ON REGIONAL MODEL SIMULATIONS OF CLIMATE CHANGE OVER NEW ZEALAND

James A. Renwick
National Institute of Water and Atmospheric Research Ltd., Wellington

CSIRO Atmospheric Research, Aspendale, Victoria, Australia

ABSTRACT
Regional model simulations of New Zealand climate have been performed for present-day conditions and for an equilibrium doubling of atmospheric CO₂ concentration. The regional model was nested within ten years output of a nine-level atmospheric general circulation model with a mixed-layer ocean. Statistics of the regional model's representation of present-day surface climate generally compare well with observations. However, it is difficult to assess the accuracy of model simulations of radiatively important clouds, since there is little reliable observational data to compare with. Moreover, although the modelled present-day surface climate is acceptable, results are sensitive to specifications of land surface parameters that are not well known at high resolution. To advance regional climate modelling for New Zealand, there is a need to better describe the characteristics of the New Zealand land surface and the climatology of clouds in the New Zealand/Tasman Sea region. Climate change simulations show a decrease in the strength of the westerly winds over New Zealand, as is typical of equilibrium simulations of CO₂ doubling. Mean temperatures over New Zealand rise at around 80% of the global mean rate. Largely through orographic influences, the decrease in the westerlies leads to precipitation and low-level cloudiness increases in eastern regions, combined with a decreased diurnal temperature range (DTR). Wintertime changes in low-level cloudiness and DTR are well-correlated, as has been found in the observational record. However, changes in both model fields may be more strongly related to modelled circulation changes than to each other. There is a need to apply regional climate modelling to the output of a number of global models, particularly to coupled ocean-atmosphere transient simulations, to assess the likely range of regional outcomes under future global climate change.

INTRODUCTION
The most comprehensive quantitative estimates of future climate change available are based on numerical simulations using general circulation models (GCMs, IPCC 1996). While such models are able to reproduce most of the large-scale features seen in the present-day atmospheric and upper oceanic circulations, they remain restricted by computing power to horizontal resolutions on the order of several hundred kilometres. To be of immediate use in impact studies, estimates of climate change must however be made at the regional scale (10-100 km). Therefore, downscaling procedures are required to interpret large-scale GCM output in terms of local-scale weather and climate variability.

New Zealand climate exhibits considerable mesoscale detail, mainly as a result of the country’s topography and its interaction with the prevailing westerly air stream. The main alpine chain cuts across the midlatitude westerlies, resulting for example in sharp east-west precipitation gradients (Salinger 1980a; Salinger 1980b; Sturman and Tapper 1996). The small geographical size of New Zealand and its sharp topography ensure that local conditions differ significantly from those in larger regions.
climate variability is not well-modelled by most GCMs. At the same time, however, much regional variation is a result of the strong influence of topography on the large-scale circulation, implying that downscaling that takes some account of topographic influences is likely to be successful for much of New Zealand.

Downscaling has long been a feature of numerical weather forecasting, where the output of global numerical weather prediction (NWP) models must be interpreted to yield time series of weather events at individual points. In both climate modelling and weather prediction, two main downscaling techniques are employed: statistical interpolation and nested regional modelling (e.g., Giorgi and Mearns 1991). For New Zealand, recent research suggests that both techniques exhibit similar levels of skill (Kidson and Thompson 1998). While both techniques work well for the present-day climate, the nested modelling approach is more likely to produce reliable results for a doubled-CO₂ climate, as it is explicitly physically based. Statistical models developed using present-day climate information must be used with caution when extrapolating to a future climate with conditions outside the range of those observed today. This paper describes downscaling using a regional climate model (RCM) to estimate enhanced greenhouse gas-induced climate change over New Zealand.

Climate model simulations are strongly controlled by the specification of boundary conditions and by the ability of the model to reproduce the long-term energy balance. Hence, on a regional scale it is important to correctly specify such features as the land surface and its characteristics, and to correctly model radiatively important components such as cloudiness. Surface boundary conditions must be realistically specified at model initialisation, and the model must be able to simulate the evolution of surface conditions such as soil moisture and snow cover in order to correctly simulate seasonal and longer-term climate variability. This is in contrast to short-term NWP, where the initial conditions are of prime importance and boundary conditions or the overall energy balance carry less weight, since the model integration typically covers only a few days.

One pre-requisite for confidence in simulated climate change is a model's ability to correctly simulate the present-day climate. A correct simulation includes both long-term mean circulation and surface fields, and includes variability on many time scales from diurnal through seasonal to decadal and beyond (e.g., Battisti 1995; IPCC 1996). A complete validation is, however, virtually impossible, because of the large number of degrees of freedom in a GCM, and because natural climate variability is not fully documented on time scales meaningful for climate change simulations (Oreskes et al. 1994 contains thoughtful comments on this topic). While model validation for the present day climate is desirable, agreement between the observed and modelled climate does not guarantee that a GCM will correctly simulate greenhouse gas-related climate change. Given the uncertainties inherent in projections of climate a century or so into the future, it is important to assess the output of a range of models, to gauge the likely range of possible outcomes.

For New Zealand, an important example of this point is illustrated by the difference between equilibrium atmosphere-only GCM results and those of transient coupled atmosphere-ocean GCMs (e.g., Whetton et al. 1996). In equilibrium simulations, the model CO₂ concentration is doubled instantaneously and the GCM is run until it reaches equilibrium with the new radiative forcing. The GCM is usually an atmosphere-only model (AGCM) with a simplified slab ocean. A transient simulation involves gradually increasing the CO₂ concentration with time, without allowing the GCM to equilibrate. The GCM is usually a fully coupled ocean-atmosphere model (CGCM). Over New Zealand, equilibrium model results suggest a decrease in the meridional temperature gradient and an associated decrease in the mid-latitude westerly circulation. For the next century or more, transient CGCMs suggest no change, or an increase in the meridional temperature gradient (due to slower warming of the southern oceans) and a possible increase in the westerlies in the New Zealand region (Whetton et al. 1996; England and Hirst 1997). These two possibilities have very different implications for changes in the rainfall distribution over New Zealand, equilibrium results implying a decrease in the east-west rainfall gradient and transient results implying an increase in the gradient.
While coupled (transient) models are in principle a more realistic representation of the climate system, there is still merit in studying equilibrium model results. Coupled models are necessarily more complex that AGCMs, and their ocean components are generally not well validated, due to the lack of extensive observations of the global ocean circulation. Moreover, to explore all possible future scenarios, it is useful to employ a hierarchy of models, from a simple energy-balance through atmosphere-only GCMs to fully coupled atmosphere-ocean models (IPCC 1996). Equilibrium AGCM results for a doubling of CO₂ may provide an indication of the state of the coupled climate after a larger increase in greenhouse gas concentration (Dix and Hunt 1998), the requirement for equilibrium effectively implying a longer projection time into the future.

For regional climate change assessment, the downscaling issue remains relevant, regardless of the GCM formulation used. Here, downscaling is discussed in terms of a nested regional climate model (RCM) forced with GCM fields taken from control and equilibrium doubled-CO₂ experiments. The purpose is to explore details of the RCM approach, with application in principle to either variety of GCM simulation. Modelled changes in several climate variables are discussed, with particular emphasis on precipitation and diurnal temperature range and their relation to changes in cloudiness and the mean low-level wind field. The results represent only a single realisation of possible climate change over New Zealand, and do not form the basis of a set of climate change scenarios, which require a suite of modelled outcomes to describe the likely range of possible future climates. A subsequent paper will report on downscaling of a range of GCM simulations of climate change.

MODELS AND MODEL VALIDATION

Models

All simulations described here make use of models developed at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Atmospheric Research (DAR, now known as CAR or CSIRO Atmospheric Research). The GCM used was the Mark 2 nine-level atmosphere model (CSIRO9) run at R21 spectral resolution with a mixed-layer ocean (Watterson et al. 1997). At New Zealand latitudes, R21 resolution corresponds to a horizontal resolution of around 400-500 km. Monthly mean oceanic heat fluxes were calculated in a prior control run using observed climatological sea-surface temperature (SST) fields. Thirty-year equilibrium simulations were carried out for control and doubled-CO₂ conditions, where the mixed layer ocean responded to both the calculated oceanic heat flux and to the modelled surface energy flux (Wilson and Mitchell 1987; Watterson et al. 1997). From the full 30-year simulations, 10 model years were selected for use in the nested runs. Comparisons between the 10-year subset and the full 30 years of GCM output suggest that the period chosen is representative of the longer-period results over New Zealand, in mean terms. The choice of 10 years for RCM integrations was a pragmatic one, in terms of computer time and storage.

The RCM used for nesting experiments was the DAR limited-area model (DARLAM), as described by Walsh and McGregor (1995) and Katzfey (1995). DARLAM is a hydrostatic, semi-Lagrangian primitive equation model incorporating a comprehensive set of physical parameterizations, many of which match those used in CSIRO9. Surface exchanges are handled through a canopy scheme (Kowalczyk et al. 1991), using surface data sets interpolated to model resolution from the 1° x 1° global data set of Dorman and Sellers (1989). DARLAM was run using the same nine vertical levels as used in CSIRO9. Clouds are diagnosed in three layers (low, middle and high, centred at about 1.5, 4.5 and 10 km altitude respectively) by a tuned version of the Slingo (1987) cloud scheme. The presence and amount of stratiform cloud in a grid square is determined as a quadratic function of relative humidity in excess of height-dependent thresholds. Convective cloudiness is calculated as a function of vertical stability (Watterson et al. 1995).

The DARLAM runs are described in some detail by Renwick et al. (1998, hereafter referred to as R98). Two levels of nesting were used, the first at 125 km resolution from CSIRO9 output (DARLAM125) then at 50 km resolution from the 125 km output (DARLAM50). The approach is the same as that used by McGregor and Walsh (1994) to model the precipitation climatology of
Tasmania, the double nesting used to avoid numerical problems with interpolation of fields near the grid boundaries. In an attempt to capture orographically-induced climatic variation, a smoothed but relatively steep envelope orography was used in DARLAM50, with peak elevations of around 1500 m. Figure 1 shows the 50 km grid region and topography (see Figure 1 of R98 for DARLAM125 grid details). The mountain barrier in DARLAM50 begins to approximate the true extent of the Southern Alps, with a considerable region of the model South Island having elevations greater than 1000 m.

For regional climate modelling purposes, New Zealand land surface characteristics are not very well described. At spatial scales typical of RCM experiments (10-50 km), little accurate information is available on such parameters as surface albedo, surface roughness, and radiatively important aspects of vegetation cover. As noted above, surface characteristics were interpolated from global data sets, with some manual modifications based on local knowledge. A number of sensitivity tests were performed to assess the importance of land surface specifications. Plausible changes in surface characteristics

Figure 1: Model orography for the 50 km simulation over New Zealand. Contours are metres starting at 250 m, with a 250 m interval.
were found to have significant effects, particularly on surface air temperatures (Table 1, and see R98). A decrease in mean surface roughness produced frequent decoupling between the surface layer and the free atmosphere, resulting in an increased diurnal and seasonal temperature range. Changes to vegetation characteristics led to increases in surface temperature (through increased insolation) and a resultant decrease in mean sea-level pressure (MSLP). For the model runs discussed here, vegetation parameters were chosen to be broadly representative of present-day land use, and albedo and surface roughness were interpolated from the Dorman and Sellers (1989) global data set.

The model sensitivity outlined above underlines the need to develop a higher-resolution regional climatology of relevant surface parameters (e.g., plant characteristics, albedo) if the reliability of local RCM experiments is to be improved. Such a climatology may be derived from a combination of satellite information (Uddstrom and Gray 1996; Uddstrom et al. 1999) and targeted surface observing campaigns (e.g., Purdie et al. 1999).

### VALIDATION OF PRESENT-DAY CLIMATE

Validation of both the GCM and RCM is reported in detail by R98. The following is a brief summary of the main points from that study. Compared against analyses from the European Centre for Medium-range Weather Forecasts (ECMWF), CSIRO9 produces a good representation of the large-scale circulation. The main deficiencies were that the model westerlies are somewhat too strong in all seasons (mean north-south pressure gradient is approximately 20% too high) and the southerly component in the wintertime circulation is over-stated (mean west-east pressure gradient is approximately 30% too high). The mean circulation in DARLAM50 is highly correlated with that of CSIRO9, apart from topographically-induced features over the New Zealand mountains.

RCM modelled local climate was compared with data from 60 climate stations distributed around the country. Ten years’ climate data were used, to match the period of the model output. DARLAM50 mean precipitation fields captured many of the main features of the observed climate, with realistic annual totals in the heaviest rainfall regions of the South Island (up to 8 m y⁻¹). A general wet bias is due largely to the tendency for too many days of light rain in the model. DARLAM50 captures much of the observed spatial and seasonal distribution of maximum, minimum and mean temperature, with biases of < 1°C and spatial correlations of > 0.7 in most cases (correlations were calculated after the removal of a latitudinal trend from observations and model output, see R98). The mean magnitude of the diurnal temperature range (DTR) was generally well-modelled (around 10°C on average), but the spatial variability in DTR was not. Relatively small latitudinal variations about the overall mean DTR were not well-captured by the RCM, as the DTR is a difference between two parameters forced by large-scale variability and is itself prone to variations over short space scales, not well-captured by the RCM at 50 km resolution.

In the climate change experiments described below, some emphasis is put on modelled changes in cloudiness. Validation of simulated present-day cloudiness is hampered by the lack of detailed cloud statistics at more than a few land stations (Zheng et al. 1997). Modelled mean cloud amounts from the control run were compared to satellite-derived
Figure 2: Winter (JJA) $2 \times$ minus $1 \times$ CO$_2$ differences: (a) MSLP (1hPa contours) and surface winds (full barb is 2.5 ms$^{-1}$), (b) Precipitation (% contour values double at each step), (c) Mean surface air temperature (0.25 K interval), (d) Diurnal temperature range (0.25 K interval), (e) Low cloud amount (% contours as in (b)), (f) High cloud amount (% as in (b)).
estimates over the oceans surrounding New Zealand (Larsen et al. 1998; 1999). Mean cloud amounts over the DARLAM50 grid were 35%, 30% and 19% occurrence for low, middle and high respectively, about double the observed values of 15%, 19% and 10% (H. Larsen, personal communication 1999). Modelled spatial patterns of cloud occurrence were close to zonal (strongly dependent on latitude) and lacked some of the longitudinally-dependent detail seen in the observations. However, the observational database from which the cloud estimates are obtained covers only three years at this stage. Both model-derived and observed cloudiness must be treated cautiously, until a longer time-series of observed cloud data becomes available. It is worth noting that Watterson (1997) found that for the CSIRO9 GCM, cloud effects on the surface radiation balance are similar to those observed in nature, even though the model representation of clouds is quite crude.

**CLIMATE CHANGE EXPERIMENTS**

Climate change results presented here are based on an equilibrium run of CSIRO9 using an instantaneous doubling of CO₂ concentration. The climate sensitivity of the GCM is rather high with a global mean temperature increase of 4.3 K, at the high end of the generally accepted range for the sensitivity of the real atmosphere of 1.5-4.5K (IPCC 1996). However, the results presented here have not been scaled as it is not clear whether a linear scaling is appropriate, especially for precipitation. The statistical significance of modelled changes is based on t-tests, assuming independent observation every three days and allowing for variance differences between control and doubled CO₂ data sets.

Figures 2 and 3 show mean changes in a number of DARLAM50 fields for winter (June-August) and summer (December-February), respectively. The pattern of CSIRO9 changes in MSLP and surface winds is very similar to those seen in DARLAM50, and is not reproduced here. Changes in surface climate brought about by a doubling in CO₂ concentrations may be understood in broad terms as a result of the changes in the low-level circulation. Decreases in surface westerlies lead to a decrease in east-west gradients in precipitation and temperature variability.

In the RCM run, mean temperatures over New Zealand rise by around 3.5 K, about 80% of the global mean sensitivity of the GCM. Temperature increases are largest on the poleward side of the grid, associated with a general decrease in the equator to pole temperature gradient in the GCM. Temperature increases are largest in winter and smallest in summer, leading to a small decrease in seasonality. All mean temperature increases are highly statistically significant (mean temperatures from the control run reproduced the observed climatology well, as described in R98). Diurnal temperature range (DTR) changes show decreases in many regions and seasons, notably over the eastern South Island. DTR changes are significant at the 95% level only over the south-eastern South Island in winter and spring, and over the western North Island in spring and summer. The magnitude of statistically significant changes in DTR is generally around 1°C, or around 10% of the observed and modelled present-day value. No station exhibits annual-mean increases in DTR. This result is in line with many GCM-based results (IPCC 1996; Watterson 1997) and is in qualitative agreement with observed New Zealand DTR trends over the last several decades (Zheng et al. 1997).

There is considerable seasonal variation in the structure of modelled MSLP changes. In all seasons, MSLP changes of more than approximately 2hPa are significant at the 99% level. In winter (Figure 2), modelled sea-level pressure changes show a decrease in the meridional gradient (1-2 hPa higher to the south, approximately 2 hPa lower to the north), with a consequent weakening of the surface westerly circulation at New Zealand longitudes. In other seasons, changes in MSLP gradients and low-level winds are smaller, although there is an anomalous easterly component south of New Zealand in all seasons. In summer, pressures are around 3 hPa lower over the whole RCM grid, as part of a general lowering in MSLP in a broad band from northeastern Australia to the southeast of New Zealand seen in the GCM output (Watterson et al. 1995).

The patterns of change in precipitation exhibit a signature of the low-level circulation
Figure 3: As in Figure 2, but for Summer (DJF) $2 \times$ minus $1 \times CO_2$ differences.
changes. Associated with the decrease in the mean wintertime westerlies, winter rainfall increases in many eastern areas and decreases slightly in the west. In summer, there is a more general increase in precipitation, linked to the rise in temperatures and consequent enhancement of the hydrologic cycle (IPCC 1996). In all seasons, fractional precipitation increases are largest over the eastern South Island. Significance tests for mean precipitation changes were applied after a cube-root transformation, as in McGregor and Walsh (1994). Changes were statistically significant (99% level and above) over much of the eastern South Island and the southeastern tip of the North Island. However, a ten year sample is rather small for statistical significance, and a longer integration would be preferable.

Cloudiness changes may be summarised as a decrease in low cloud amounts particularly over ocean areas, and an increase in high clouds particularly over land areas, with little change at middle levels (the latter not shown). As clouds are diagnosed from the relative humidity profile, such changes imply a small decrease in low-level relative humidity and an increase in the upper troposphere, brought about by enhanced convection and a decrease in vertical stability. Over New Zealand, the largest percentage increases are over the southern South Island, a region of relatively strong warming and high model orography, again suggesting enhanced convection.

In winter especially, and over the year as a whole, there are strong spatial correlations over New Zealand between patterns of precipitation, low cloudiness, DTR and minimum temperature. Spatial correlation coefficients over the New Zealand land mass (points within 50 km of the coast) are shown for winter and summer in Tables 2 and 3, respectively. The wintertime correlations suggest that modelled DTR decreases are associated with changes in the night-time surface radiation balance, through an increase in cloudiness (and associated precipitation). In summer, DTR changes are most strongly related to changes in maximum temperature, both of which strongly reflect land-sea contrasts, with large gradients near the coasts.

The largest changes in DTR, precipitation and low cloudiness occur in the lee of the highest topography (eastern South Island), the region most sensitive to changes in the strength of the westerly winds, in the winter season when the westerlies decrease the most. While the link between low cloud, precipitation and DTR is physically plausible, it may be that changes in all three parameters are driven by changes in the strength of the westerlies. Statistically significant modelled 2 x CO₂

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<th>DTR</th>
<th>T&lt;sub&gt;max&lt;/sub&gt;</th>
<th>T&lt;sub&gt;min&lt;/sub&gt;</th>
<th>Low Cloud</th>
<th>High Cloud</th>
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<tr>
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<td>0.59</td>
<td>0.86</td>
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<td>0.38</td>
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Table 2: Wintertime (JJA) spatial correlation coefficients between RCM modelled changes in precipitation (%), DTR, maximum/minimum temperature, low and high cloudiness (%). Grid points only over New Zealand or within 50 km of the coast have been used.

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<th>DTR</th>
<th>T&lt;sub&gt;max&lt;/sub&gt;</th>
<th>T&lt;sub&gt;min&lt;/sub&gt;</th>
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<td>0.10</td>
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Table 3: Summertime (DJF) spatial correlation coefficients between RCM modelled changes in precipitation (%), DTR, maximum/minimum temperature, low and high cloudiness (%). Grid points only over New Zealand or within 50 km of the coast have been used.
wintertime changes in MSLP (approximately 2 hPa) are the same order of magnitude as the differences between the control run and observed MSLP fields (R98). Hence, the rather large magnitude wintertime changes in precipitation and related fields in eastern regions should be treated with caution.

**SUMMARY**

The results described in R98 show that statistics of the New Zealand climate may be well modelled by a high-resolution RCM nested within the output of a coarse-resolution GCM. However, the model's surface climate is sensitive to land surface and vegetation parameters used in the canopy algorithm. The sensitivity is strongest for surface air temperatures, but feeds right through to a discernible mean influence on precipitation and even MSLP fields. To improve the reliability of regional climate and climate change modelling, more research is required to properly specify the NZ land surface in terms of albedo, roughness length and characteristic vegetation types.

The RCM shows a mean decrease in DTR over New Zealand with a doubling of CO₂ concentration, consistent with recent observed trends (Karl et al. 1993; Zheng et al. 1997). Spatial correlations between patterns of simulated changes in DTR, precipitation, low cloudiness and minimum temperature suggest that DTR decreases in the model are related to changes in the night time surface radiation balance resulting from an increase in low cloudiness. The question of whether observed DTR trends are related to cloudiness changes is not currently addressable, as suitable time series of cloud properties are lacking. To investigate this question further, and to facilitate future model validation work, longer time series of satellite-based cloud information must be developed (e.g., Larsen et al. 1999).

Modelled changes in precipitation and cloudiness are strongly related to mean circulation changes, especially in winter. Both GCM and RCM results show a decrease in the mean strength of the westerlies, which is typical of such equilibrium climate change experiments. Evidence from recent transient CGCM runs suggests that in the short to medium-term (next 100 years or so), the strength of the westerlies may remain roughly constant or may increase in the New Zealand region (Whetton et al. 1996). This behaviour is associated with the sequestration of heat in the southern ocean and a consequent initial increase in the meridional temperature gradient (e.g., England and Hirst 1997).

Because of the tight coupling between the circulation and regional climate, such inter-model differences are very important for climate change scenarios. While the results presented here are internally consistent, GCM simulations showing increased westerlies through the 21st century would result in different changes in precipitation over New Zealand, at least. The modelled changes shown here may be more indicative of New Zealand three or four centuries in the future. There is a need to develop regional scenarios for New Zealand based on a range of different GCM results.

**ACKNOWLEDGEMENTS**

The authors wish to thank many members of CSIRO Atmospheric Research for useful discussions, particularly E. Kowalczyk and P. Whetton. The first author is grateful to Barrie Hunt for making CSIRO resources available. Two reviewers provided useful comments which helped to clarify some points. Thanks to Howard Larsen and David Wratt for insightful comments on an earlier draft. This work was funded by the New Zealand Foundation for Research Science and Technology under contracts CO1522 and CO1628.

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