Regional climate modelling in New Zealand: Comparison to gridded and satellite observations.

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Abstract

The climate of New Zealand is highly variable, both spatially and temporally, due to a mixture of complex topography and location in the Southern Hemisphere, mid-latitude westerlies. The representation of New Zealand climate in General Circulation Models (GCMs) is too coarse to provide meaningful regional climate statistics. Therefore empirical-statistical or dynamical downscaling methods should be applied to global model data to understand regional climate in terms of the large scale flow. In this study, the focus is on dynamical downscaling where a Regional Climate Model (RCM) is used. The RCM is forced by both reanalysis and GCM data and run for thirty years in each case. Climate statistics from the model for 1980-1999 are compared with gridded observations. The geographical distribution of maximum and minimum surface air temperatures compare well with the gridded observational data (spatial correlation values >0.9) with low temperatures in upland areas and higher temperatures in lowland and northern areas. However, temperature biases are also evident, with maximum surface air temperature being too low and minimum surface air temperatures too high. The model also captures the west–east gradient in precipitation across the mountainous South Island very well (spatial correlation values >0.75). Biases in precipitation are also analysed and tend to be negative (too little precipitation), especially in winter. Biases in the GCM-forced regional model results are similar to, but slightly larger than, those in the reanalysis-forced run, owing to additional circulation errors coming from the global model.

1. Introduction

New Zealand is located in the Southern Hemisphere (SH) mid-latitude westerly wind belt, which governs the climate state of the country (see Sturman and Tapper, 2006). Highly localised variations in climate exist across New Zealand due to the interaction of the complex topography with the prevailing westerly winds (see Salinger 1980a, b). Also, as New Zealand is located between approximately 34°S – 48°S the country is influenced by both tropical and polar air flow. Furthermore, New Zealand’s climate is influenced by modes of interannual and decadal-scale variability such as the El-Niño Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (Mullan, 1995 and Salinger and Mullan, 1999).

Due to the low spatial resolution (approximately 200 km) of General Circulation Models (GCMs), meaningful high-resolution climate data cannot be provided for New Zealand from GCM output directly. However, understanding regional climate variability and change is very important for informing local government and other end-users on how to respond to possible future climate change.

There are two methods to acquire higher-resolution data from the GCMs. Firstly, statistical models (e.g. regression equations) can be developed between local-scale climate variations and the large-scale circulation using historical data. This is known as
empirical statistical downscaling. The regression models can then be applied to large-scale climate projection data from GCMs to produce local climate forecasts (see Benestad, 2004; Ministry for the Environment, 2008; Mullan et al., 2001, for examples). Secondly, data from a driving GCM can be used to provide lateral boundary conditions for a higher resolution Regional Climate Model (RCM). This is known as dynamical downscaling and has been undertaken previously for the New Zealand region by Bhaskaran et al. (1999, 2002), Drost et al. (2007), Ministry for the Environment (2008) and Renwick et al. (1998). Both methods have been used in Christensen et al. (2007) in assessing the plausible regional impacts of future climate change. However, this study will focus only on the dynamical downscaling method as empirical statistical downscaling has already been undertaken for New Zealand using a variety of GCM simulations (Ministry for the Environment, 2008).

The aim of this study is to evaluate RCM simulations centred on New Zealand by comparing model output with satellite and land-based gridded observations. Section 2 describes the experimental setup and the observational temperature and precipitation data used. Section 3 contains the results of the comparison between the models and the gridded observational data sets available. The final discussion and main conclusions are given in Section 4.

2. Model setup, experiments and observational data

2.1 Model Setup
The GCM used for the experiments described in this paper is the Hadley Centre Atmospheric Model version 3 (HadAM3P), which is a higher resolution version (of the atmospheric component) of the Hadley Centre Coupled Model (HadCM3). HadAM3P is a hydrostatic grid point model with a horizontal resolution of 1.875° longitude and 1.25° latitude, with the time step set to 15 minutes. There are 19 vertical levels in the atmospheric model, which used a hybrid σ-p co-ordinate system (see Johns et al., 1997). The model resolution dictates that several of the model processes cannot be resolved explicitly and so these sub-grid scale processes are simplified into parameterisations. The parameterised processes in HadAM3P are clouds, radiation, diffusion, gravity wave drag, advection, precipitation and the sulfur cycle. More in-depth discussion of the Hadley Centre model used in this study (and previous versions of the model) can be found in Gordon et al. (2000), Gregory et al. (1994), Pope et al. (2000), Pope and Stratton (2002) and Stratton (1999).

The Regional Climate Model (RCM) used in this study was HadRM3P (Jones et al., 2004), and used the same parameterisation schemes as those in HadAM3P. The RCM was developed for use in the New Zealand region by Bhaskaran et al. (1999, 2002) and developed further by Drost et al. (2007). Versions of the Hadley Centre Regional Climate Model have been used in several other studies, for other regions of the globe (see Frei et al., 2003; Hudson and Jones, 2002; Zhang et al., 2009), which indicates that the model may be applied to represent the New Zealand climate.

A map of the domain used in this study, in relation to the New Zealand region of the Southern Hemisphere (SH), can be seen in Figure 1. A study by Leduc and Laprise (2009) suggested that small-scale processes (such as precipitation formation) may not have time to develop in a small RCM domain. Tests using a larger RCM domain have previously been undertaken, however the climate of the large and small domains differed little in tests (not shown) and so the domain in Figure 1 (small) was adopted to reduce the computational expense.

The RCM grid was rotated from the location in Figure 1 to a new location with north polar coordinates of 48°N and 176°E to obtain quasi uniform grid box spacing in the computational domain (Jones et al., 2004).
Numerical instability issues associated with fast moving waves arising due to convergence of the meridians at high latitudes are mostly resolved by using a rotated grid (as described in Drost et al., 2007). Despite the rotation, the high resolution of the model required a time step of 3 minutes. The characteristics of the RCM used in this study can be seen in Table 1 along with those used by Drost et al. (2007). The domain is smaller than in Drost et al. (2007), but the horizontal resolution is higher. The parameterisation schemes of HadRM3P used in this study are similar to those used in Drost et al. (2007).

The model orography and vegetation datasets were updated from the data used in Drost et al. (2007), to the high resolution surface topography dataset used in the operational forecast model at the National Institute for Water and Atmospheric Research (H. Oliver, personal communication and originally derived from the GLOBE, 1999 data archive see: http://www.ngdc.noaa.gov/mgg/topo/globe.html). With the new topography, the altitudes of the North Island grid-points were generally lower (except around the central plateau), compared to the Drost et al. (2007) topography. The largest difference between the two orography data sets occured throughout the Southern Alps, which were reduced in height by 200m or more and suggested that the topographical heights used by Drost et al. (2007) were too high. There was very little difference in the vegetation fields.

2.2 Experimental setup

Two experiments were undertaken with the regional climate model:

1. European Centre for Medium Range Weather Forecasts Re-Analysis, lateral boundary condition data (ERA-40): The RCM was forced at its boundaries by ERA-40 data (see Uppala et al., 2005 for more information on ERA-40) to give the best estimate of the past atmospheric circulation across New Zealand. This run will be referred to subsequently as RCM1. The RCM1 run did not use the chemistry scheme and had the sulfur cycle switched off, as the ERA-40 boundary data did not contain the necessary sulfate aerosol. Values for the domain Sea Surface Temperatures (SSTs) were taken from the HadISST1.1 data set (Rayner et al.,
This simulation used a Gregorian calendar (including leap years).

2. GCM lateral boundary conditions: In this experiment the global GCM was run with observed SSTs (HadISST1.1) with the atmosphere free to respond to those SSTs. Lateral boundary conditions were generated by the GCM (HadAM3P) for the RCM in this run, and will be different from those in RCM1. This run will be referred to in the text as RCM2. The RCM2 run included the chemistry scheme, which represents the sulfur cycle (see Ackerley et al., 2009 and Jones et al., 2001). The use of the chemistry scheme improves the radiative transfer processes of the model. This simulation used a 360-day calendar (12 months of 30 days).

Both RCM1 and RCM2 were initialized on 1st December 1969 and run until December 1st 2000. Averages were made between the years 1980 to 1999 to follow the convention used in the IPCC AR4 report (Solomon et al., 2007) and to avoid the early years of the simulation where errors may occur due to the initial ‘spinning up’ of the model. All references to the seasons will be DJF (December-January-February), MAM (March-April-May), JJA (June-July-August) and SON (September-October-November), unless otherwise stated in the text.

2.3 Observational data
2.3.1 Virtual Climate Station Network (VCSN) data.

In this study, we use the gridded fields of the Virtual Climate Station Network (VCSN) at NIWA, which was produced from observed station data using the methods described in Tait et al. (2006) and Tait (2008). We compare the daily maximum temperature ($T_{\text{max}}$), daily minimum temperature ($T_{\text{min}}$) and the daily accumulation of precipitation from the VCSN data with the RCM output over the 1980–1999 period. This is different to the method employed in Drost et al. (2007), who calculated the mean temperature from the VCSN $T_{\text{max}}$ and $T_{\text{min}}$ values and compared that to their RCM mean temperatures. Biases in the modelled values of $T_{\text{max}}$ and $T_{\text{min}}$ may cancel out when the mean is calculated, which can mask errors in the model data. Treating $T_{\text{max}}$ and $T_{\text{min}}$ separately removes this issue.

The major differences noted by Drost et al. (2007) between the gridded observational data and their RCM simulations were too much rainfall over the western South Island and too little on the eastern South Island, along with cold biases in western areas and warm biases to the east. Drost et al. (2007) attributed these differences to the grid-point heights used by the RCM and the gridded data set (VCSN). To avoid this possibility in this study, the spline method used by Tait et al. (2006) and Tait (2008) was applied to the climatological station data using the grid-spacing specifications of the model (30km resolution) and the model’s topography. This ensured temperatures were being compared at the same altitude in both VCSN and RCM data sets. Despite reducing the errors due to previously using different topographical datasets, other errors do still occur in the VCSN data. One example occurs in upland areas where winter temperature inversions can alter the relationship between $T_{\text{min}}$ and elevation due to deviations from the atmospheric lapse rate (Tait, 2008). However, by using the model topography, the spline method (Tait et al 2006; Tait, 2008) reproduces the observed data on the model grid and allows a fairer comparison with the model data.

Unfortunately the same method cannot be applied to the precipitation data as, unlike temperature where a lapse rate can be used to estimate temperature at altitude, there is no direct relationship between land-surface height and precipitation. Therefore, there are likely to be systematic differences between the model and VCSN precipitation, which are not due to deficiencies in the modelled processes. Such systematic biases should be largely removed for temperature.

Any dataset of gridded observations will have
spatially variable errors associated with it, and these can be expected to be primarily a function of the density of the stations in and surrounding any given gridbox. Quantifying this error is difficult, simply because the true precipitation distribution is not known. For precipitation, Tait et al. (2006) attempted to quantify the error in the VCSN methodology in two ways. The first was to use a ‘leave one out’ methodology where one station is removed from the interpolation, and the interpolated answer at the station location is compared to the observed values. This method gave an average root mean squared error (RMSE) for daily rainfall of 4.8 mm. In the second method, the rainfall amounts over selected river catchments were compared to estimated river flows. When averaged over a number of years, this comparison requires only knowledge about the river flow and evapotranspiration. The error in these two components was not quantified. The average bias in annual rainfall for the catchments considered was -7%, composed of -1% in the North Island and -11% in the South Island. This implied that the VCSN was underestimating the total rainfall, especially in high elevation terrain where a number of catchments were approximately 25% too dry. For this study any additional effect on the error of interpolating to the 30 km grid has not been quantified, but it is expected to be minimal.

For temperature, Tait (2008) determined the accuracy of daily interpolations by selecting 20 validation sites which were not included in the stations used for the interpolation. For $T_{\text{max}}$ the daily mean RMSE was 1.2 °C and for $T_{\text{min}}$ 1.6 °C. The largest errors occurred at high elevation sites. Errors for seasonal or annual means were not provided, but if the errors are assumed to be random then the values stated could be expected to be reduced in magnitude by the square root of the number of independent days used in any average.

2.3.2 Satellite data
This study also uses the high-resolution SRTex-derived satellite data for New Zealand cloud cover in 1995, taken from Uddstrom et al. (2001). The cloud cover data were used to evaluate the capability of the RCM to represent the cloud cover fraction over New Zealand.

3. Results
3.1 RCM1 compared to gridded and satellite observations
3.1.1 Maximum surface air temperature ($T_{\text{max}}$)
The annual mean $T_{\text{max}}$ for RCM1 and the observations can be seen in Figures 2(a) – (b). The RCM captures the geographical distribution of the temperatures well (the spatial correlation between VCSN and RCM1 data is 0.96) with the coldest values in mountainous areas (such as the central North Island and the southern and western South Island) and the warmest temperatures in low-lying areas (such as the northwestern North Island and the eastern South Island). Similarly, the summer (DJF, Figures 2(d) – (e)) and winter (JJA, Figures 2(g) – (h)) distribution of $T_{\text{max}}$ broadly matches those of the observations (spatial correlations of 0.92 and 0.97, respectively), albeit with warmer (cooler) temperatures in DJF (JJA).

However, the annual values of $T_{\text{max}}$ are generally too low throughout much of New Zealand (see Figure 2(c), which includes the New Zealand mean difference along with Figures 2(i) and (f)), with the coldest biases in the South Island in JJA (Figure 2(i)). The North Island is also generally cooler in the model than the VCSN data, but there are warm biases in northeastern areas which extend throughout much of the lower North
Figure 2: The annual mean maximum surface air temperature ($T_{\text{max}}$, °C) for (a) RCM1, (b) VCSN data and the difference (c) RCM1 – VCSN (non-statistically significant differences, $p>0.05$ using a student t-test, are unshaded). Equivalent figures are also plotted for DJF (d, e, and f) and JJA (g, h and i). Note the different colour bars for ANN, DJF and JJA. The “corr. with RCM1” in the centre column plots refers to the spatial correlation between the RCM1 and VCSN data.
Figure 3: The annual mean minimum surface air temperature ($T_{\text{min}}$, °C) for (a) RCM1, (b) VCSN data and the difference (c) RCM1 – VCSN (non-statistically significant differences, $p>0.05$ using a student t-test, are unshaded). Equivalent figures are also plotted for DJF (d, e, and f) and JJA (g, h and i). Note the different colour bars for ANN, DJF and JJA. The “corr. with RCM1” in the centre column plots refers to the spatial correlation between the RCM1 and VCSN data.
Island and the far north of the South Island in DJF (when they are at their maximum, see Figure 2(f)). These biases in temperature appear to be greater than the RMSE error expected for the VCSN gridded data described in Section 2.3.1.

3.1.2 Minimum surface air temperature (T\textsubscript{min})

The modelled and observed values of annual (Figure 3(a) – (b)), summer (DJF, Figures 3(d) – (e)) and winter (JJA, Figures 3(g) – (h)) mean T\textsubscript{min} both display a similar geographical distribution of temperatures. In a similar manner to T\textsubscript{max} (see Figure 2), the lowest values of T\textsubscript{min} are found in the upland areas (central North Island, southern and western South Island) in JJA and the warmest temperatures can be seen in the lowland areas (northern North Island and eastern South Island) in DJF. The spatial correlations between the VCSN and RCM1 data are also very high (≥0.96) for T\textsubscript{min} (see Figure 3).

However, unlike T\textsubscript{max} there is more of a tendency for warmer temperatures in the model, compared to the VCSN data, for the annual mean T\textsubscript{min} (see Figure 2(c)), which implies that the diurnal temperature range is likely to be too small in RCM1. This is particularly evident in the North Island, where T\textsubscript{min} is generally >1°C warmer in the model than the observations (except in the middle of the central North Island during JJA, see Figure 3(j)). The South Island however, has a mixture of cold and warm biases throughout the year. Warm biases dominate many areas of the South Island during DJF (Figure 3(f)), with colder biases more prevalent during JJA (Figure 3(i)).

3.1.3 Precipitation

Maps of daily mean precipitation for RCM1 and the VCSN data can be seen in Figure 4, which were averaged annually (Figures 4(a) – (b)), and during the summer (Figures 4(d) – (e)) and winter (Figures 4(g) – (h)) seasons. RCM1 successfully represents the strong west – east gradient in precipitation across the South Island in all seasons, while also capturing the seasonality of rainfall in the far western South Island (more precipitation in DJF than JJA). RCM1 also captures the increased precipitation totals in the central North Island and the northeastern North Island. Similarly, the low precipitation amounts in the eastern South Island are well represented in the annual, summer and winter averages. Also, low summer precipitation amounts in the northwestern and southern North Island during DJF are reproduced by the model. The visual agreement seen in Figure 4 is confirmed by the high spatial correlations between the VCSN and RCM1 data for precipitation annually (0.81), in DJF (0.84) and in JJA (0.77); however these correlations are lower than those of the temperature data (see Sections 3.1.1 and 3.1.2).

Despite the good representation of precipitation amounts in RCM1 spatially, there are some obvious biases, which can be seen in Figures 4(c), 4(f) and 4(i). The North Island has a mixture of dry and wet biases with a tendency towards conditions that are too dry in the model compared to the VCSN data. The dry biases are at their strongest in JJA (the wettest season of the year), with the wet biases peaking in DJF. The modelled South Island precipitation also has a mixture of dry and wet biases compared to the VCSN data. However, there appears to be a more systematic wet bias in the southern South Island, which is strongest in DJF. Conversely, there are dry biases in the far northwestern, eastern and southern parts of the South Island. We note that for the large part, the biases in the model are of a similar magnitude to the error expected in the VCSN data. The comparison of the VCSN with river flows (Tait et al., 2006) showed an average bias of -7%. In particular, that the RCM is wetter in high mountainous areas, cannot be identified as a weakness, since it is in better agreement with the river flow data than the VCSN. The daily RMSE values provided in Tait et al. (2006) represent an average error in the annual mean of 1%.
Figure 4: The annual, daily mean precipitation (Precip, mm/day) for (a) RCM1, (b) VCSN data and the difference (c) RCM1 – VCSN (%) (non-statistically significant differences, $p>0.05$ using a student $t$-test, are unshaded). Equivalent figures are also plotted for DJF (d, e, and f) and JJA (g, h and i). The “corr. with RCM1” in the centre column plots refers to the spatial correlation between the RCM1 and VCSN data.
Figure 5: The annual, New Zealand mean (a) $T_{\text{max}}$ (°C), (b) $T_{\text{min}}$ (°C) and (c) daily mean precipitation (mm day$^{-1}$) from VCSN (black lines), RCM1 (red lines) and RCM2 (yellow lines) data between 1980 - 1999. The correlation values (given in the key for each graph) are between the VCSN time series and each of the model time series separately. Statistically significant correlations ($p \leq 0.05$ using a student t-test) are given an asterisk.
A number of locations can be identified where the interaction of the flow with the model topography causes an enhancement of the RCM’s precipitation. However, this enhancement is often not aligned perfectly with the observed enhancement, which is likely to cause some of the ‘noisy’ differences in Figures 4(c), (f) and (i). Another cause of the differences may be due to a lack of rain gauges in upland areas (such as the Southern Alps in the western South Island), which causes the observational data to be smoothed over some of the peaks whereas the model may actually resolve the high rainfall amounts in each grid box.

3.1.4 Interannual variability
The annual mean $T_{\text{max}}$ and $T_{\text{min}}$ for New Zealand from the VCSN data and RCM1 over the period 1980–1999 can be seen in Figure 5, along with the annually-averaged daily mean precipitation. In all cases, the interannual variation of RCM1 matches the variation in the VCSN data very well. This is expected as RCM1 is driven by reanalysis data, which represents the actual sequence of weather systems impinging on the boundary of the RCM domain, and therefore the conditions that lead to increased or decreased $T_{\text{max}}$, $T_{\text{min}}$ and precipitation should be well represented. However, the systematic underestimation (overestimation) of $T_{\text{max}}$ ($T_{\text{min}}$) is apparent in all years of the RCM simulation (Figures 5(a) and (b)) and demonstrates that the biases noted in Figures 2 and 3 are present in all years of the simulation. The precipitation is slightly different however as there is generally less in RCM1 than the VCSN data, except in 1992, 1993 and 1997 where RCM1 precipitation is higher. However, the interannual variation of precipitation in RCM1 does often match the variability of the VCSN data.

3.1.5 Cloud cover
From the observed SRTex data it is apparent that cloud-free days occur less frequently over the ocean and more frequently over the land (Figure 6a). Over land, the highest percentage of cloud-free events (approximately 40%) occur throughout the eastern and northern South Island and throughout the Cook Strait (which lies between the North and South Islands). The lowest no-cloud frequencies are found along the west coast and in southeastern areas of the South Island.

The model is able to output cloud cover fraction and we convert the cloud cover fraction for the model representation of 1995 to a cloud-free percentage (Figure 6(b)). Areas where the model surface topography are above 750 m are shaded white and approximately match those of Figure 6(a), which are shaded grey and indicate regions of high surface reflectivity where satellite data could not be interpreted as cloudy or clear. While the model derived cloud-free fraction is not calculated in the same way as in Uddstrom et al. (2001), the spatial variations are comparable.

The high occurrence of cloud-free conditions (Figure 6(b)) over the ocean in the model is symptomatic of the lack of cloud cover in GCM simulations for the Southern Hemisphere (Trenberth and Fasullo, 2010). Over the land however, the cloud-free fractions are more comparable, with very similar values in the eastern South Island for RCM1 and approximately 5 – 10% too little cloud in the northern and southeastern South Island (and over the Cook Strait). The west coast of the South Island appears to be deficient in cloud in RCM1, although there are several grid boxes that contain more cloud and are comparable with Figure 6(a).

3.1.6 Discussion
It is not possible to rule out errors in the driving ERA-40 data set, or in the observed SST datasets, which may be responsible for some of the biases presented here. However, it is more likely that the biases are a reflection of failures in the models physical parameterisations. Some of these biases are likely to be improved by using a model with higher resolution; for instance adequately
Figure 6: (a) Cloud cover data from Uddstrom et al. (2001) showing the frequency of occurrence of cloud-free (or “no cloud”) conditions in each pixel during 1995. Land points over 750 m altitude are shaded grey and indicate areas of where data retrieval was not possible (© American Meteorological Society. Reprinted with permission) and (b) the equivalent data from RCM1.
Figure 7: The differences between RCM2 and RCM1 for (a) annual mean $T_{\text{max}}$ ($^\circ$C), (b) DJF mean $T_{\text{max}}$ ($^\circ$C), (c) JJA mean $T_{\text{max}}$ ($^\circ$C), (d) annual mean $T_{\text{min}}$ ($^\circ$C), (e) DJF mean $T_{\text{min}}$ ($^\circ$C), (f) JJA mean $T_{\text{min}}$ ($^\circ$C), (g) annual mean Precip. (%), (h) DJF mean Precip. (%) and (i) JJA mean Precip. (%). Non-statistically significant differences, $p>0.05$ using a student t-test, are unshaded.
resolving topographical features that are important for precipitation generation. In addition some parameterisations, such as precipitation, are tuned to give the best possible average results over as many regions of the Earth as possible. This may not give the best possible result for New Zealand’s maritime and mountainous environment. Finally surface information, such as the physical properties of vegetation cover, can directly influence the surface climate in the model and it is important that these are as realistic as possible. All of these areas are actively being pursued as a means of improving the simulation of New Zealand climate by the RCM.

3.2 The RCM2 simulation in comparison to RCM1

The second RCM simulation (RCM2) described in Section 2.2 was forced by boundary conditions that were produced from a free running GCM that did not include data assimilation (for example observational weather station and satellite data). This means that the sequence of daily weather patterns will not match observations, and there are likely to be differences in the modelled mean climate between RCM2 and the reanalysis forced RCM1 simulation. Because this is the approach that must be used for future climate simulations it is important that any differences due to the free running GCM are documented. The interannual variability is also likely to be different between RCM1 and RCM2, although both model runs are forced by the same observed sea surface temperatures (HadISST1.1). The geographical distributions of $T_{\text{max}}$, $T_{\text{min}}$ and precipitation are very similar in RCM2 and RCM1 (not shown) and so we focus only on the differences between the two models.

3.2.1 $T_{\text{max}}$, $T_{\text{min}}$ and Precipitation

RCM2 generally has higher values of $T_{\text{max}}$ than RCM1, which can be seen in Figure 7(a) for the annual mean. Higher values of $T_{\text{max}}$ also occur during DJF (Figure 7(b)), but in winter (Figure 7(c)) there are several regions where $T_{\text{max}}$ is lower in RCM2 than RCM1. These low values tend to occur in the more upland areas of both the North and South Islands (such as the western and northern South Island). The largest differences in $T_{\text{max}}$ between the two simulations are approximately $\pm 1^\circ\text{C}$; with the New Zealand annual mean difference (RCM2 – RCM1) being $+0.29^\circ\text{C}$.

In contrast, the annual mean $T_{\text{min}}$ values are generally slightly less in RCM2 than RCM1, although the positive and negative values cancel out somewhat for the average over New Zealand compared to the other seasons (see Figure 7(d), (e) and (f)). The lower values of $T_{\text{min}}$ are more dominant in the South Island and the eastern North Island during DJF with warmer values in western and northern parts of the North Island (Figure 7(e)). There is a reversal in JJA with the North Island colder in RCM2 than RCM1 with little cooling in the eastern and southern South Island (Figure 7(f)). As with $T_{\text{max}}$, the differences between RCM2 and RCM1 are approximately within $\pm 1^\circ\text{C}$. The difference between $T_{\text{max}}$ values from RCM2 and RCM1 are generally of opposite sign to the RCM1 biases, making the biases slightly smaller in RCM2.

The difference in annual mean precipitation can be seen in Figure 7(g), and there is very little difference between the two models, although RCM2 is slightly wetter than RCM1. However, there are some differences in the seasonality of the rainfall in the DJF and JJA seasons (Figures 7(h) and (i)). In RCM2, precipitation is much lower in the west of both islands in DJF, with higher precipitation in the eastern North Island and parts of the eastern South Island, whereas during JJA the North Island is generally wetter in RCM2 along with the southern South Island.

The values in RCM2 were generally less variable than RCM1 and the VCSN data although RCM2 managed to capture some of the variability (Figure 5). For example, in RCM2 $T_{\text{max}}$ and $T_{\text{min}}$ compared well with VCSN data between 1980 and 1985 as does
Figure 8: The difference in fractional cloud cover (between RCM2 and RCM1) for (a) the annual mean, (b) the DJF mean and (c) the JJA mean (p≥0.05, using a student t-test, unshaded). The difference in SLP (hPa) between RCM2 and RCM1 for (d) the annual mean, (e) the DJF mean and (f) the JJA mean.
the precipitation between 1990 and 1994. RCM2 also captured the increased rainfall in 1998, but the value was much larger than in VCSN. However, the correlations between the RCM2 T$_{\text{max}}$, T$_{\text{min}}$ and precipitation time series and the corresponding VCSN series were lower than those between RCM1 and the VCSN data (see Figure 5 keys). These differences between the RCM simulations would be expected as RCM2 was driven by a ‘free running’ (no data assimilation) GCM simulation, which had different circulation characteristics to the reanalysis simulation. Nevertheless, the RCM2 T$_{\text{max}}$ and T$_{\text{min}}$ correlations with the VCSN time series were still statistically significant over 1980–1999, indicating the influence of observed SSTs on the interannual variability of New Zealand land temperatures. Despite the different interannual variability, RCM2 had similar systematic biases to RCM1. This is further evidence that these biases result from inadequacies of the models’ physical parameterisations.

3.2.2 Cloud cover fraction

For the annual mean, the cloud cover fraction is about 5% lower in RCM2 than RCM1, with the largest, negative differences occurring in DJF (Figures 8(a) and (b)).

3.2.3 Discussion

Cloud cover has been shown to reduce the value of T$_{\text{max}}$ in observational studies (for example see Dai et al., 1999), which may be influencing the surface air temperatures. The reduced cloud cover fraction in RCM2 would allow more incoming solar radiation (insolation) to reach the surface and could be an important driver of the increased T$_{\text{max}}$ both in the annual and DJF means shown in Section 3.2.1. In JJA however (Figure 8(c)), there is little difference in cloud cover for RCM2 relative to RCM1 with some increased values in the southern South Island. The small differences in cloud cover also agree with the much smaller differences in T$_{\text{max}}$ between RCM2 and RCM1 in Figure 7(c).

One possible cause of the different cloud cover may be the different atmospheric circulation represented in the two simulations. Indeed the RCM2 modelled sea level pressure is higher over the land mass than in RCM1 (Figure 8(d)). As such it is a reasonable hypothesis that increased SLP has driven increased descent and in turn reduced cloud cover. Also, the location of the centre of the high anomaly indicates that the air flow is more southwesterly in RCM2 than RCM1, which may be partly responsible for some of the lower values of T$_{\text{min}}$ in Figure 7(d). The SLP is also higher in DJF for RCM2 (Figure 8(e)) across New Zealand, but the more southern location of the pressure anomaly centre compared to the annual mean (Figure 8(d)) results in a more southeasterly flow. The increased southeasterly is likely to be responsible for the increased (decreased) precipitation in the east (west) of both islands (as indicated by Kidston et al., 2009, Mullan, 1998 and Salinger and Mullan, 1999) while also reducing nocturnal temperatures (T$_{\text{min}}$) as shown in Section 3.2.1. In JJA, SLP is higher over New Zealand (except in the far southern South Island) in RCM2 and the pressure anomaly indicates more southerly flow over the North Island in particular, which may be responsible for the higher precipitation in Figure 7(i) and the lower values of T$_{\text{min}}$ (particularly in the western North Island) in Figure 7(f).

Overall, there are differences in T$_{\text{max}}$, T$_{\text{min}}$ and precipitation between RCM1 and RCM2, which are likely caused by the cloud cover and sea level pressure (and therefore circulation) differing between the two simulations. These differences in cloud cover and sea level pressure ultimately arise from using lateral boundary conditions from two disparate model simulations (ERA-40 and a free running GCM). However, these changes are smaller than the differences between these models and the observations. The difference in cloud cover between RCM2 and RCM1 and the resultant changes in T$_{\text{max}}$ may indicate that the model cloud is a driver of the differences between the RCM
4. Summary and Conclusions

The results presented in this study have provided an evaluation of the regional climate model used at the National Institute for Water and Atmospheric Research (NIWA) in comparison to the available observational data. The main outcomes from this study are:

- The broad geographical distribution of high and low values for T_{\text{max}} and T_{\text{min}} (in the models) agree well with the VCSN data (high spatial correlations >0.9), with lower values in upland areas and higher values in northern and lowland regions.

- The geographical distribution of precipitation also agrees well between the models and VCSN data (high spatial correlations >0.75), especially the gradient from the west coast to the east coast of the South Island across the Southern Alps.

- There are systematic biases in T_{\text{max}} (too low) and T_{\text{min}} (too high) in both model simulations, which implies that the diurnal temperature range is too small.

- Precipitation is also slightly lower in the models compared to the VCSN data except in DJF. Because of the difficulties in observing precipitation this difference is comparable with the expected error in the VCSN data.

- The interannual variability in RCM1 for T_{\text{max}}, T_{\text{min}} and precipitation matches well with the VCSN data between 1980 and 1999 (correlations >0.75), whereas RCM2 matches less well but some of the interannual variation is still represented. This reflects the identical SSTs used in the simulations.

- The cloud cover fractions over land in RCM1 are slightly lower that those observed in 1995 from satellite data.

- T_{\text{max}} is generally higher and T_{\text{min}} lower for RCM2 relative to RCM1.

- The annual daily mean precipitation is similar for RCM2 and RCM1 but with more (less) precipitation in RCM2 in winter (summer).

- RCM2 has reduced cloud cover relative to RCM1, which may contribute to the higher values of T_{\text{max}}.

- The differences in the annual and seasonal mean SLP (and subsequent circulation) between RCM2 and RCM1 led to differences in precipitation.

This study has presented the main climatological features of the NIWA RCM run from both reanalysis and GCM data. The RCM data have also been compared to the available observational datasets to evaluate the models. Despite the systematic biases in the models compared to the VCSN data, the models do very well at representing the overall geographical distribution of temperature and precipitation despite the complex topography of New Zealand and its situation in the mid-latitude westerly belt. However, the systematic biases are important and understanding their cause is the focus of further work.

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References


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