

Causes of Late Twentieth-Century Trends in New Zealand Precipitation

CAROLINE C. UMMENHOFER, ALEXANDER SEN GUPTA, AND MATTHEW H. ENGLAND

Climate Change Research Centre, University of New South Wales, Sydney, Australia

(Manuscript received 9 November 2007, in final form 6 June 2008)

ABSTRACT

Late twentieth-century trends in New Zealand precipitation are examined using observations and reanalysis data for the period 1979–2006. One of the aims of this study is to investigate the link between these trends and recent changes in the large-scale atmospheric circulation in the Southern Hemisphere. The contributions from changes in Southern Hemisphere climate modes, particularly the El Niño–Southern Oscillation (ENSO) and the southern annular mode (SAM), are quantified for the austral summer season, December–February (DJF). Increasingly drier conditions over much of New Zealand can be partially explained by the SAM and ENSO. Especially over wide parts of the North Island and western regions of the South Island, the SAM potentially contributes up to 80% and 20%–50% to the overall decline in DJF precipitation, respectively. Over the North Island, the contribution of the SAM and ENSO to precipitation trends is of the same sign. In contrast, over the southwest of the South Island the two climate modes act in the opposite sense, though the effect of the SAM seems to dominate there during austral summer. The leading modes of variability in summertime precipitation over New Zealand are linked to the large-scale atmospheric circulation. The two dominant modes, explaining 64% and 9% of the overall DJF precipitation variability respectively, can be understood as local manifestations of the large-scale climate variability associated with the SAM and ENSO.

1. Introduction

There is much evidence of recent changes to the hydrological cycle with impacts on precipitation patterns across the planet, especially during the late twentieth century (e.g., Oki and Kanae 2006). Coinciding with these changes, some climate modes have also undergone substantial shifts, such as the annular modes in both hemispheres (e.g., Fyfe et al. 1999; Thompson et al. 2000), the North Atlantic Oscillation (e.g., Hurrell 1995), and the El Niño–Southern Oscillation (ENSO) (e.g., Fedorov and Philander 2000). In addition, key drivers of precipitation, such as sea surface temperature (e.g., Levitus et al. 2000) and sea level pressure (e.g., Gillett et al. 2003; Marshall 2003) are showing widespread changes over recent decades. The goal of this study is to examine late twentieth-century New Zealand precipitation trends and their association to changes in Southern Hemisphere climate modes.

Over recent decades, large-scale changes to the atmospheric circulation in the Southern Hemisphere have been documented. They include a positive trend in the meridional sea level pressure (SLP) gradient between the high and midlatitudes and a corresponding strengthening and southward shift in the subpolar westerlies (e.g., Thompson and Solomon 2002; Renwick 2004). Model results have shown that these trends are consistent with the observed depletion in stratospheric ozone, which in turn leads to reduced temperatures over the polar cap and a strengthening of the stratospheric polar vortex and circumpolar flow (Thompson and Solomon 2002; Gillett and Thompson 2003). Since the photochemical ozone loss is enhanced by solar radiation, the depletion is accelerated in spring and summer (Hartmann et al. 2000) and trends become especially apparent during the December to May period (Thompson and Solomon 2002; Arblaster and Meehl 2006). Other studies also implicate enhanced greenhouse gas forcing, as the observed circulation changes also occur in simulations forced solely by increases in atmospheric greenhouse gases (e.g., Fyfe et al. 1999; Kushner et al. 2001; Cai et al. 2003).

The trends in the Southern Hemisphere circulation

Corresponding author address: Caroline Ummenhofer, Climate Change Research Centre, University of New South Wales, Sydney, NSW 2052, Australia.
E-mail: c.ummehofer@unsw.edu.au

can be understood, in large part, as a shift toward the high-index positive phase of the southern annular mode (SAM) (Marshall 2003; Renwick 2004). The SAM is the leading mode of variability in the extratropical Southern Hemisphere, explaining around 47% of the natural variability of zonal-mean geopotential height for 1000–50 hPa south of 20°S (Thompson and Wallace 2000). The SAM represents a redistribution of mass between the polar latitudes south of 60°S and the midlatitudes centered around 45°S and results in an out-of-phase modulation in the easterly and westerly wind field centered at 35° and 60°S, respectively (Thompson et al. 2000; Sen Gupta and England 2006). The trend in the SAM has been widely documented in observations (Jones and Widmann 2003; Marshall 2003; Jones and Widmann 2004; Marshall et al. 2004), reanalyses (Marshall 2003), and proxy records (Jones and Widmann 2003). As described above, trends in the SAM have been linked to both increases in greenhouse gases and stratospheric ozone depletion (Thompson and Solomon 2002; Gillett and Thompson 2003). Ensembles of twentieth-century simulations applying both natural and anthropogenic forcings confirm that natural variability in itself cannot account for the observed trends (Arblaster and Meehl 2006). Experiments with coupled climate models extending into the twenty-first-century project that this trend will continue under further increases in greenhouse gases (Fyfe et al. 1999; Kushner et al. 2001) with possible consequences for midlatitude winds, ocean currents (Cai et al. 2005a; Cai 2006; Fyfe 2006), and precipitation (e.g., Cai et al. 2005b).

With the SAM trending toward a more positive phase, atmospheric circulation changes also affect climate conditions over midlatitudes, including South Africa (Reason and Roualt 2005), Australia (Cai et al. 2005b; Cai and Cowan 2006; Hendon et al. 2007; Meneghini et al. 2007), and South America (Silvestri and Vera 2003). Ummenhofer and England (2007) recently demonstrated that a positive-index SAM is associated with anomalously dry conditions in parts of New Zealand. It is therefore of interest to also analyze the trend in New Zealand precipitation over the past few decades and investigate how much of this can be accounted for by different Southern Hemisphere climate modes, in particular the SAM, but also ENSO.

ENSO has been implicated in various changes to the Southern Hemisphere climate (e.g., Diaz et al. 2001). Over the period 1861–1992, Vecchi et al. (2006) describe a weakening of the observed tropical atmospheric circulation across the Pacific Ocean, consistent with theoretical predictions for enhanced greenhouse forcing and reproduced by model simulations incorporating both natural and anthropogenic forcings. Varia-

tions in the zonal atmospheric overturning in the tropical Pacific, that is, the Walker circulation, are closely linked to ENSO (Vecchi et al. 2006); thus, changes in the Walker circulation could impact on the frequency and strength of El Niño and La Niña events. For 1977–2006, Power and Smith (2007) describe a period of unprecedented El Niño dominance with the lowest 30-yr average value on record of the June–December Southern Oscillation index (SOI). This coincides with the highest SST and weakest surface wind stresses on record in the equatorial Pacific, all indicative of a weakening of the Walker circulation. Fedorov and Philander (2000) demonstrate a recent increase in the frequency of El Niño events compared to paleoclimate records that they suggest might be due to global warming. Similarly, Verdon and Franks (2006) find El Niño events to be more frequent during warmer periods, taken from a 400-yr paleoclimate record. In a climate model forced by future greenhouse warming, Timmermann et al. (1999) show a more frequent occurrence of El Niño-like conditions, but also stronger cold events in the equatorial Pacific. In a multimodel intercomparison, Guilyardi (2006) finds an enhanced El Niño amplitude with increasing greenhouse forcing, though changes in the frequency are much less consistent across the models. Changes in the El Niño frequency and amplitude are believed to contribute to trends in the regional atmospheric circulation, for example to the migration of the South Pacific convergence zone (Juillet-Leclerc et al. 2006).

Salinger and Griffiths (2001) investigated southwest Pacific climate trends for the period 1861–1990 and discovered inconsistent precipitation trends for different decades during the second half of the twentieth century. They suggest that the major twentieth-century changes in atmospheric circulation across the New Zealand region occurred around 1950 and 1976. They found more anomalous southerly/southwesterly airflow during the period 1930–50, followed by anomalously easterly/northeasterly flow between 1951 and 1975, and then westerly/southwesterly airflow anomalies again during 1976–98, with a strengthened tropical anticyclonic belt over northern New Zealand. During 1930–50, Salinger and Mullan (1999) found conditions to be wetter in the northeastern part of the South Island, drier in the north and west of the South Island, and cooler over the entire country. The period 1951–75 was warmer throughout, wetter in the north of the North Island and drier in the southeast of the South Island. During the latest period of heightened westerly airflow (1976–98), precipitation has increased for much of the South Island, while it has decreased in the north of the North Island. Hence, trends in New Zealand precipita-

tion over the South Island seem to be associated with changes in the incidence of westerlies, which Salinger and Mullan (1999) attribute to a recent increased frequency of El Niño events. Via modulations of tropical eastern Pacific SST, ENSO was also found to be well correlated with New Zealand surface air temperatures on annual to decadal time scales (Folland and Salinger 1995). Despite these studies, large-scale twentieth-century changes in the atmospheric circulation of the Southern Hemisphere and their link to New Zealand precipitation trends have not been examined in great detail.

On seasonal to interannual time scales, New Zealand precipitation appears to be modulated by the SAM (Clare et al. 2002; Renwick and Thompson 2006), ENSO (Fitzharris et al. 1997; Kidson and Renwick 2002), and the Interdecadal Pacific Oscillation (IPO) (Salinger et al. 2001). Renwick and Thompson (2006) link the positive (negative) phase of the SAM to below (above) average daily rainfall and warm (cold) maximum daily temperature anomalies over western regions of the South Island of New Zealand. The associations between the SAM, ENSO, and interannual variations in New Zealand precipitation are described in detail by Ummenhofer and England (2007). That study focused on understanding links between New Zealand precipitation and the SAM and ENSO on interannual time scales for the period 1960–2004, using observations, reanalysis data, and output from a multicentury climate model simulation. In this follow-up study, we aim to determine if processes and mechanisms influencing New Zealand precipitation on these shorter interannual time scales can also account for the long-term trends. In the previous study, Ummenhofer and England (2007) found some suggestion of small differences in New Zealand precipitation between opposite phases of the SAM, but large-scale circulation patterns across the region showed a linear response. Therefore, our analysis technique here, which assumes linearity between positive and negative phases of the SAM, seems warranted. To our knowledge, this is the first study to *quantify* the contribution of changes in the large-scale Southern Hemisphere climate modes toward recent New Zealand precipitation trends.

The remainder of the paper is structured as follows: section 2 describes the datasets used, both observations and reanalysis. The results in section 3 cover a breakpoint analysis of seasonal New Zealand precipitation (section 3a), an analysis of seasonal precipitation trends (section 3b), an assessment of the links between precipitation trends and the climate modes ENSO and SAM (section 3c), and an evaluation of the precipitation trends corresponding to the dominant precipitation

modes (section 3d). Associations between different climate modes and the Southern Hemisphere circulation are presented in section 3e. The final section includes a discussion and a summary of the major findings of this study.

2. Observational and reanalysis data

The New Zealand precipitation dataset analyzed in this study is from the National Institute of Water and Atmospheric Research (NIWA) Climate Database. It comprises daily New Zealand station data that has been interpolated to give a gridded dataset with a 0.05° latitude–longitude (approximately 5 km) resolution for the entire country. Tait et al. (2006) describe the data and method of thin-plate smoothing spline interpolation used for the gridded product. For further information see also http://www.niwa.co.nz/ncc/tools/mapping/other_products. The daily gridded precipitation data for the period 1960–2006 is converted to seasonal averages.

The data for regional and large-scale analysis of atmospheric parameters, such as SLP and surface winds, is from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis project (Kalnay et al. 1996; Kistler et al. 2001). The NCEP–NCAR reanalysis (NNR) assimilates land- and ocean-based observations and satellite measurements and, by employing a global spectral model, generates a dataset with global coverage for a wide set of climatic parameters with a T62 horizontal resolution (approximately 2° latitude–longitude) covering the period 1948 to the present day. However, we focus our analyses on seasonal data for the more recent period 1979–2006, after the establishment of satellite records. Problems regarding data coverage and quality in the high latitudes of the Southern Hemisphere prior to 1979 have been documented in several studies particularly for daily fields (e.g., Hines et al. 2000; Marshall and Harangozo 2000; Kistler et al. 2001; Marshall 2002, 2003; Renwick 2004). However, after 1979 on monthly to interannual time scales, the NNR fields are in overall good agreement with observations (Hines et al. 2000; Kistler et al. 2001). Our analyses focus on the austral summer season, December–February (DJF) post-1979, when the skill of the NNR over the Southern Hemisphere high latitudes is much improved over the winter season, June–August (JJA), and, in fact, comparable to the skill over continental areas with denser observational networks during winter (Bromwich and Fogt 2004). Bromwich and Fogt (2004) do, however, demonstrate superior skill and reliability in the European Centre for Medium-Range

Weather Forecasts (ECMWF) 40-yr Re-Analysis (ERA-40) (Uppala et al. 2005) compared to NNR. To check the robustness of our results obtained with the NNR data, we repeat key analyses with the ERA-40 data for the overlapping period 1979–2001. The two reanalysis products produce very similar results, and consequently we only present analyses from the longer NNR dataset, but refer to ERA-40 where appropriate. Monthly SST for 1979–2006 is obtained from the extended reconstructed dataset developed by the National Oceanic and Atmospheric Administration with a 2° latitude–longitude resolution. Smith and Reynolds (2003, 2004) describe the techniques and details for the construction of this historical SST dataset.

The monthly SAM index used is available at <http://www.nerc-bas.ac.uk/icd/gjma/sam.html> and described by Marshall (2003). It is based on mean SLP observations at 12 stations, with anomalies calculated relative to the 1971–2000 period, approximating the SAM definition of Gong and Wang (1999). The monthly ENSO index is based on the SOI, calculated as the difference in standardized SLP between Tahiti and Darwin, provided by the NOAA Climate Prediction Center (<http://www.cpc.ncep.noaa.gov/data/indices/soi>). The SOI is used as an indication of ENSO variability, as we focus on changes in the general atmospheric circulation most appropriately represented by an atmospheric, not oceanic, index.

3. Results

a. Breakpoint analysis

The period 1979–2006 is chosen in this study to ensure data quality, as the extratropical Southern Hemisphere suffers from sparse data coverage prior to the satellite era. To further check that this period is also appropriate for investigating linear New Zealand precipitation trends, we perform a breakpoint analysis of seasonally averaged precipitation data over the country for the period 1960–2006. Seasonal averages of precipitation are calculated for the gridded data with the long-term monthly cycle removed. The breakpoint analysis performs a bilinear regression at each grid point (the two lines are not constrained to be continuous at the breakpoint). The breakpoint is defined as the year with the minimum least squares error. A t test is performed to assess the significance of a particular breakpoint. A breakpoint is only regarded as significant if both the trend before and after the breakpoint differs significantly (at the 95% confidence level) from the trend of the entire time series (i.e., with no breakpoint).

The breakpoint analysis of New Zealand precipita-

tion trends reveals very different patterns for the four seasons (Fig. 1). During the DJF season much of the mountainous west coast of the South Island experiences a significant breakpoint in the mid to late 1970s (Fig. 1a). This is in accordance with results of Salinger and Mullan (1999) and Salinger and Griffiths (2001), who describe a change in the predominant zonal airflow over the country in the mid-1970s, while Salinger et al. (1995) find these local changes to be part of large-scale trends affecting the entire southwest Pacific region. No other spatially consistent breakpoints are found for DJF. All other seasons show high spatial and temporal heterogeneity for significant breakpoints (Figs. 1b–d). Locally, some regions along the east coast of the South Island indicate a breakpoint in the mid-1970s for the JJA and September–November (SON) seasons (Fig. 1c, d), possibly related to the change in zonal flow regime mentioned above. Overall, the breakpoint analysis reveals large areas of significance for the mid to late 1970s, locally some early breakpoints in the 1960s, but no substantial areas with breakpoints post-1980. This provides further justification for using linear analysis techniques and for limiting our study to the 1979–2006 period and to the DJF season.

b. Precipitation trends

Following results from the breakpoint analysis, trends in New Zealand precipitation are stratified by season and their significance determined with a t test for the period 1979–2006. Over the past three decades, New Zealand has undergone considerable changes in precipitation, shown for the four different seasons in Fig. 2 (shown as a percentage change). Across all four seasons, a general trend toward drier conditions is observed, especially pronounced over the west coast of the South Island during DJF (up to $2\% \text{ yr}^{-1}$ drier), for the South Island east coast during March–May (MAM) and JJA ($1\%–3\% \text{ yr}^{-1}$ drier), and over the North Island during MAM ($1\%–3\% \text{ yr}^{-1}$ drier). Negative trends in North Island autumn rainfall are consistent with Salinger and Mullan (1999) for their analysis period of 1976–94. However, they find both summer and winter trends considerably wetter for the west coast of the South Island, while our results indicate a very small area there with a positive trend in precipitation for MAM, JJA, and SON with no significant positive trend for DJF. By restricting our analyses to the shorter time period 1979–94, similar to Salinger and Mullan (1999), the wetter conditions along the South Island west coast during JJA become more prominent, agreeing with their findings. The southern half of the North Island is the only extensive region of New Zealand with a posi-

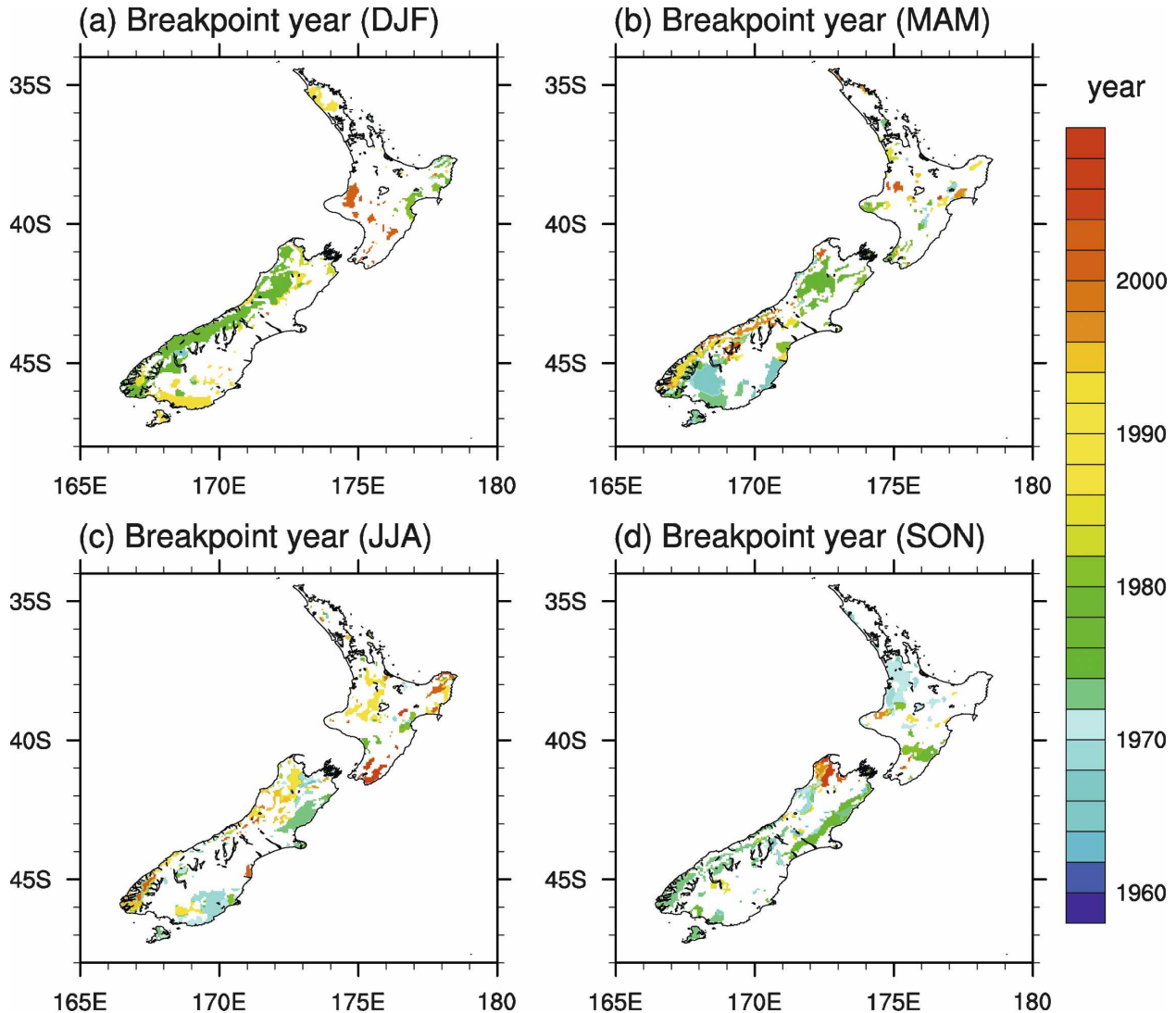


FIG. 1. Year of breakpoint analysis for New Zealand precipitation for the seasons (a) DJF, (b) MAM, (c) JJA, and (d) SON over the period 1960–2006. Values are only color shaded where the breakpoint is significant at the 95% confidence level.

tive precipitation trend (up to $2\% \text{ yr}^{-1}$ wetter), but only during the SON season (Fig. 2d).

The magnitude of these precipitation trends is considerable: for example, over the 27-yr period a drop in precipitation is observed of more than 400 mm overall for much of the South Island during the DJF season. Considering an area average of 2085 mm yr^{-1} across the South Island (Ummenhofer and England 2007), a drop of 400 mm for the DJF season is considerable. For example, this signifies a 40% reduction in precipitation along the high-rainfall region along the west coast. It is therefore of interest to explore the mechanism(s) for the observed long-term trends in New Zealand precipitation. DJF precipitation shows a continuous and significant trend after the mid-1970s. In addition, the trend

in the SAM is only significant in DJF, and the ENSO trend (while not significant at the 90% confidence level) is greatest in the austral summer. As a result we focus our remaining analyses on the trends during the DJF season.

c. Precipitation trends linked to SAM and ENSO

An attempt is made here to explain and quantify the trends in New Zealand precipitation in relation to long-term changes in the large-scale modes of climate variability. The method used follows that of Thompson et al. (2000), who related trends in the Northern Hemisphere extratropical circulation to the northern annular mode. Owing to the short and sparse record of high quality data in the Southern Hemisphere, Thompson et

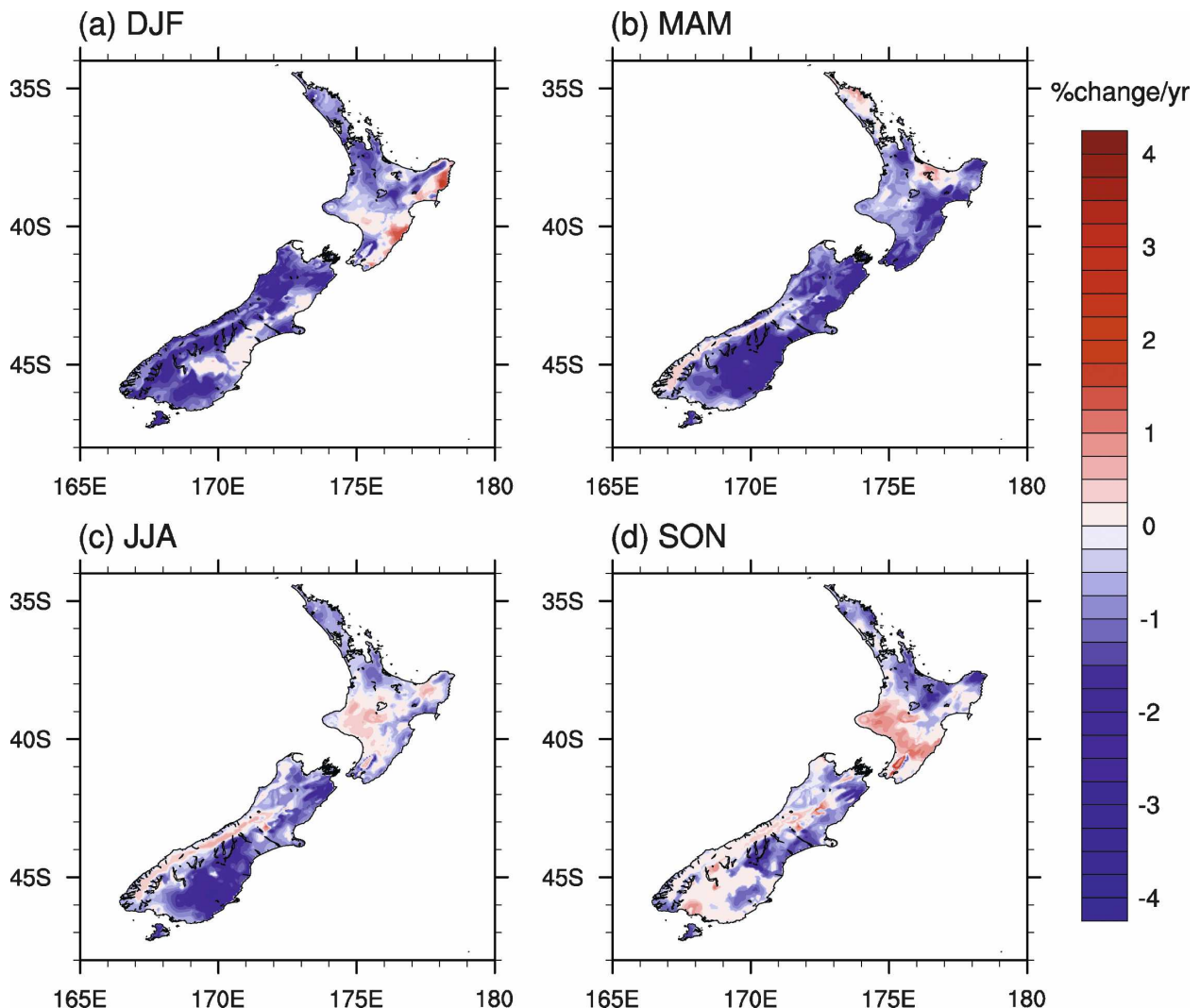


FIG. 2. Monthly precipitation trends (significant at the 90% confidence level) for New Zealand for the seasons (a) DJF, (b) MAM, (c) JJA, and (d) SON averaged over the period 1979–2006 (values are shown as a percentage change per year).

al. (2000). did not attempt the same analysis here. In this present work we are now able to extend their data record by 10 years.

The method divides the observed precipitation trend into a component that is linearly congruent with a specific time series (e.g., the SAM index) and a residual component that is linearly independent of the index. The linearly congruent component is calculated as the regression coefficient of the standardized and detrended index onto precipitation anomalies (mean, trend, and seasonal cycle removed) multiplied by the previously removed trend in the index. The fraction of the observed precipitation trend attributable to the index is derived by dividing the component of the trend that is linearly congruent with the index by the overall observed precipitation trend. To avoid artificially high

values (resulting when the observed trend is small), fractions are only calculated for those grid points where the observed precipitation trend is significant (at the 90% confidence level). The respective contributions of the SAM and SOI to New Zealand precipitation trends are quantified for the DJF season over the period 1979–2006 in this way.

Recent changes in the extratropical Southern Hemisphere atmospheric circulation have been widely documented (e.g., Salinger et al. 1995; Kushner et al. 2001; Thompson and Solomon 2002; Fyfe 2003; Gillett and Thompson 2003; Marshall et al. 2004; Renwick 2004; Cai et al. 2006; Cai 2006) and partially linked to trends in the SAM (e.g., Kushner et al. 2001; Thompson and Solomon 2002; Gillett and Thompson 2003; Marshall et al. 2004). These trends in the SAM are strongest during

austral summer (e.g., Thompson et al. 2000; Thompson and Solomon 2002). Figure 3a shows the time series of the SAM averaged for the DJF season with a trend of 0.048 standard deviation (SD) month⁻¹ in the SAM index (significant at the 90% confidence level) over the period 1979–2006. The regression of precipitation onto the SAM time series is presented in Fig. 3c. The SAM is associated with below-average precipitation (Gillett et al. 2006)—in excess of 50 mm month⁻¹ for a one SD positive SAM index—along the western and southern regions of both islands (Fig. 3c). In contrast, the eastern edges of the two islands experience wetter conditions. These findings are consistent with earlier studies on daily to interannual time scales (Renwick and Thompson 2006; Ummenhofer and England 2007). This out-of-phase relationship between eastern and western regions of New Zealand is noted by Salinger et al. (1995) and linked to the interaction of the regional circulation, that is, strength in the prevailing westerlies and frequency of blocking anticyclones east of New Zealand, with the generally north–south aligned orography. During the positive phase of the SAM, easterly airflow anomalies over the country lead to a less frequent passage of rain-bearing fronts and depressions, and increased anticyclonic blocking east of New Zealand, resulting in reduced (increased) precipitation in the west (east) of the country. The situation is reversed during the negative phase of the SAM. Rao et al. (2003) link interannual variations in midlatitude storm tracks to the SAM. For the latitude band 30°–40°S in the New Zealand sector, Rao et al. (2003) show the positive phase of the SAM to be associated with decreased zonal wind shear, increased baroclinic stability, and lowered Eady growth rate during DJF. Each of these factors aid in explaining the reduced precipitation along the western regions of both islands of New Zealand during the positive phase of the SAM (Fig. 3c). The trend in the SAM could thus potentially account for a good proportion of the precipitation trends over New Zealand, especially over the North Island where in some regions more than 80% of the precipitation trend is consistent with the SAM (Fig. 3e). For the South Island, the SAM trend is congruent with increasingly drier conditions over the mountainous western regions. However, only 30%–60% of the precipitation trend there is accounted for by the SAM.

The tropical circulation across the Pacific Ocean region has sustained considerable changes over recent decades (e.g., Fedorov and Philander 2000; Vecchi et al. 2006; Power and Smith 2007; Vecchi and Soden 2007). Recent and future changes to ENSO frequency and amplitude are still debated (e.g., Guilyardi 2006), and trends in different ENSO indices are only at most mar-

ginally significant, dependent on season and study period. Despite these ambiguities, it is still of value to assess the contribution of changes in ENSO to New Zealand precipitation trends (see Figs. 3b,d,f). During the DJF season the SOI indicates a nonsignificant positive trend of 0.044 SD month⁻¹ (Fig. 3b). As El Niño events are associated with the negative SOI phase, a significant positive trend in the SOI would indicate a decrease in El Niño incidence. Despite the fact that the trend in the SOI is not distinguishable from zero, we retain the analysis to allow a comparison with the results of the EOF analysis. The positive phase of the SOI is associated with mostly wetter conditions across the northern regions of the North Island, with precipitation in excess of 20 mm month⁻¹ above normal (Fig. 3d, see also Salinger et al. 1995). Reduced precipitation occurs over the entire mountainous west coast of the South Island (Ummenhofer and England 2007). The fraction of observed precipitation trends congruent with the SOI is highest for the east coast of the North Island (Fig. 3f). The contribution of the SOI trend to the South Island drying along the west coast does not generally exceed 20% of the observed trend.

In summary, changes in New Zealand precipitation could be partially accounted for by trends in the Southern Hemisphere climate modes, the SAM and ENSO. However, there still remain considerable areas over which the magnitude of the observed precipitation trends cannot be explained by these climate modes. To explore the mechanism(s) responsible for the New Zealand precipitation trends not sufficiently explained by the SAM and ENSO, we now examine the leading modes of variability in New Zealand precipitation, their trends, and their associations with the general atmospheric circulation.

d. Precipitation trends linked to dominant New Zealand precipitation modes

To investigate the leading modes of variability in New Zealand precipitation an EOF analysis (using a covariance matrix) is performed on the gridded seasonal DJF precipitation anomalies. The anomalies were weighted prior to analysis to account for the smaller surface area of grid boxes at higher latitudes. Figure 4 shows the principal component (PC) time series of the first two EOF modes, the regression of New Zealand DJF precipitation onto the PCs, and their respective contribution to precipitation trends. Unlike a composite analysis, which highlights nonlinearity between positive and negative phases, an EOF analysis assumes linearity as there is only a sign difference between positive and negative events. If not otherwise stated, we always

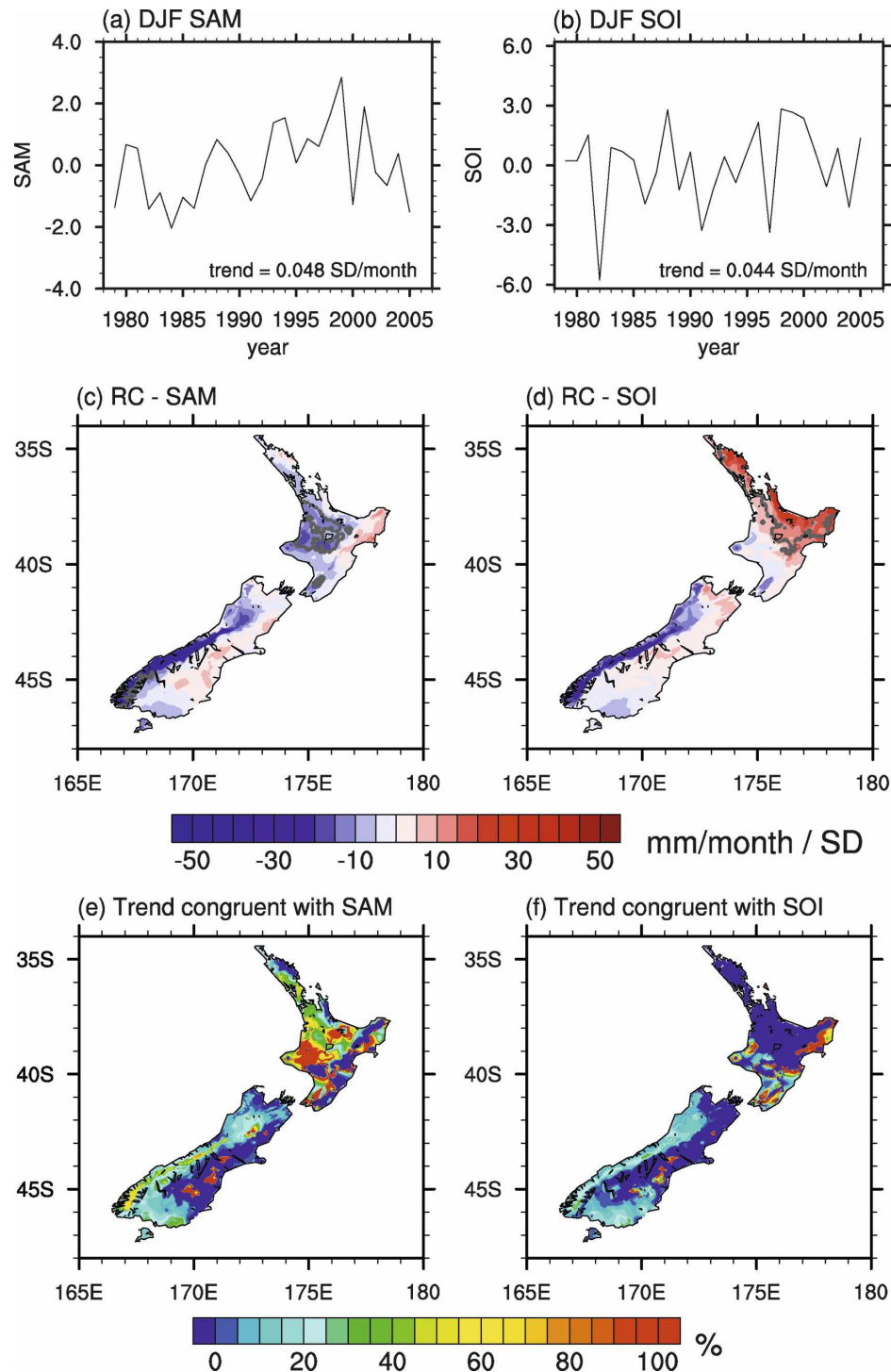


FIG. 3. Time series of the (a) SAM and (b) SOI for the DJF season for the period 1979–2006 (with the year given for the first month in the summer season). Regression of the (c) SAM and (d) SOI onto New Zealand precipitation for the DJF season, with gray dashed lines indicating significant regression coefficients at the 95% confidence level as estimated after Sciremammano (1979); DJF trends in New Zealand precipitation linearly congruent with the (e) SAM and (f) SOI, averaged over the period 1979–2006 as a fraction of the monthly DJF precipitation trend. The fractions were only calculated for those grid points in which the DJF precipitation trend was significant at the 90% confidence level. The average monthly DJF trends (in SD per month) in the SAM and SOI time series are indicated at the bottom right of (a) and (b).

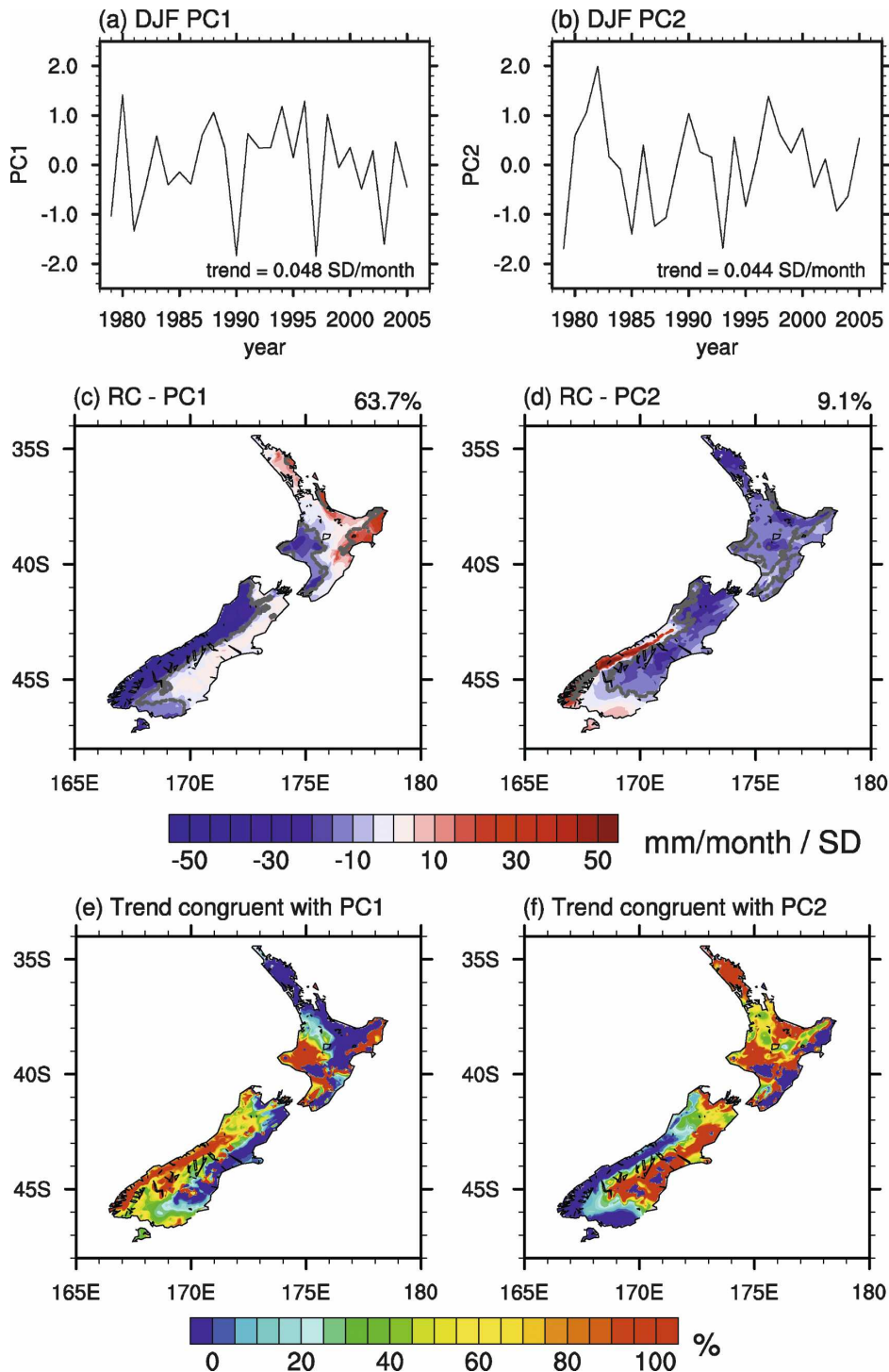


FIG. 4. As in Fig. 3 but for (a), (c), and (e) PC1 and (b), (d), and (f) PC2. The fraction of overall variability explained by EOF1 and EOF2 is indicated at the top of (c) and (d).

refer to the positive phase when describing the resulting EOF patterns.

The standardized time series of PC1 of DJF precipitation shows a positive trend of $0.048 \text{ SD month}^{-1}$, sig-

nificant at the 97% level (Fig. 4a). The regression of detrended New Zealand precipitation onto the detrended PC1 time series represents the first EOF mode, which explains approximately 64% of the observed pre-

precipitation variability during DJF (Fig. 4c). EOF1 is characterized by drier conditions (in excess of 50 mm month⁻¹ drier) over much of the western and southern regions of New Zealand (Fig. 4c). In contrast, significantly more rainfall occurs for the coastal regions in the northeast of the North Island. This pattern closely resembles the leading mode (based on rotated principal component analysis) of monthly New Zealand precipitation station data for the period 1951–75 described by Salinger (1980), although his sign convention is reversed to that used here. The positive phase shown in Fig. 4c is characterized by a weakening of the zonal circulation with a less frequent passage of eastward-moving wave depressions, influenced by a reduced north–south pressure gradient over New Zealand (Salinger 1980). The out-of-phase relationship between the southwest and northeast regions of the two islands seen in Fig. 4c is reminiscent of the projection of New Zealand precipitation onto the SAM (Fig. 3c). However, the time series of SAM and PC1 are not significantly correlated (correlation coefficient of 0.29, which is not significant at the 90% level) during DJF. The trend in PC1 can almost completely account for the observed drier conditions along the west coast of the South Island, and the southwestern regions of the North Island, during austral summer (Fig. 4e).

The time series of PC2 also has a significant (at 95% confidence level) positive trend of 0.044 SD month⁻¹ (Fig. 4b). EOF2, explaining 9% of the variability, shows drier conditions for much of the country, with precipitation up to 50 mm month⁻¹ below normal (Fig. 4d). This is especially apparent over the North Island and northern and eastern regions of the South Island. Increases in precipitation are only observed for the mountainous southwestern corner of the South Island. The precipitation distribution associated with the positive phase of EOF2 resembles the pattern linked to El Niño events by Ummenhofer and England (2007). This pattern is due to increased southwesterly airflow over the country (see also Kidson and Renwick 2002; Waugh et al. 1997), which Salinger and Griffiths (2001) link to increased frequency of showery precipitation events. In contrast, the match with the regression pattern of the SOI (Fig. 3d) is rather poor, despite a significant correlation at the 90% level of the SOI and PC2 time series (correlation coefficient of -0.36). As an El Niño event is associated with the negative phase of the SOI, we would expect Figs. 3d and 4d to be mirror images. Trends in the PC2 time series can account for much of the negative precipitation trends over the North Island and eastern regions of the South Island (up to a 100% in places, Fig. 3f).

e. Climate modes and the Southern Hemisphere circulation

To associate the dominant modes of precipitation variability over New Zealand with the large-scale atmospheric circulation, SLP, winds, and SST anomalies are regressed onto the standardized and detrended SAM, SOI, PC1, and PC2 time series across the Australasian and surrounding region. Significance levels are estimated following the method of Sciremammano (1979).

The regression of SLP onto the SAM index is characterized by an increased meridional SLP gradient with a positive pressure anomaly at midlatitudes for 30°–55°S and reduced values over the polar regions south of 55°S (Fig. 5a) for a positive SAM phase (e.g., Gillett et al. 2006). The winds adjust to the changed SLP field and show a strengthening of the subpolar westerlies of up to 2 m s⁻¹ in the latitude band 50°–65°S and an easterly anomaly over 25°–40°S (Fig. 5c). More regionally, around New Zealand, the positive phase of the SAM is associated with increased easterly to northeasterly flow over the country, as shown also by Ummenhofer and England (2007). When using ERA-40 data instead of NNR, the area of significant easterly anomalies in the wind field across New Zealand is slightly reduced. The SST around New Zealand and across the Tasman Sea are negatively correlated with the SAM, as is the equatorial Pacific Ocean (Fig. 5e). These characteristic signals in SST associated with the SAM can be attributed to anomalous Ekman transport and heat fluxes due to the enhanced zonal wind anomalies (e.g., Hall and Visbeck 2002; Sen Gupta and England 2006).

Regressing SLP onto the SOI shows extensive negative anomalies over the Australasian region and Antarctica, while positive values extend over New Zealand and the southwestern Pacific Ocean (Fig. 5b). This regression can be interpreted as a one SD positive anomaly in the SOI, that is, corresponding to moderate La Niña conditions. The wind anomalies in Fig. 5d are predominantly easterly across the western equatorial Pacific, as expected, and easterly also over New Zealand (see also Mullan 1995; Waugh et al. 1997; Kidson and Renwick 2002; Ummenhofer and England 2007). As is widely known, a negative phase ENSO is associated with reduced SST along the equatorial central and eastern Pacific, while above-average SST occurs to the south and north in the Pacific as well as in the western warm pool region, as seen in Fig. 5f. In addition, positive SST anomalies are observed around New Zealand and in the Southern Ocean south of Australia.

In contrast to the regressions onto the SAM and ENSO time series, those related to PC1 and PC2 are

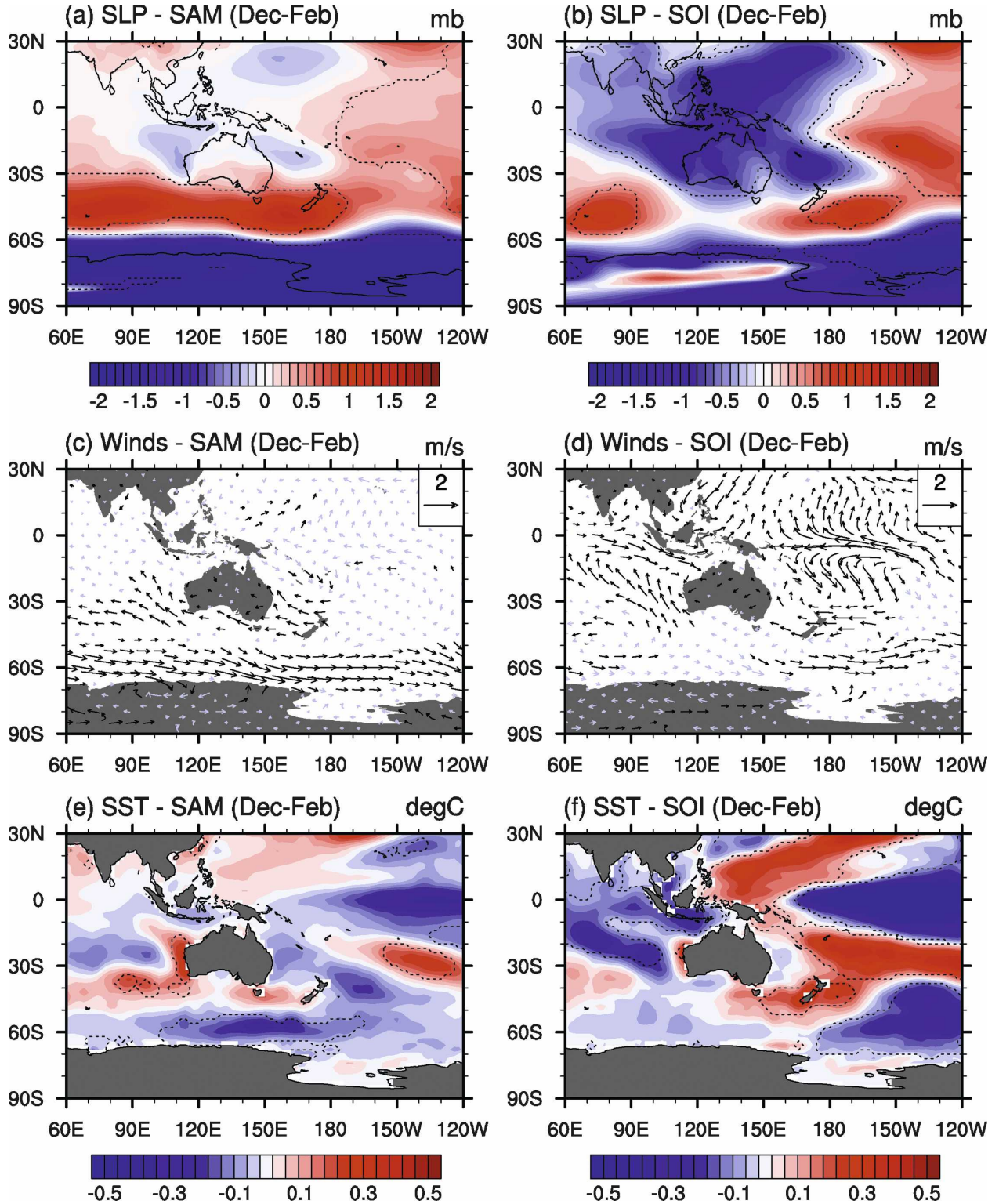


FIG. 5. Regression of the (left) SAM and (right) SOI time series for the period 1979–2006 onto (a), (b) SLP; (c), (d) winds; and (e), (f) SST. Dashed lines in (a), (b), (e), and (f) and black vectors in (c) and (d) indicate significant regression coefficients at the 95% confidence level, as estimated after Sciremammano (1979).

associated with a more local circulation anomalies. PC1 projects strongly onto an anomalously positive area of SLP across New Zealand, extending west to the Australian Bight and south to 60°S (Fig. 6a). Negative correlations between PC1 and SLP occur to the north of New Zealand and over parts of Antarctica. The adjustment of the wind to the region of positive SLP across and south of New Zealand seen for PC1 results in anomalous easterly airflow across the country and a strengthening of the subpolar westerlies for 120°E–160°W (Fig. 6c). The area of significantly increased subpolar westerlies is slightly smaller when using ERA-40 (figure not shown) as opposed to NNR data (shown in Fig. 6). This local wind anomaly pattern over New Zealand linked to PC1 is reminiscent of the one associated with a positive SAM phase (Fig. 5c). Salinger (1980) describes similar regional pressure and circulation anomalies associated with the leading mode of New Zealand precipitation, with a reduced north–south pressure gradient weakening westerly airflow over New Zealand, resulting in a less frequent passage of rain-bearing low pressure systems. This leads to reduced precipitation along western regions of both islands, while increased blocking east of New Zealand is responsible for wetter conditions over the east (Salinger 1980). PC1 is further associated with anomalously cold SST to the northeast of Australia across the Coral Sea, while above-average SST appears in the latitude band 40°–50°S south of Australia and New Zealand and across the Tasman Sea, although only parts of this regression are statistically significant (Fig. 6e). In contrast, PC2 shows a positive correlation with SLP for the Australasian region, while negative values are observed over the southwestern Pacific (Fig. 6b). This pattern bears close resemblance to the ENSO projection (Fig. 5b), though of opposite sign due to the negative nature of the SOI. However, the center is more intense and located more directly over New Zealand, while the negative center in the southwest Pacific is situated more to the southwest for PC2 than for ENSO. The predominant wind direction associated with PC2 is westerly (more southwesterly in ERA-40; figure not shown) across New Zealand, as previously suggested to be associated with a positive phase ENSO (cf. Fig. 5d) (Mullan 1995; Waugh et al. 1997; Kidson and Renwick 2002; Ummenhofer and England 2007). Salinger and Griffiths (2001) ascribe an increased frequency of rain-producing synoptic disturbances and showers to such an enhanced westerly circulation regime, consistent with the precipitation pattern (Fig. 4d). In addition, the regression of PC2 onto SST (Fig. 6f) closely mirrors the ENSO projection (Fig. 5f).

The regression of different climate variables onto the

four time series—namely, ENSO, SAM, PC1, and PC2—further demonstrates that the SAM and PC1 and ENSO and PC2 show many similarities. The SAM, trending toward its positive phase, with an increased meridional SLP gradient and a coinciding strengthening and southerly shift in the westerlies, is thus able to explain some of the negative precipitation trends over much of New Zealand (seen already in Fig. 3e). In fact, over New Zealand the signature in the wind field linked to PC1 (Fig. 6c; with PC1 explaining 64% of the observed precipitation variability including the prominent west coast precipitation trends as seen in Fig. 4c,e) closely resembles circulation changes expected under a SAM trend toward a more positive phase. While over New Zealand the circulation anomalies associated with PC1 are locally consistent with an increasingly positive SAM: this is not the case on a larger scale across the Southern Hemisphere.

To further investigate this discrepancy, a “direct” SLP-derived SAM index is computed for the Australian–New Zealand sector only. The use of a regional index is warranted on two counts: First, there exists substantial zonal asymmetry in the spatial structure of the SAM (e.g., Codron 2005, 2007). Secondly, the mid-latitude synoptic systems that form the building blocks of the mode will not be temporarily coherent at all latitudes. This type of “regional” SAM index has been used in previous studies (e.g., Meneghini et al. 2007). The index is computed as the difference between zonally averaged SLP centered at 45°S and at 65°S for the regional domain 140°E–160°W. This definition of a “direct” index follows the approach used by Marshall (2003) and Gong and Wang (1999) for their SAM index, but using NNR SLP for the DJF season over the period 1979–2006. Unlike Marshall, who employs SLP station data at 40° and 65°S, we use SLP centered at 45° and 60°S here as this provides an improved correlation with the global SAM index. This is due to a slight southward shift in the maximum correlation of SLP with the SAM index over the New Zealand sector, with the highest correlation centered near 45°S (cf. Fig. 5a). We also calculate a similar direct index using global zonal averages. This global direct index is strongly correlated with the Marshall (2003) index ($r = 0.91$, significant at the 99% confidence level). The direct regional SAM index is also strongly correlated with both the direct global index ($r = 0.79$) and the Marshall index ($r = 0.76$), all significant at the 99% confidence level. The EOF-based SAM pattern is annular in part by virtue of the statistical technique used to define it. The SAM actually comes about as a result of synoptic systems with a circumpolar distribution in the midlatitudes that are not necessarily temporally correlated. As such, a

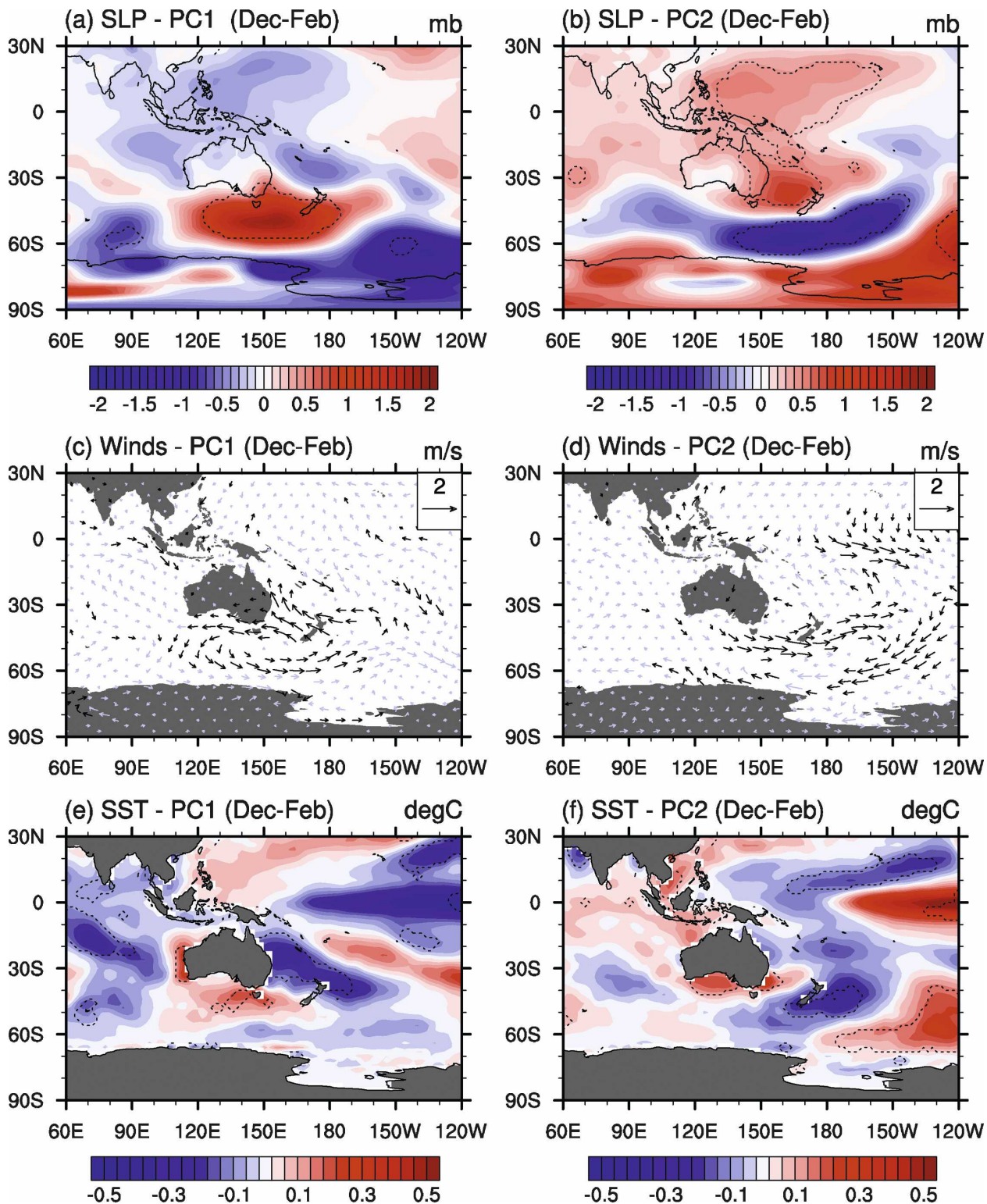


FIG. 6. As in Fig. 5, but of the (left) PC1 and (right) PC2 time series.

regional index, while based on a subdomain of the actual SAM, will highlight local circulation features and will have a stronger relationship to local impacts such as New Zealand precipitation. Therefore, key analyses in the study are repeated with this regional SAM index. All of the new results obtained indicate that the regional SAM index can explain a much higher proportion of the New Zealand precipitation trends (i.e., in excess of 60% almost everywhere) compared to the traditional SAM index (figures not shown). The regional SAM index also shows features closely related to PC1 and, indeed, the two indices are significantly correlated ($r = 0.36$, significant at the 90% confidence level). This further corroborates the conclusion that PC1 represents a regional manifestation in the atmospheric circulation of the large-scale SAM. As such, differences between the Southern Hemisphere atmospheric response to the large-scale SAM (Fig. 5) and to PC1 (Fig. 6) can be understood as a hemisphere-wide phenomenon versus its regional manifestation in the local circulation. The regional SAM index resolves this discrepancy, as it highlights local features and thus bridges the gap between a hemisphere-wide index and its direct local impact.

4. Discussion and conclusions

We have investigated how trends in New Zealand precipitation over the period 1979–2006 might be linked to, and explained by, recent changes in the large-scale atmospheric circulation of the Southern Hemisphere. Results of the breakpoint analysis (Fig. 1) seem to support a regime shift over New Zealand in the mid-1970s, with a change from predominantly easterly/northeasterly to westerly/southwesterly airflow (Salinger and Mullan 1999; Salinger and Griffiths 2001), affecting the country's precipitation. Increasingly drier conditions across much of New Zealand during austral summer since 1979 (Fig. 2) are, in large part, consistent with recent trends in ENSO and the SAM (Fig. 3). In particular, over the North Island in excess of 80% and over western regions of the South Island 30%–60% of the negative trends in precipitation can be accounted for by the SAM. This compares with large areas in the west of both islands with more than 80% of the recent DJF drying being consistent with trends in the leading mode of New Zealand rainfall, which we show has features typical of a *regional* manifestation of the SAM. The contribution of ENSO to these drying trends is of considerably smaller magnitude, especially when considering the uncertainties associated with recent changes in ENSO behavior.

During the period 1976–98 westerly and southwest-

erly airflow anomalies dominated over New Zealand (Salinger and Griffiths 2001) and were associated with increased frequency of El Niño events (Salinger and Mullan 1999). Increased westerly airflow over the country is a feature at odds with a trend toward the positive-index phase of the SAM. A positive phase in the SAM would normally be associated with predominantly easterly to northeasterly wind anomalies over New Zealand (Fig. 5c) and drier conditions for western regions of both islands (Fig. 3c) (Ummenhofer and England 2007). Considering the observed trends in New Zealand precipitation (Fig. 2), at least during austral summer and autumn when changes in the SAM are maximal (Thompson and Solomon 2002; Arblaster and Meehl 2006), the SAM's effect appears to dominate with widespread drying. The apparent contradiction in zonal flow anomaly by Salinger and Griffiths (2001) and Salinger and Mullan (1999) with the present work might be due to differences in the data (daily/monthly station data versus gridded precipitation data used here), the different study periods, and/or our focus on the DJF season. Decadal variations in the SAM's influence, both on long-term trends and on seasonal to interannual time scales, can also not be excluded so that the exact contribution of the SAM to trends might be dependent on the time period being investigated. The sparse data record prior to 1979 in the Southern Hemisphere makes it difficult to extend these analyses further back in time, at least based on observation/reanalysis data. Jones and Widmann (2003) find the SAM index, estimated and reconstructed from tree rings and station-based data for the past century, to vary in its influence on the general atmospheric circulation over the New Zealand region on decadal to multidecadal time scales. They suggest that the SAM strongly modulates the circulation during the period 1930–75, while its impact is weaker for the period 1976–94.

In addition, considering New Zealand's rich orography and its interaction with the atmospheric flow, local modulation of large-scale circulation changes can be expected. However, when looking at the relatively close match of Figs. 5 and 6 and the findings related to the regional SAM index, local variations seem to be aligned fairly well with more broad features of the large-scale changes. The upward trend in the SAM is not mirrored by increasing frequency of dry years for the two New Zealand islands for the period 1960–2004 (Ummenhofer and England 2007). This could be due to opposing precipitation trends for the western and eastern regions of the islands. In contrast, for the North Island over the last few decades, both a more positive SAM and an increased frequency of El Niño events (Salinger and Griffiths 2001) potentially act in concert toward

overall drier conditions for the entire island, a feature already apparent in the multidecadal precipitation decline of -8.13 mm yr^{-1} averaged over the North Island (Ummenhofer and England 2007).

Changes in precipitation in other regions of the Southern Hemisphere have recently been linked to trends in the SAM. For the DJF season trends in the SAM seem to contribute to wetter conditions over southeastern Australia during 1979–2005 (Hendon et al. 2007). For southwest Western Australia (SWWA) up to 70% of the recent observed decline in austral winter rainfall is found to be congruent with trends in the SAM (Cai and Cowan 2006). In contrast, Menneghini et al. (2007) suggest that the long-term trend in SWWA winter rainfall is not related to the SAM, while current short-term decreases in winter rainfall in southern South Australia, Tasmania, and Victoria are. Despite these possible contradictions, implications for water management are considerable, especially as climate model simulations for the twenty-first-century project continued upward trends in the SAM toward its high-index phase (Fyfe et al. 1999; Kushner et al. 2001). Thus, regions presently experiencing SAM-related precipitation changes are likely to be affected further. For New Zealand, this situation could be further exacerbated if precipitation trends due to the SAM and ENSO act in concert, as shown to be the case over the North Island of New Zealand in this study.

Acknowledgments. We thank the National Institute of Water and Atmospheric Research in New Zealand for providing the precipitation data set used in this study. Use of reanalysis data from the National Center for Atmospheric Research, jointly developed with the National Center for Environmental Prediction and provided through the NOAA Climate Diagnostics Center (<http://www.cdc.noaa.gov>), and the ERA-40 data by the European Centre for Medium-Range Weather Forecasts is gratefully acknowledged. We are grateful to Andrea Taschetto for help with some of the statistical analyses employed. The comments of three anonymous reviewers helped improve the original manuscript. CCU and ASG were supported by the University of New South Wales under a University International Postgraduate Award, and MHE was supported by the Australian Research Council.

REFERENCES

- Arblaster, J. M., and G. A. Meehl, 2006: Contributions of external forcings to southern annular mode trends. *J. Climate*, **19**, 2896–2905.
- Bromwich, D. H., and R. L. Fogt, 2004: Strong trends in the skill of the ERA-40 and NCEP–NCAR reanalyses in the high and midlatitudes of the Southern Hemisphere, 1958–2001. *J. Climate*, **17**, 4603–4619.
- Cai, W., 2006: Antarctic ozone depletion causes an intensification of the Southern Ocean super-gyre circulation. *Geophys. Res. Lett.*, **33**, L03712, doi:10.1029/2005GL024911.
- , and T. Cowan, 2006: SAM and regional rainfall in IPCC AR4 models: Can anthropogenic forcing account for southwest Western Australian winter rainfall reduction? *Geophys. Res. Lett.*, **33**, L24708, doi:10.1029/2006GL028037.
- , P. H. Whetton, and D. J. Karoly, 2003: The response of the Antarctic Oscillation to increasing and stabilized atmospheric CO_2 . *J. Climate*, **16**, 1525–1538.
- , G. Shi, T. Cowan, D. Bi, and J. Ribbe, 2005a: The response of the Southern Annular Mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. *Geophys. Res. Lett.*, **32**, L23706, doi:10.1029/2005GL024701.
- , —, and Y. Li, 2005b: Multidecadal fluctuations of winter rainfall over southwest Western Australia simulated in the CSIRO Mark 3 coupled model. *Geophys. Res. Lett.*, **32**, L12701, doi:10.1029/2005GL022712.
- , D. Bi, J. Church, T. Cowan, M. Dix, and L. Rotstayn, 2006: Pan-oceanic response to increasing anthropogenic aerosols: Impacts on the Southern Hemisphere oceanic circulation. *Geophys. Res. Lett.*, **33**, L21707, doi:10.1029/2006GL027513.
- Clare, G. R., B. B. Fitzharris, T. J. H. Chinn, and M. J. Salinger, 2002: Interannual variation in end-of-summer snowlines of the Southern Alps of New Zealand, and relationships with Southern Hemisphere atmospheric circulation and sea surface temperature patterns. *Int. J. Climatol.*, **22**, 107–120.
- Codron, F., 2005: Relation between annular modes and the mean state: Southern Hemisphere summer. *J. Climate*, **18**, 320–330.
- , 2007: Relations between annular modes and the mean state: Southern Hemisphere winter. *J. Atmos. Sci.*, **64**, 3328–3339.
- Diaz, H. F., M. P. Hoerling, and J. K. Eischeid, 2001: ENSO variability, teleconnections and climate change. *Int. J. Climatol.*, **21**, 1845–1862.
- Fedorov, A. V., and G. S. Philander, 2000: Is El Niño changing? *Science*, **288**, 1997–2002.
- Fitzharris, B. B., T. J. Chinn, and G. N. Lamont, 1997: Glacier balance fluctuations and atmospheric circulation patterns over the Southern Alps, New Zealand. *Int. J. Climatol.*, **17**, 745–763.
- Folland, C. K., and M. J. Salinger, 1995: Surface temperature trends and variations in New Zealand and the surrounding ocean, 1871–1993. *Int. J. Climatol.*, **15**, 1195–1218.
- Fyfe, J. C., 2003: Extratropical Southern Hemisphere cyclones: Harbingers of climate change? *J. Climate*, **16**, 2802–2805.
- , 2006: Southern Ocean warming due to human influence. *Geophys. Res. Lett.*, **33**, L19701, doi:10.1029/2006GL027247.
- , G. J. Boer, and G. M. Flato, 1999: The Arctic and Antarctic Oscillations and their projected changes under global warming. *Geophys. Res. Lett.*, **26** (11), 1601–1604.
- Gillett, N. P., and D. W. J. Thompson, 2003: Simulation of recent Southern Hemisphere climate change. *Science*, **302**, 273–275.
- , F. W. Zwiers, A. J. Weaver, and P. A. Stott, 2003: Detection of human influence on sea-level pressure. *Nature*, **422**, 292–294.
- , T. D. Kell, and P. D. Jones, 2006: Regional climate impacts of the Southern Annular Mode. *Geophys. Res. Lett.*, **33**, L23704, doi:10.1029/2006GL027721.
- Gong, D., and S. Wang, 1999: Definition of Antarctic Oscillation index. *Geophys. Res. Lett.*, **26** (4), 459–462.

- Guilyardi, E., 2006: El Niño–mean state–seasonal cycle interactions in a multi-model ensemble. *Climate Dyn.*, **26**, 329–348.
- Hall, A., and M. Visbeck, 2002: Synchronous variability in the Southern Hemisphere atmosphere, sea ice, and ocean resulting from the annular mode. *J. Climate*, **15**, 3043–3057.
- Hartmann, D. L., J. M. Wallace, V. Limpasuvan, D. W. J. Thompson, and J. R. Holton, 2000: Can ozone depletion and global warming interact to produce rapid climate change? *Proc. Natl. Acad. Sci. USA*, **97**, 1412–1417.
- Hendon, H. H., D. W. J. Thompson, and M. C. Wheeler, 2007: Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode. *J. Climate*, **20**, 2452–2467.
- Hines, K. M., D. H. Bromwich, and G. J. Marshall, 2000: Artificial surface pressure trends in the NCEP–NCAR reanalysis over the Southern Ocean and Antarctica. *J. Climate*, **13**, 3940–3952.
- Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. *Science*, **269**, 676–679.
- Jones, J. M., and M. Widmann, 2003: Instrument- and tree-ring-based estimates of the Antarctic Oscillation. *J. Climate*, **16**, 3511–3524.
- , and —, 2004: Early peak in Antarctic Oscillation index. *Nature*, **432**, 290–291.
- Juillet-Leclerc, A., S. Thiria, P. Naveau, T. Delcroix, N. Le Bec, D. Blamart, and T. Corrége, 2006: SPCZ migration and ENSO events during the 20th century as revealed by climate proxies from a Fiji coral. *Geophys. Res. Lett.*, **33**, L17710, doi:10.1029/2006GL025950.
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.
- Kidson, J. W., and J. A. Renwick, 2002: Patterns of convection in the tropical Pacific and their influence on New Zealand weather. *Int. J. Climatol.*, **22**, 151–174.
- Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.*, **82**, 247–267.
- Kushner, P. J., I. M. Held, and T. L. Delworth, 2001: Southern Hemisphere atmospheric circulation response to global warming. *J. Climate*, **14**, 2238–2249.
- Levitus, S., J. I. Antonov, T. P. Boyer, and C. Stephens, 2000: Warming of the world ocean. *Science*, **287**, 2225–2229.
- Marshall, G. J., 2002: Trends in Antarctic geopotential height and temperature: A comparison between radiosonde and NCEP–NCAR reanalysis data. *J. Climate*, **15**, 659–674.
- , 2003: Trends in the southern annular mode from observations and reanalyses. *J. Climate*, **16**, 4134–4143.
- , and S. A. Harangozo, 2000: An appraisal of NCEP/NCAR reanalysis MSLP data variability for climate studies in the South Pacific. *Geophys. Res. Lett.*, **27**, 3057–3060.
- , P. A. Stott, J. Turner, W. M. Connolley, J. C. King, and T. Lachlan-Cope, 2004: Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. *Geophys. Res. Lett.*, **31**, L14205, doi:10.1029/2004GL019952.
- Meneghini, B., I. Simmonds, and I. N. Smith, 2007: Association between Australian rainfall and the Southern Annular Mode. *Int. J. Climatol.*, **27**, 109–121.
- Mullan, A. B., 1995: On the linearity and stability of Southern Oscillation–climate relationships for New Zealand. *Int. J. Climatol.*, **15**, 1365–1386.
- Oki, T., and S. Kanae, 2006: Global hydrological cycles and world water resources. *Science*, **313**, 1068–1072.
- Power, S. B., and I. N. Smith, 2007: Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed? *Geophys. Res. Lett.*, **34**, L18702, doi:10.1029/2007GL030854.
- Rao, V. B., A. M. C. do Carmo, and S. H. Franchito, 2003: Interannual variations of storm tracks in the Southern Hemisphere and their connections with the Antarctic Oscillation. *Int. J. Climatol.*, **23**, 1537–1545.
- Reason, C. J. C., and M. Roualt, 2005: Links between the Antarctic Oscillation and winter rainfall over western South Africa. *Geophys. Res. Lett.*, **32**, L07705, doi:10.1029/2005GL022419.
- Renwick, J. A., 2004: Trends in the Southern Hemisphere polar vortex in NCEP and ECMWF reanalyses. *Geophys. Res. Lett.*, **31**, L07209, doi:10.1029/2003GL019302.
- , and D. Thompson, 2006: The Southern Annular Mode and New Zealand climate. *Water Atmos.*, **14**, 24–25.
- Salinger, M. J., 1980: New Zealand climate: I. Precipitation patterns. *Mon. Wea. Rev.*, **108**, 1892–1904.
- , and A. B. Mullan, 1999: New Zealand climate: Temperature and precipitation variations and their links with atmospheric circulation 1930–1994. *Int. J. Climatol.*, **19**, 1049–1071.
- , and G. M. Griffiths, 2001: Trends in New Zealand daily temperature and rainfall extremes. *Int. J. Climatol.*, **21**, 1437–1452.
- , R. E. Basher, B. B. Fitzharris, J. E. Hay, P. D. Jones, J. P. Macveigh, and I. Schmidely-Leleu, 1995: Climate trends in the southwest Pacific. *Int. J. Climatol.*, **15**, 285–302.
- , J. A. Renwick, and A. B. Mullan, 2001: Interdecadal Pacific Oscillation and South Pacific climate. *Int. J. Climatol.*, **21**, 1705–1721.
- Sciremammano, F., 1979: A suggestion for the presentation of correlations and their significance levels. *J. Phys. Oceanogr.*, **9**, 1237–1276.
- Sen Gupta, A., and M. H. England, 2006: Coupled ocean–atmosphere–ice response to variations in the southern annular mode. *J. Climate*, **19**, 4457–4486.
- Silvestri, G. E., and C. S. Vera, 2003: Antarctic Oscillation signal on precipitation anomalies over southeastern South America. *Geophys. Res. Lett.*, **30**, 21, doi:10.1029/2003GL018277.
- Smith, T. M., and R. W. Reynolds, 2003: Extended reconstruction of global sea surface temperatures based on COADS data (1854–1997). *J. Climate*, **16**, 1495–1510.
- , and —, 2004: Improved extended reconstruction of SST (1854–1997). *J. Climate*, **17**, 2466–2477.
- Tait, A., R. Henderson, R. Turner, and X. Zheng, 2006: Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *Int. J. Climatol.*, **26**, 2097–2115.
- Thompson, D. W. J., and J. M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate*, **13**, 1000–1016.
- , and S. Solomon, 2002: Interpretation of recent Southern Hemisphere climate change. *Science*, **296**, 895–899.
- , J. M. Wallace, and G. C. Hegerl, 2000: Annular modes in the extratropical circulation. Part II: Trends. *J. Climate*, **13**, 1018–1036.
- Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner, 1999: Increased El Niño frequency in a climate model forced by future greenhouse warming. *Nature*, **398**, 694–697.
- Ummenhofer, C. C., and M. H. England, 2007: Interannual extremes in New Zealand precipitation linked to modes of

- Southern Hemisphere climate variability. *J. Climate*, **20**, 5418–5440.
- Uppala, S. M., and Coauthors, 2005: The ERA-40 Re-Analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.
- Vecchi, G. A., and B. J. Soden, 2007: Global warming and the weakening of the tropical circulation. *J. Climate*, **20**, 4316–4340.
- , —, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison, 2006: Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature*, **441**, 73–76.
- Verdon, D. C., and S. W. Franks, 2006: Long-term behavior of ENSO: Interactions with the PDO over the past 400 years inferred from paleoclimate records. *Geophys. Res. Lett.*, **33**, L06712, doi:10.1029/2005GL025052.
- Waugh, J., H. Freestone, and D. Lew, 1997: Historic floods and droughts in New Zealand. *Floods and Droughts: The New Zealand Experience*, M. P. Mosley and C. P. Pearson, Eds., New Zealand Hydrological Society Inc., 29–50.