (SPO) are the main blocking region, with blocking occurring predominantly in winter. The CMIP5 historical simulations also agree well with ERA-I for annual and seasonal BE locations and frequencies. A reduction in BEs is observed in the SPO in the 2071–2100 period in the RCP4.5 projections, and this is more pronounced for the RCP8.5 projections and occurs predominantly during the spring and summer seasons. Preliminary investigations imply that the southern annular mode (SAM) is negatively correlated with blocking activity in the SPO in all seasons in the reanalysis. This negative correlation is also observed in the GCM historical output. However, in the RCP projections this correlation is reduced in three of the four models during summer, suggesting that SAM may be less influential in summertime blocking in the future.

1. Introduction

In the midlatitudes of the Southern Hemisphere (SH) the passage of cyclones and anticyclones form the basis of synoptic weather (Trenberth and Mo 1985). These features have a predisposition to form at certain locations and travel along favored paths, owing to a combination of atmospheric and geographical conditions. Blocking events (BEs) are large-scale features linked to regions of high pressure, and they can exist on longer time scales than other synoptic-scale features; therefore, they can also influence the paths of transient synoptic-scale features (Trenberth and Mo 1985; Liu 1994; Sinclair 1996).

A BE is often defined by the mean westerly flow splitting around a long-lived anticyclone, generally situated within the high latitudes or at the latitudes of the storm tracks. The deflection of the mean flow can be detected by the gradients in the geopotential height field; this methodology has previously been used to define BEs (Rex 1950a,b; Tibaldi et al. 1994; Mendes et al. 2008; Matsueda et al. 2009; Mendes and Cavalcanti 2014).

In the mid- to high latitudes persistent positive anomalies (PPAs) in the geopotential height or surface pressure fields, which are effectively long-lived stationary/slow moving anticyclones, can also be thought of as BEs. Thus, BEs can also be determined by identifying a prolonged positive departure from the mean in the data field, based on a subjective threshold. This methodology has been used in a variety of studies (Dole and Gordon 1983; Sinclair 1996; Renwick 2005) and is utilized in this study.

While the PPA events may not fit the classic flow-splitting definition of a BE by Rex (1950a), they still embody features of blocking, such as their persistent nature and ability to influence the passage of synoptic-scale events. However, the gradient and PPA methodologies were compared by Liu (1994), who determined that at higher latitudes the PPA approach can satisfy the blocking criteria established by Rex (1950a,b). Also, the two-dimensional nature of the PPA methodology is beneficial in the visualization of blocking occurrence at a range of latitudes and longitudes.

The underlying mechanisms of blocking are not yet fully understood (Barnes et al. 2012; Cowan et al. 2013; Christensen et al. 2013). However, some mechanisms...
have been suggested: the blocking system appears to be prolonged by absorbing smaller transient eddies through meridional transport of anticyclonic vorticity from low latitudes, thus maintaining the anticyclonic (positive) anomaly (Trenberth and Mo 1985; Yamazaki and Itoh 2009). In the SH, zonal wavenumber 3 (ZW3) is also thought to reinforce BEs (Trenberth and Mo 1985; Renwick 2005; Berrisford et al. 2007). However, the higher average zonal wind speed in the SH is also thought to reduce the duration of BEs compared to the Northern Hemisphere (NH) (Trenberth and Mo 1985; Kiladis and Mo 1998).

This study is concerned with BEs, or PPAs, determined using a similar approach to that detailed in Renwick (2005), and the future projections of these BEs in the SH using general circulation model (GCM) output from phase 5 of the Coupled Model Intercomparison Project (CMIP5) archive. We are interested in investigating if there is a change in the future BE frequency and their geographical distribution.

Initial studies of blocking were motivated by a desire to enhance weather forecasting ability, as these stable long-lived positive features were considered an ideal candidate to assist in providing an extended weather forecast (Liu 1994). Blocking can also interrupt the regional weather sequences, thereby causing anomalous weather patterns upstream (Sinclair 1996). Another reason for studying blocking is that its prediction has long been difficult and prone to error (Liu 1994; Tibaldi et al. 1994; Renwick and Wallace 1996).

Strong BEs generally occur in the South Pacific Ocean (SPO) region (Trenberth and Mo 1985; Wiedenmann et al. 2002; Renwick 2005; Mendes et al. 2008). New Zealand (NZ) has also been noted as a primary region in which blocking events occur; this region may also be enhanced by quasi-stationary planetary waves of zonal wavenumber 3 (ZW3) (Trenberth and Mo 1985; Renwick 2005).

Trenberth and Mo (1985) provided a detailed statistical analysis of the BE frequency and distributions in the SH, using a PPA approach. During winter it is noted that a ZW3 pattern appears to reinforce the BE and also the BEs have a tendency to reform at the same location. Although, as noted in Renwick (2005), Trenberth and Mo (1985) used an early dataset that was deficient in detail over much of the Southern Ocean (SO).

Sinclair (1996) also provides an overview of anticyclones and blocking; their study used an objective tracking scheme for the anticyclones and a PPA methodology to identify the BEs. In that study a time period of five days and 6- or 15-hPa pressure anomaly thresholds were used in determining the PPA BEs. Stronger BEs, greater than 15 hPa, were limited to the SPO region and found only during winter.

More recently Oliveira et al. (2013) investigated the role of El Niño–Southern Oscillation (ENSO) and southern annular mode (SAM) on blocking and established a climatology using the NCEP-1 reanalysis, using a height gradient approach. No statistically significant trends in the blocking were determined within the reanalysis data. However, a significant ($p < 0.05$) reduction in blocking was observed during La Niña events, occurring between longitudes 175° and 130°W. Mendes and Cavalcanti (2014) investigated the blocking in the SH from 1979 to 2000 and SAM, applying the gradient approach of Tibaldi et al. (1994), and found a decrease in blocking events during SAM+ in a south-eastern Pacific sector, defined as 120°–80°W.

BEs can often have significant impacts on weather because of their persistent nature. For example, precipitation patterns in Australia have been related to blocking; this variation is caused by the BE modifying the position of the subtropical ridge, which in turn displaces the midlatitude westerlies resulting in modified precipitation patterns (Cowen et al. 2013). Extreme weather events can also be influenced by these features (Barnes et al. 2012; Dunn-Sigouin and Son 2013). The location of the BE can impede the movement of fronts, which can cause extreme weather events such as flooding, caused by prolonged precipitation as the front stalls. Australia is also susceptible to heat waves, drought, and wildfires, and these have also been linked to BE (Pezza et al. 2011). Mendes et al. (2008) determined a blocking climatology using the gradient methodology of Tibaldi et al. (1994) and NCEP-1 data. Low pressure anomalies were observed on the equatorward flank of the blocking events, which may influence precipitation events.

The ability of GCM output to portray BEs correctly is therefore important. However, studies have shown that BE representation in GCMs is often questionable, with GCMs generally underestimating blocking frequency (Palmer et al. 2008). This model issue has been linked to the low spatial resolution of GCMs, suggesting they are not able to accurately resolve the smaller eddies, which are thought to aid in maintaining the blocking anomalies (Masato et al. 2013). Matsueda et al. (2009) completed a model study using three different horizontal resolutions (20, 60, and 180 km) found only the highest GCM resolution was able to simulate the observed blocking frequency, likely linked to the lower-resolution GCM not resolving small transient eddies.

Barnes et al. (2012) investigated 14 CMIP3 GCMs and determined that the blocking persistence remained constant; however, a significant reduction in blocking frequency was observed in the NH with increased GHG forcing in the A2 scenario (2081–2100). Barriopedro et al. (2010b) reviewed previous studies to determine an
index that can be applied to a multitude of different studies, and this method was then applied in Barriopedro et al. (2010a). Dunn-Sigouin and Son (2013) investigated blocking in the NH with reanalysis and CMIP5 models, using historical and representative concentration pathway 8.5 (RCP8.5) projections. The CMIP5 models tested were generally able to reproduce the reanalysis blocking climatology.

The SAM is a large mode of variability that has a strong influence on the SH weather and climate in the high to midlatitudes (Thompson et al. 2011). There has been a positive trend in the SAM indices, and this has been linked to the Antarctic ozone hole and greenhouse gas (GHG) increase (Arblaster and Meehl 2006). The Antarctic ozone hole can influence the SAM, as the reduction of ozone in the austral autumn and winter causes a reduction in stratospheric temperature. This temperature reduction then causes a change in the geopotential height, which in turn causes a strengthening of the circumpolar flow (Arblaster and Meehl 2006; Thompson et al. 2011).

During the positive phase of SAM (SAM+) there is an increase in the strength of the westerly winds over the SO at ~60°S and a weakening at ~40°S (Thompson et al. 2011). Therefore, we might expect some variability in SH blocking due to its interference on the midlatitude westerlies and associated storm tracks. However, the positive trend in the SAM occurs in the austral summer and the majority of SH blocking activity occurs during the winter. Additionally, as ozone depletion recovers the SAM trend is expected to weaken even though GHG increase will still drive a positive trend (Son et al. 2010; Arblaster et al. 2011; Christensen et al. 2013).

There is a consensus of observed blocking event climatology in the SH from these different methodologies using reanalysis data—namely, the majority of BE occur in the SPO during winter. The IPCC Fifth Assessment Report (AR5) has noted, with only “medium confidence,” that future SH BEs will not increase; however, the persistence and intensity of BEs are uncertain (Christensen et al. 2013). The literature is currently deficient in SH GCM blocking studies. Thus, further knowledge of blocking using the latest reanalysis and GCM projections is beneficial to increase confidence and understanding of this important phenomenon. This work is exploratory in nature—hence the small ensemble of GCMs used.

2. Methodology

a. Data

The following data are used in the analysis: ERA-Interim (ERA-I) (Dee et al. 2011) and CMIP5 GCM output (Taylor et al. 2012), using the historical run and RCP4.5 and RCP8.5 projections for future scenarios. ERA-I is considered an improvement on earlier reanalysis and is considered good quality for mean sea level pressure (MSLP) in the SH (Bromwich et al. 2011; Bracegirdle and Marshall 2012). RCP4.5 is a lower emission future that rises then stabilizes in the mid-twenty-first century, thus assuming some mitigation strategies have been implemented, and RCP8.5 represents a “business as usual” scenario with continuing high forcings (Moss et al. 2010).

The GCM output is organized into four 30-yr periods: 1976–2005, 2011–40, 2041–70, and 2071–2100. The ERA-I data are not available before 1979, and the GCM historical data stop at 2006; thus, there is a 4-yr period with no overlap between the historical GCM output (1976–2005) and reanalysis (1979–2008).

A small ensemble of GCMs is utilized in this study, owing to the exploratory nature of this work. The model selection is displayed in Table 1 and was influenced by work detailed in B. Mullan (2013, personal communication) in which CMIP5 GCMs were ranked by their ability to simulate the SH and GCM output availability for the periods selected with 6-hourly output. The first ensemble member is selected when multiple realizations are available.

The SH region is limited to 5°–85°S. The reanalysis and GCM data have been bilinearly interpolated to a common grid resolution of 1.25° latitude × 1.875° longitude, resulting in a 65- by 192-point grid (12,480 data points). MSLP data was utilized because of the availability of this field in the CMIP5 archive at 6-h frequency. Previous studies of PPAs and blocking have often utilized a higher atmospheric level (e.g., 500 hPa); however, the patterns observed at this level are also well represented at the surface level (Renwick 2005).

b. Blocking

Our blocking methodology is similar to that of Renwick (2005), also used in Dole and Gordon (1983) and Sinclair (1996). We define BEs to be positive anomalies that exist for an extended period of time—hence PPAs. The anomaly for each grid point is determined by removing that grid point’s overall mean, determined from the full 30-yr dataset. Each grid point is

<table>
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<th>Table 1. Data sources. (MOHC is Met Office Hadley Centre, and AORI is Atmosphere and Ocean Research Institute.)</th>
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<td>Model</td>
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<td>CCSM4</td>
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<td>HadGEM2-ES</td>
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<td>MIROC5</td>
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then tested to determine if its anomaly is greater than a subjective threshold (8 hPa). If 5 days’ worth of consecutive data at that grid point are above the threshold, it is then considered a BE and those 5 days are counted as “blocked” at a given grid point.

The frequency of BEs is counted in terms of the total number of days of PPAs, not the number of events. Thus one 10-day BE is equivalent to two 5-day BEs, in terms of blocking frequency in our analysis. Blocking anomalies are defined in relation to the relevant 30-yr time period in question to remove the potential impacts of long-term changes in the MSLP over the entire record.

A range of thresholds were evaluated, between 6 and 16 hPa and 2.5 and 10 days. The subjective choice of 8 hPa and 5 days is based on data exploration and comparison with the earlier work of Renwick (2005) and is used for the majority of the analysis. However, a persistence of 5 days and a pressure threshold of 16 hPa are also used for some comparison with the work of Sinclair (1996). The largest point of difference in the methodology used between this work and Renwick (2005) is that we use MSLP anomalies; our thresholds are 5 days and 8 hPa instead of 500-hPa geopotential height anomalies of a 100-m, 5-day threshold. However, Renwick (2005) noted that patterns between the 500- and 1000-hPa levels were similar.

Later in this study, we also use a smaller region in the SPO to examine statistical trends. It is defined as latitudes 45°–70° S and longitudes 180°–90°W and is displayed in Fig. 1a as the red outlined domain. The SAM index used in this study is determined from surface pressure zonal mean differences at latitudes 40° and 65°S, as described in Gong and Wang (1999).

3. Results

We focus our analysis and discussion of the results on the differences between the GCM historical runs and RCP projections. The reanalysis data are predominantly used to compare our results with previous work and the GCM historical runs; this allows us to identify the integrity of the results from the various GCMs.

The differences are determined between the historical and future projections for each of the individual models, and the mean of the four model differences is then presented as an absolute percentage. Thus a frequency of 10% represents ~36.5 days of blocking activity. A difference of −10% between the historical and RCP projection would equate to a reduction in blocking of ~36.5 days from the historical period. The seasonal results are reported in a similar manner—however, as a seasonal percentage. The results and discussion focus on the 8-hPa threshold unless otherwise stated.
a. Reanalysis

The ERA-I 1979–2008 annual frequency of occurrence of BEs is displayed in Fig. 1a as a percentage of annual occurrence. The BE maximum is observed in the SPO, located near 60°S and between 135° and 90°W. The broader BE region extends westward to NZ and the ocean south of Australia. Similar patterns have been observed in a number of previous studies (Kiladis and Mo 1998; Sinclair 1996; Renwick 2005).

The seasonality of the BEs is displayed in Fig. 1b. The majority of BEs are observed during the austral winter (JJA) in the SPO at 60°S and between 135° and 90°W, in the same region as observed in the annual pattern. Austral autumn displays the next highest frequency of occurrence. The location of the maximum is still observed in the SPO, though reduced in intensity. The blocking activity also extends south of Australia, centered at 45°S, 90°E into the Indian Ocean. During austral summer (DJF) the highest frequency of BEs occurs poleward of 60°S, peaking in the SPO, close to the Ross Sea. Another band of BEs is centered on 45°S between 90°W and 90°E. Austral spring (SON) has the lowest occurrence of BEs when compared to the other seasons. However, the spring BE maximum is still located in the same SPO region, although this maxima is more diffuse than in other seasons. Secondary regions are also present to the east of NZ and over the South Atlantic Ocean.

A higher threshold of 16 hPa was also tested, but the results are not shown. With this threshold, blocking is limited to the SPO and occurs primarily during the winter. This agrees with the findings of Sinclair (1996), who also found BEs to be limited to the SPO and winter when using a threshold of 15 hPa.

b. GCM output—Historical

We now examine the BEs from the GCM historical output and compare them with the reanalysis to determine the quality of the representation of BEs. The spatial correlation coefficient between the historical GCM and ERA-I output is displayed at the top of Fig. 2 and is also presented in Table 2.

The ensemble mean of the GCM historical run is displayed in Fig. 2a. A similar distribution as seen in the reanalysis is apparent, with the maximum located in the SPO at 60°S; however, the BE frequency is slightly reduced in the mean of the four model runs compared to that derived from ERA-I. The GCM historical BEs also extend farther into the Indian Ocean and South Atlantic Ocean than the reanalysis. Despite these small variations in the GCM ensemble, the spatial pattern and frequency compare well with ERA-I (Fig. 1a), as shown by the spatial correlation of 0.98 (see Table 2).

Fig. 2. (a) Historical GCMs BE ensemble annual mean frequency of occurrence 1976–2005 (%) for a 8-hPa threshold. The contour interval is 2, starting at 2, and every second contour line is thickened and labeled. The correlation with the reanalysis is also displayed at the top of the figure. (b) As in (a), but for seasonal values. The contour interval is 4, starting at 8, and the 16 contour line is thickened and labeled.
The GCM historical ensemble seasonal BE frequencies are displayed in Fig. 2b, and these results are again similar to the reanalysis with the highest frequency of BEs occurring during winter with these BEs also predominantly located in the SPO between 45° and 60°S and 135°W and 90°E. However, in the GCM historical output the band of BEs between 45° and 60°S extends farther east in winter. Spring also displays a smoother distribution than in the reanalysis, with a higher occurrence of BEs in the SPO. Summer also has a maximum occurrence of BEs poleward of 60°S, surrounding the coast of Antarctica. Secondary regions of elevated BE counts are approximately centered on 45°S in the SPO and 90°E in the Indian Ocean. During autumn a more annular structure of BEs occurs and is centered on 45°S, with a maximum at 90°W. The seasonal correlations range between 0.92 and 0.93.

We now consider the response of the individual GCMs in the ensemble. The differences between the annual frequency of occurrence for each of the GCMs’ historical run and the reanalysis is displayed in Fig. 3. CCSM4 displays reduced BEs and MIROC5 increased BEs in the SPO region. MIROC5 also has elevated BEs in the southern Indian Ocean and Tasman Sea. Slightly increased BEs are displayed in ACCESS1.0 and HadGEM2; however, these are not located in the SPO region.

The annual correlation coefficients are also displayed and are above 0.95 (Fig. 3 and Table 2), which compares well with the ensemble mean of 0.98. Thus, each of the GCMs is capable of emulating the broadscale BE patterns observed in the SH.

However, as we increase temporal resolution from annual to seasonal, greater disparity between the reanalysis and individual GCM output is evident, as seen in the reduced correlation coefficients in Table 2.

Based on the correlation coefficients in Table 2 the four model ensemble average out performs any of the individual models during the annual or seasonal periods. This clearly shows that the GCM ensemble is capable of generating the observed blocking as geographical patterns do not change appreciably. However, MIROC5 appears positively biased during winter and negatively biased in summer when compared to the other GCMs (not shown).

c. GCM output—Future scenarios

Figures 4a and 4b display the annual mean BE frequency for the 2071–2100 period for the RCP4.5 and RCP8.5 projections, respectively. The geographical distribution of the BEs is similar between simulations and time periods (2011–40 and 2041–70, not shown). However, there are less BEs in the primary SPO region in the later periods in both scenarios. The reduction in annual BE frequency is apparent over the three periods in both the RCP4.5 and RCP8.5 projections. However, this change is relatively minor in the RCP4.5 scenario and it is more pronounced in the RCP8.5 scenario.

The ensemble annual mean differences between the RCP4.5 and RCP8.5 projections at 2071–2100 and the historical output are displayed in Figs. 5a and 5b, respectively. A reduction in the BEs is evident during both periods.

### Table 2. Correlation coefficients between GCM historical and the reanalysis (for 8- and 16-hPa thresholds see text).

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<tr>
<th></th>
<th>Annual</th>
<th>Summer</th>
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<tr>
<td>8 hPa</td>
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<td>ACCESS1.0</td>
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<tr>
<td>Ensemble</td>
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<td>0.92</td>
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<td>16 hPa</td>
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of the RCP projections but is more pronounced in the RCP8.5 projection (Fig. 5b). The largest change is observed in the SPO where the BE maximum is reduced in extent and frequency. The reduction in BEs from 60°S to Antarctica is seen across each of the three 30-yr periods in both RCP projections. In addition, the Indian Ocean has a decrease between 30° and 45°S. Figure 5b also shows a small increase in BEs in the midlatitudes, centered on 30°S in the SPO. However, this region is at the edge of the observed blocking activity (Fig. 4b) and is also associated with low frequency of occurrence in the historical period.
The mean GCM historical BE frequency maximum was 15.3% and the RCP8.5 2071–2100 is reduced to 12.9%. This 2.4% reduction relates to a relative decrease of ~15.7%, or ~9 fewer days of blocking per annum in the region of the maxima.

The seasonal BE projections follow a similar pattern, in that the RCP8.5 displays a similar structure to the RCP4.5 pattern but with a larger reduction in the frequency of occurrence. Figures 6a and 6b display the seasonal mean BE differences between the RCP4.5 and RCP8.5 projections, for the 2071–2100 period and the historical output, respectively.

During the summer there is also a change in location and frequency of the BEs with a reduction in the previous maximum located at 45°S, 135°W and an increase in BE between 45° and 60°S in the Indian Ocean. Autumn has a reduction in the SPO region and an increase over the South Atlantic Ocean relative to the historical patterns. During winter there is a large reduction in BE frequency south of Tasmania, and a ZW3-like pattern is also evident. Spring also displays a general reduction in BE across the SH; however, an equatorward shift in latitude is observed in the SPO maxima. These seasonal changes are seen in both RCPs but are more pronounced in RCP8.5 (Fig. 6b) than in RCP4.5 (Fig. 6a).

The GCM ensemble contains four models; comparison of individual ensemble members suggests that there is agreement in the annual BE distributions. However, the seasonal variation between models is more varied. The small ensemble size also means that a single model output could dominate the ensemble mean. Figure 7 displays the summer BE frequency differences for the four GCMs during the RCP8.5 2071–2100 period. During the summer season all of the GCMs display a consensus with a BE reduction in the SPO region, though of varying magnitude.

The previous results have given a qualitative description of the projected BEs in the SH. To provide a more quantitative analysis, we now focus our analysis on the SPO region defined as latitudes 45°–70°S and longitudes 180°–90°W and displayed in Fig. 1a. Since the majority of the observed blocking occurs in this region it is deemed worthy of further investigation.

The mean of the 21 × 49 grid points in the SPO region is determined for each season and year of the 30-yr periods. These are presented as an annual BE frequency of occurrence (%); thus the four seasons blocking frequency sums to the annual frequency (Table 3). The differences are determined between the reanalysis and historical periods and the historical and the latter period (2071–2100) for the RCP projections. The standard deviations are determined from the yearly means, and since these values represent the ensemble SPO area
mean they are reduced in value when compared to the previously seen spatial patterns.

The RCP4.5 mean ensemble displays a reduction across all three time periods (Table 3). However, this reduction is subtle when the standard deviation is taken into consideration, and the RCP4.5 reductions reflect the previously seen differences in the spatial distributions (Figs. 5a and 6a). The RCP4.5 2071–2100 ensemble has a reduction of 1.0% in the annual frequency of occurrence of BE, and this occurs predominantly during summer and spring seasons.

As before, the RCP8.5 projection displays a greater reduction in BEs when compared to the RCP4.5 projection. The reductions observed are of borderline significance, less than one standard deviation. However, despite the high uncertainties the reduction in the SPO BEs is consistent across the three time periods and in the annual and seasonal periods. There is an annual BE reduction of 2.01%, with a standard deviation 2.95%. This reduction occurs mostly in the summer and spring, with a reduction of −0.86% and −0.85%, respectively.

These results are the absolute frequency of occurrence. When a relative frequency of occurrence is used the reduction is more striking. A BE reduction of 32.6% during summer and 31.3% during spring between the historical and RCP8.5 2071–2100 period is identified. However, these results need to be tempered by the high standard deviation and the size of the SPO region.

### 4. Influence of SAM

We now examine the influence of the SAM on BE occurrence in the reanalyses and GCM projections. SAM has a large influence on the climate in the SH; during SAM+ the wind speed in the SH higher latitudes is enhanced and in the midlatitudes it is reduced (Arblaster and Meehl 2006; Thompson et al. 2011). The

![Table 3. SPO region ensemble means and standard deviation in parentheses of the annual BE frequency of occurrence (%). The absolute differences are generated between the reanalysis and historical, and the historical and RCP projections, using the later period (2071–2100). The differences as a relative percentage are also shown.](image-url)
seasonality of SAM is also an important factor, with SAM being more pronounced and more zonally symmetric during summer. Thus we would expect BEs to be less frequent during the SAM+ and summer as the increased wind speed should disrupt blocking events.

Figure 8a displays the annual mean frequency of occurrence of BEs in the SPO region and the annual mean SAM index, determined using the Gong and Wang (1999) methodology, derived from ERA-I during summer 1979–2008. There is a high negative correlation of -0.77 between the BEs and the SAM index. A positive trend of 0.052% yr\(^{-1}\) is observed in the SAM index, while the BEs experiences a reducing trend of -0.043% yr\(^{-1}\). The observed trend toward SAM+ in the summer is well documented in the literature (Son et al. 2010; Arblaster et al. 2011) and has been linked to increased GHG and the reduction of stratospheric ozone in spring.

Figure 8b displays the mean summer BE frequency in the SPO region and the SAM index for each of the GCMs during the historical period, 1976–2005. Each GCM has a different realization; thus, the models should not be directly compared to each other on a year-to-year basis. Just the overall trend and correlation is important. All of the GCMs display a strong negative correlation, ranging from -0.55 to -0.78 and all have increasing SAM+ trends, while also displaying a reduction in BEs; thus, each is in good agreement with ERA-I.

Table 4 displays the correlation coefficients between the SAM index and BE frequency in the SPO during summer, winter, and monthly for each GCM, time period, and RCP projection. A 3–month running mean is applied to the monthly BEs and SAM index. Of interest is the latter period 2071–2100 in both the RCP4.5 and RCP8.5 projections where the correlation coefficient is reduced in three of the models during summer (RCP8.5 displayed in Fig. 9). During winter the historical and RCP projection correlations appear to be more stable and do not display the reduction observed in CCSM4, HadGEM2-ES, and MIROC5 during the summer.

This suggests that SAM is potentially less important in suppressing BEs toward the end of the twenty-first century which given ozone recovery might be expected. However, the correlation response across the models is quite varied during the RCPs projections. Additionally the SAM in the GCM projections may be less certain owing to competing forcings, ozone recovery, and increased GHG and how the individual GCMs parameterize these processes.

5. Conclusions

A persistent positive anomaly methodology has been applied to ERA-I and four CMIP5 GCMs over the SH and regions of blocking activity have been determined. We believe this is the first SH blocking study to utilize CMIP5 output with a PPA methodology. The GCM historical simulations have been compared to the reanalysis, and each GCM’s historical simulation has been compared to its own RCP4.5 and RCP8.5 projections.
Our results can be broadly summarized as follows:

1) GCMs can replicate SH BE (historical) spatial patterns and frequency of occurrence.

2) Reductions in BEs are observed in RCP4.5 and RCP8.5 projections during summer in the SPO, with a greater reduction in RCP8.5 2071–2100.

3) SAM and SPO BEs are negatively correlated in ERA-I and historical GCM output. However, the SAM versus BE correlation is reduced in RCP projections.

In more depth, the annual BEs spatial distributions from ERA-I data and the CMIP5 historical GCM output broadly agree with each other with spatial correlations $>0.9$. These results also agree with previous studies that show the majority of BEs occurring during the winter and being located in the SPO region (Kiladis and Mo 1998; Sinclair 1996; Renwick 2005). However, at the seasonal scale increased variation in the BE spatial and seasonal patterns in individual GCMs is evident.

A reduction in the extent and frequency of future blocking events between the CMIP5 historical and both RCP projections was observed. In particular, in the SPO region the annual frequency of BEs at the higher latitudes is reduced, as the extent of the historical maximum contracts in size and frequency. The SPO region has been previously noted as the main center of blocking activity in the SH, and this is therefore an interesting finding. While both RCP projections display a reduction in BEs, this is more pronounced in the higher-forcing RCP8.5 scenario. This reduction agrees in sign with work detailed in Barnes et al. (2012), who observed a reduction in blocking frequency with increased GHG forcing in the NH.

The BE reduction occurs during the austral summer and spring and is observed in all four of the GCMs. The mean GCM historical annual BE frequency maximum was 15.3% and the RCP8.5 2071–2100 one is reduced to 12.9%. This 2.4% reduction relates to a relative decrease of $-15.7\%$. Small increases in the BE occurrence are also observed in other regions, but these are not robust between models.

We have also examined the relationship between BEs and SAM; as expected SAM is negatively correlated with BEs in the SPO region. In the SPO region ERA-I BEs are negatively correlated ($-0.77$) with the SAM index during summer (Fig. 8a). The GCMs also exhibit this negative correlation, ranging between $-0.55$ and $-0.78$ (Fig. 8b). However, during the RCP projections the GCM response is less consistent, as seen in Table 2 and Fig. 9. ACCESS1.0 maintains a high negative correlation across both scenarios and time periods. However, the negative correlation is reduced in the other models (CCSM4, HadGEM2-ES, and MIROC5). During winter the models retain similar negative correlations to those previously observed in the

### Table 4. SPO region BE and SAM correlations during summer (DJF), winter (JJA), and monthly (mon) for the individual GCMs; a 3-month running mean has been applied to the monthly data.

<table>
<thead>
<tr>
<th>Historical</th>
<th>ACCESS1.0</th>
<th>CCSM4</th>
<th>HadGEM2-ES</th>
<th>MIROC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976–2005</td>
<td>DJF -0.68</td>
<td>-0.55</td>
<td>-0.77</td>
<td>-0.78</td>
</tr>
<tr>
<td></td>
<td>JJA -0.61</td>
<td>-0.59</td>
<td>-0.73</td>
<td>-0.80</td>
</tr>
<tr>
<td></td>
<td>Mon -0.62</td>
<td>-0.52</td>
<td>-0.58</td>
<td>-0.49</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>DJF -0.77</td>
<td>-0.33</td>
<td>-0.73</td>
<td>-0.75</td>
</tr>
<tr>
<td></td>
<td>JJA -0.58</td>
<td>-0.60</td>
<td>-0.67</td>
<td>-0.67</td>
</tr>
<tr>
<td></td>
<td>Mon -0.59</td>
<td>-0.43</td>
<td>-0.54</td>
<td>-0.51</td>
</tr>
<tr>
<td>2041–70</td>
<td>DJF -0.85</td>
<td>-0.37</td>
<td>-0.79</td>
<td>-0.60</td>
</tr>
<tr>
<td></td>
<td>JJA -0.47</td>
<td>-0.47</td>
<td>-0.56</td>
<td>-0.81</td>
</tr>
<tr>
<td></td>
<td>Mon -0.63</td>
<td>-0.36</td>
<td>-0.50</td>
<td>-0.46</td>
</tr>
<tr>
<td>2071–2100</td>
<td>DJF -0.61</td>
<td>-0.34</td>
<td>-0.40</td>
<td>-0.42</td>
</tr>
<tr>
<td></td>
<td>JJA -0.55</td>
<td>-0.76</td>
<td>-0.74</td>
<td>-0.58</td>
</tr>
<tr>
<td></td>
<td>Mon -0.49</td>
<td>-0.45</td>
<td>-0.50</td>
<td>-0.39</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>DJF -0.59</td>
<td>-0.34</td>
<td>-0.64</td>
<td>-0.36</td>
</tr>
<tr>
<td></td>
<td>JJA -0.46</td>
<td>-0.77</td>
<td>-0.70</td>
<td>-0.68</td>
</tr>
<tr>
<td></td>
<td>Mon -0.53</td>
<td>-0.50</td>
<td>-0.51</td>
<td>-0.36</td>
</tr>
<tr>
<td>2041–70</td>
<td>DJF -0.72</td>
<td>-0.17</td>
<td>-0.70</td>
<td>-0.54</td>
</tr>
<tr>
<td></td>
<td>JJA -0.46</td>
<td>-0.69</td>
<td>-0.50</td>
<td>-0.73</td>
</tr>
<tr>
<td></td>
<td>Mon -0.57</td>
<td>-0.42</td>
<td>-0.41</td>
<td>-0.49</td>
</tr>
<tr>
<td>2071–2100</td>
<td>DJF -0.74</td>
<td>-0.15</td>
<td>-0.41</td>
<td>-0.22</td>
</tr>
<tr>
<td></td>
<td>JJA -0.64</td>
<td>-0.54</td>
<td>-0.71</td>
<td>-0.70</td>
</tr>
<tr>
<td></td>
<td>Mon -0.54</td>
<td>-0.28</td>
<td>-0.42</td>
<td>-0.41</td>
</tr>
</tbody>
</table>
historical period. Thus, it appears that the negative relationship observed in summer between BE frequency and SAM is less clear in the RCP projections than in the historical period. However, since the GCMs show less agreement it is hard to determine the future influence of SAM on blocking considering the small GCM ensemble size used in this study. Therefore further investigation is warranted.

In conclusion, the GCM ensemble displays a consensus with a reduction in BE during summer and spring. However, owing to the high year-to-year variability of these BE values, while they are large relative to the historical period, their significance is questionable (Table 3).

We have shown a high negative correlation between SAM and BE in the SPO region; during periods of SAM+ BE are reduced in summer in the reanalysis and GCM historical output. The summer BE reduction in future projections may be associated with the SAM, but the GCM projections do not show a clear consensus on this point. This may be associated with the small GCM ensemble size. Finally, this exploratory study has yielded some informative and interesting results, and it has also provided the motivation for further work.

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