A Comparison of Statistical and Model-Based Downscaling Techniques for Estimating Local Climate Variations

JOHN W. KIDSON AND CRAIG S. THOMPSON

National Institute of Water and Atmospheric Research, Ltd., Wellington, New Zealand

(Manuscript received 3 January 1997, in final form 28 July 1997)

ABSTRACT

The respective merits of statistical and regional modeling techniques for downscaling GCM predictions have been evaluated over New Zealand, a small mountainous country surrounded by ocean. The boundary conditions were supplied from twice-daily European Centre for Medium-Range Weather Forecasts analyses at 2.5° resolution for the period 1980–94, which were taken as the output of a ''perfect'' climate model. Daily and monthly estimates of minimum and maximum temperature and precipitation from both techniques were validated against readings from a network of 78 climate stations.

The statistical estimates were made by a screening regression technique using the EOFs of the regional height fields at 1000 and 500 hPa, and local variables derived from these fields, as predictors. The model interpolations made use of the RAMS model developed at Colorado State University running at 50-km resolution for 1990–94 only. The model values at the nearest grid point to each station were rescaled using a simple linear regression to give the best fit to the station values.

The results show both methods to have comparable skill in estimating daily and monthly station anomalies of temperatures and rainfall. Statistical estimates of monthly departures were better obtained directly from monthly mean forcing than from a combination of daily estimates; however, daily values are needed if one wishes to estimate variability.

While there are good physical grounds for using the modeling technique to estimate the likely effects of climate change, the statistical technique requires considerably less computational effort and may be preferred for many applications.

1. Introduction

The horizontal resolution of current general circulation models (GCMs) is generally too coarse to represent regional climate variations on scales needed for assessment of their economic and social impact. The efforts to bridge this gap have been reviewed by Giorgi and Mearns (1991) and, subsequently, in the recent International Panel on Climate Change report (IPCC 1995). The principal techniques involve a semiempirical (statistical) approach or the use of regional climate models nested within a GCM.

Statistical techniques have their origin in the model output statistics (MOS) and ''perfect prog'' approaches to forecasting surface weather elements (e.g., Klein 1982; Glahn 1985). They include the use of regression analysis (e.g., Kim et al. 1984; Klein and Bloom 1989; Karl et al. 1990; Hewitson 1994), canonical correlations (von Storch et al. 1993), and neural networks (Hewitson 1997). While correlation techniques may be appropriate to continuous variables such as temperature, they are less applicable to precipitation and other elements, which show little continuity from day to day. This has prompted the use of weather typing schemes coupled to stochastic weather generators (e.g., Mearns et al. 1984; Bardossy and Plate 1992; Wilks 1992; Wilson et al. 1992; Zorita et al. 1995).

Regional modeling techniques have been attempted by a number of groups in order to evaluate their skill in simulating local climate with boundary conditions specified from analyses of observations (e.g., Bates et al. 1995; Jones et al. 1995; Podzun et al. 1995), or to specify local climate change from forcing by a GCM (e.g., Giorgi et al. 1994; Semazzi et al. 1993; Hirakuchi and Giorgi 1995; Jones et al. 1997). In most of these examples the outermost rows of the regional model have been subjected to a relaxation process in an attempt to ensure that the larger-scale components of the regional flow are preserved within it. Newer techniques involve the use of spectral boundary conditions (Kida et al. 1991; Sasaki et al. 1995) so that the large-scale components from the GCM are augmented by the high wave-

Corresponding author address: Dr. John W. Kidson, National Institute of Water and Atmospheric Research, Ltd., 301 Evans Bay Parade, Greta Point, P.O. Box 14-901 Kilbirnie, Wellington, New Zealand.
E-mail: j.kidson@niwa.cri.nz

© 1998 American Meteorological Society

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

number components generated by the regional model. Typically the regional model has a grid spacing on the order of 50 km and covers an area with sides of several thousand km. The optimum size of the grid is determined by the need to constrain the large-scale components of the solution while still allowing the development of finescale features without damping or distortion from the lateral boundaries (Jones et al. 1995).

These interpolation techniques are not only useful for local estimates of climate change but are also likely to be applicable to the output from proposed global climate forecasting centers, such as the International Research Institute for Climate Prediction (IRI 1995). Such centers may also be expected to distribute coarse-resolution global forecasts for regional application centers to develop local forecasts of appropriate climatic and hydrological variables. From a daily forecasting viewpoint it is also instructive to compare the accuracy of both statistical and modeling techniques to predict local weather elements, given sets of coarse-resolution forecasts from a global center. At issue is the potential benefit to a smaller meteorological service of developing a mesoscale modeling capability of its own, compared to following the less demanding statistical approach.

While both statistical and dynamical methods have been used and promoted widely, there appear to have been few, if any, comparisons of their relative skill in predicting local weather and climate variations. Both methods are, of course, susceptible to errors in the large-scale flow (e.g., Mitchell et al. 1987; Giorgi and Mearns 1991). To compare their performance in ''ideal'' conditions, this study provides input to both with analyses from a global analysis and weather forecasting system, which is presumed to represent accurately the large-scale features of the circulation. The interest is not necessarily in seeing how well regional climate variations can be reproduced by a nested mesoscale model but whether the model output contains signals from which the correct daily or monthly variations in temperature and precipitation can be inferred.

New Zealand provides an excellent opportunity for this comparison. As Fig. 1 shows, it is a mountainous country with the principal ranges extending from the southwest to the northeast of the South Island, where they reach elevations exceeding 1500 m, and parallel to the east coast of the North Island. The interactions of weather systems with the orography causes marked regional climatic variations and considerably wetter conditions on the west coast of the South Island, which lies in the path of the prevailing westerlies (e.g., Maunder 1971; Sturman and Tapper 1996).

The model-based interpolation makes use of the RAMS model (Pielke et al. 1992) with boundary forcing provided by twice-daily analyses at 2.5° resolution from the European Centre for Medium-Range Weather Forecasts (ECMWF) from 1990 to 1994. Regression estimates are computed using indicators of local and regional flow derived from these same analyses as predictors over both the 1990–94 period and a longer 15-yr sample from 1980–94. Variance reductions achieved by the regression approach are compared to squared correlation coefficients between RAMS and observed daily maximum and minimum temperatures and precipitation from a network of 78 climate stations.

2. Data and methods

a. Boundary forcing

The basic level III dataset from the ECMWF between 1980 and 1994 provided both boundary forcing for the RAMS model and input to the statistical forecasting procedures. This dataset has a resolution of 2.5° lat × 2.5° long and is available twice daily at 0000 and 1200 UTC. For the 1980–89 period the data were supplied at seven levels—1000, 850, 700, 500, 300, 200, and 100 hPa. Between 1990 and 1993 the number of levels was increased to 14 with the addition of 400, 250, 150, 70, 50, 30, and 10 hPa data, and in 1994 the 925-hPa level was also added. The fields provided included the geopotential height, temperature, wind components, and relative humidity. All variables except the vertical motion, ω, were used to provide boundary conditions to the RAMS mesoscale model, but only the 1000- and 500-hPa geopotential heights were used in the statistical analysis.

The quality and representativeness of this dataset have been reviewed by Trenberth and Olson (1988). Differences with corresponding analyses from the National Meteorological Center (now the National Centers for Environmental Prediction) in Washington were small in areas with good observational coverage, where both can be considered reliable.

b. Station data

The results of both prediction techniques were evaluated against the daily readings from a selection of 78 climate stations from a network maintained by the National Institute of Water and Atmospheric Research (NIWA). From Fig. 1 we see that these provide good coverage over most of New Zealand. Following standard climatological practice, daily readings were made at 0900 LT of accumulated precipitation, R, and maximum and minimum temperatures, T_x and T_n, over the 24-h period. The minimum temperature was assumed to have occurred on the morning of the observation and was credited to that day, while the maximum temperature and accumulated precipitation were assigned to the previous day. New Zealand Standard Time is 12 h ahead of Universal Time so that the local readings were made at 2100 UTC in winter (approximately March–October) and at 2000 UTC in the summer months. The change in observation time over the summer months should not affect the temperature extremes and should have only a minor impact on the accumulated precipitation. In a

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

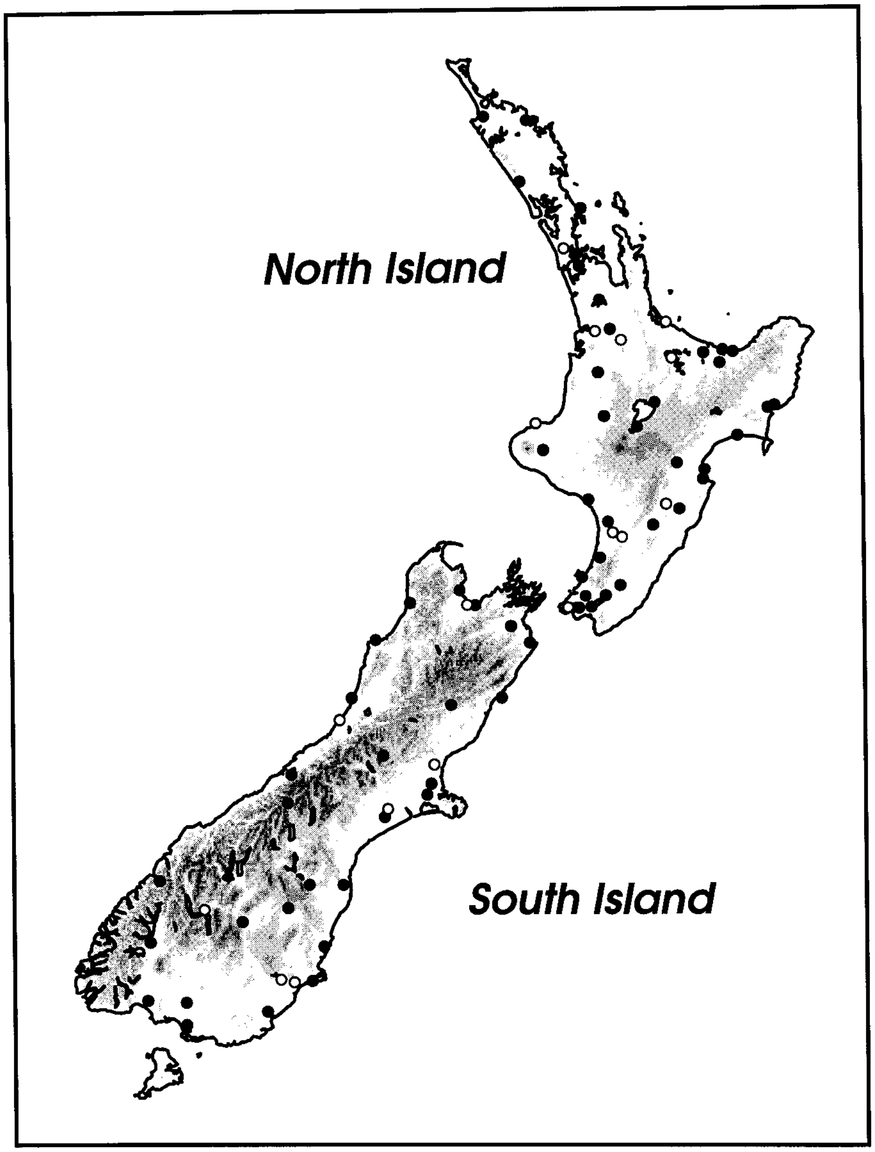


FIG. 1. Locations of the 78 climate stations used to assess the performance of the prediction techniques superimposed on a relief map of New Zealand. Stations plotted as an open circle had inadequate coverage for the 1990–94 period. The shading indicates 500-m contours, with the darkest band showing land above 1500-m elevation.

small number of cases precipitation was reported as an accumulation over several days rather than as discrete 24-h totals. This will result in a slight degradation of skill in the daily precipitation forecasts but should affect the two interpolation techniques equally.

The annual cycle, expressed as a sum of 12- and 6-month Fourier components, was removed from the temperature data before its use in either interpolation scheme. A cube root transform (WMO 1983; Katz and Acero 1994) was applied to daily precipitation data to obtain a more normal distribution for the regression analysis and led to better results than obtained from the untransformed data. No transformation was applied to monthly totals.

The station records proved to be less complete for 1990–94 than for 1980–89 with only 60 stations having precipitation data and 59 temperature data for at least half of the 60 months. This subset of the data (indicated by closed circles in Fig. 1) was used to interpret the RAMS model results and to compare variance reductions with those obtained by the statistical technique.

Since daily precipitation totals, in particular, lack continuity between adjacent stations we also attempted validations against areal averages obtained through rotated

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

principal component analysis (e.g., Richman 1986) of daily station values. The explained variances were generally similar to, or less than, those for individual stations in the same areas and this approach was abandoned.

c. Statistical downscaling

For the statistical downscaling only the 1000- and 500-hPa height fields between 160°E–175°W and 25°–55°S were used as predictors. Previous testing on multilevel synoptic classification schemes (Kidson 1997), suggested there was little independent information at the 850- and 700-hPa levels. The annual cycle was first removed as the sum of 12- and 6-month Fourier components and the significant variation over the 143 grid points in the region was isolated by S-mode EOF analysis (Richman 1986). Five EOFs were obtained at each level from analysis of the daily anomaly patterns between 1980 and 1989, in each case accounting for 93.6% of the variance. The resulting EOF patterns were similar at each level apart from a westward slope with height. They will not be reviewed here as their main purpose was to represent the significant variance of the regional height fields with the smallest possible number of predictors. The series of the time coefficients was extended to 1994 with data that were subsequently obtained. For further details of the method and the individual patterns, see Kidson (1997).

In addition to the 1000- and 500-hPa EOFs, local predictors were computed at each 2.5° grid point and the nearest of these predictor sets was used for each station. These local variables comprised the anomalous geostrophic wind components u and v; the scalar wind speed, $F = (u^2 + v^2)^{1/2}$, at 1000 and 500 hPa; the anomalous 1000–500-hPa thickness and 1000-hPa relative vorticity; and terms proportional to the advection of 1000–500-hPa thickness and 500-hPa relative vorticity. No other information from the ECMWF analyses was used, as temperatures may be inferred from the thickness data, while vertical motion and relative humidity data were considered unreliable (e.g., McNally and Vesperini 1996).

The statistical estimates were obtained using the screening regression technique (e.g., Draper and Smith 1981). Each regression equation was limited to a maximum of five predictors and each predictor had to provide a minimum variance reduction of 1% at a significance level of 1% using a standard F test for the ratio of the variances. No assumptions were made about serial correlation reducing the effective number of degrees of freedom in the F test. This is likely to affect relatively few of the equations where the last predictors selected had passed the other two selection criteria. There should be minimal effects on the explained variance.

The first author's previous experience in statistical weather forecasting for New Zealand stations has shown little or no advantage in deriving separate equations for different seasons, even though the variance of the forecast elements changes significantly throughout the year. (The standard deviation of daily minimum temperature increases by a factor of 1.5 to 2 from spring to summer, maximum temperature by 2–3 from winter to summer, and precipitation by an average of 2 from spring to summer–autumn). The influence of these changes on explained variance is evidently small because the regression equations tend to express linear physical relationships such as that between 1000- and 500-hPa thickness and surface temperature, or the effects of onshore winds. In view of this previous experience and the relatively short validation period common to both downscaling techniques, the derivation of regression equations for individual seasons was not attempted. It was assumed that any disadvantage would apply equally to both techniques.

The explained variances were found to differ by a few percent between separate subsamples of the 15-yr period and reductions of this order on independent data would also be expected. For example, the application of equations developed for minimum temperatures over 1980–89 to the 1990–94 period gave a mean drop in explained variance of 3.9%. For comparison with the RAMS model output, regression equations were derived for the entire 1980–94 period and the variance reductions on this dependent dataset are presented, along with those for the same equations applied to the 1990–94 period only.

d. Local area mesoscale modeling

The RAMS model was chosen to simulate the regional climate since it is a state of the art mesoscale model with advanced parameterizations of physical processes (Pielke et al. 1992; Walko et al. 1995a). It is used, both internationally and within NIWA, for mesoscale meteorological and air quality investigations. RAMS has been modified for use in regional climate studies (Copeland et al. 1996) and has the capability to interface with global model output. It was set up to interpolate from the 2.5° ECMWF grid onto a grid with 50-km resolution covering New Zealand and the ocean areas around it (Fig. 2). The local grid extends farther to the west from where most weather systems approach, under the influence of the prevailing winds. The choice of the east–west extent of the grid and its position relative to central New Zealand were guided by the criteria of Phillips (1990), assuming a mean zonal wind speed of $\sim$25 m s^{-1} and updating of the boundary values at 12-h intervals. The north–south dimensions are, however, smaller than recommended by Phillips to reduce the computational requirements.

As will be seen in section 3, the size of the grid appears to be adequate to allow regional climatic variations to develop over New Zealand without any obvious interference from the boundaries. It was found later that convective precipitation estimates were not

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

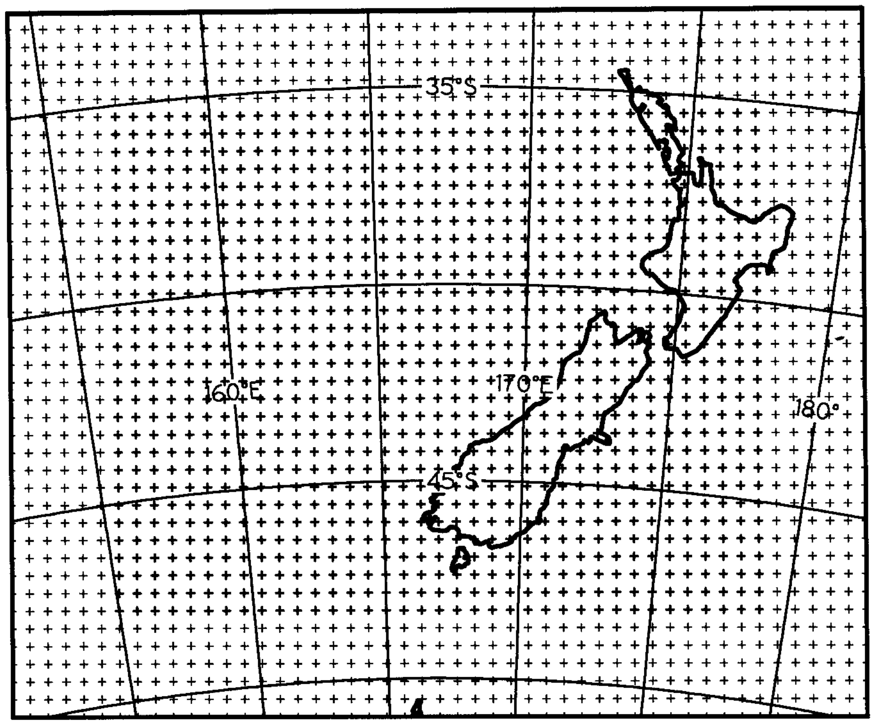


FIG. 2. The grid specified for the RAMS model, comprising 49 × 41 points at 50-km resolution. The outermost six rows, indicated by the lighter crosses, have a nudging adjustment applied from the ECMWF boundary values.

available for the outer rows of the grid where the boundary values are adjusted to match the large-scale forcing. This convective contribution is missing from the total precipitation in the extreme north and east of the North Island.

1) MODEL OPTIONS

We used the recently released version 3b, with modifications dating from early 1996, taking, in most cases, the options recommended in the current user guide (Walko et al. 1995b). The remaining parameter selections were as follows.

- The grid shown in Fig. 2 has 49 × 41 points at 50-km spacing and 23 levels in the vertical up to a height of 18.5 km. The spacing between levels increased with height from 100 m at the surface to 1.5 km at the top. There were five levels below ground in the soil model with the lowest at 0.5 m.
- The nonhydrostatic, hybrid time-differencing scheme was used with a time step limited to 100 s by the stability of the convection scheme.
- The Mahrer–Pielke long- and shortwave radiation schemes were applied with updates at 1200-s intervals.
- The full microphysics options were selected, involving all types of hydrometeor with default values for the particle sizes.
- The outermost six rows of the grid were updated by nudging with linearly interpolated values from the ECMWF analyses at 12-h intervals. A timescale of 1200 s was applied at the outermost row increasing to 21 600 s at the sixth row in.
- The surface properties were set as follows.
  - (i) An envelope orography (Wallace et al. 1983) was specified as shown in Fig. 3. This reproduces the main topographic features in Fig. 1. Somewhat greater fidelity would be achieved by the choice of a 25-km grid but at a significant cost in computer time.
  - (ii) The mean sea temperature for each month was interpolated at each grid point from a monthly mean dataset with 2° spatial resolution prepared by the Climate Analysis Center in Washington, D.C. (Reynolds 1988).
  - (iii) The surface vegetation type was obtained from the 1° climatology of Dorman and Sellers (1989) as subsequently modified by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Atmospheric Research (Kowalcyk et al. 1991). This climatology has type 12 (crops and trees) covering most of the country, which was assigned to

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

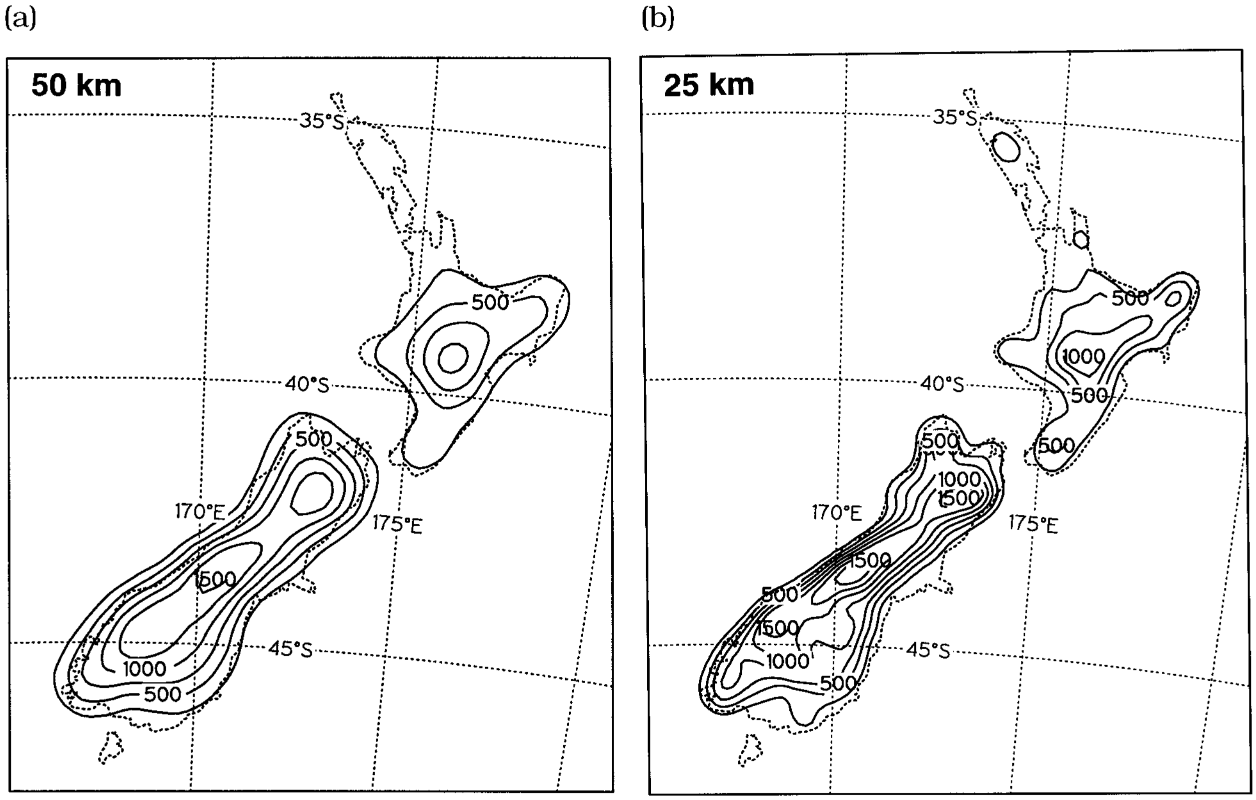


FIG. 3. Model orography as defined for the 50-km grid used for the comparison with statistical results, and for a 25-km grid showing the potential gain in resolution. Contour interval is 250 m.

RAMS type 1 (crop/mixed farming). Over the west coast of the South Island, CSIRO type 4 (Needleleaf evergreen) was assigned to RAMS type 3 (evergreen needleleaf).

(iv) Soil textures were also set to the Kowalcyk et al. values and a straightforward mapping to RAMS values was possible for each of the types (sand–loamy sand, clay loam–silt loam, clay, sand loam–loam, and silty clay) encountered over New Zealand. The initial moisture content of the soil was set to 0.5 of the maximum at each level.

(v) The surface roughness was set to the monthly values in the Kowalcyk et al. climatology, and ranged from a few cm to around 1 m, depending on the time of year.

Ground temperature and soil moisture are subsequently forecast by the model and result in changes in the surface albedo. Sea surface temperatures and surface roughness remain constant for the duration of the run.

The grid area, resolution, and time step were chosen to give the best representation of local weather that was possible while allowing the project to be completed within a reasonable time. The computer used for the forecasts was a DEC2100 SMP Unix system with model 5/250 processors, each of which is approximately one-third of the speed of a Cray Y/MP processor. The 5-yr simulation was carried out as a series of 60 1-month runs, to minimize operator intervention and allow the appropriate surface boundary conditions to be set. The initial values were interpolated by the RAMS software from the complete set of ECMWF fields for 0000 UTC on the first day of the month. The 5-yr integration at 50-km resolution took approximately 3 months to complete. Runs at ~20 km-resolution would have taken almost 4 yr and were clearly not feasible.

2) POSTPROCESSING

Output fields were written every hour, including the temperature, accumulated precipitation (both resolved and subgrid-scale convective), and scalar wind speed. Subsequent processing provided integrals of both forms of precipitation over 24-h periods ending at 2100 UTC and the maximum and minimum hourly temperatures encountered over the same period, allowing a direct comparison with the climate station records. The annual cycles in the model's maximum and minimum temperatures, obtained by fitting 12- and 6-month harmonics, were removed from the daily values at each grid point

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

while the daily precipitation totals were transformed to the same 0.33 power as the daily station values. The skill of the model's predictions was assessed by correlating station values with those at the nearest model grid point. Preliminary results showed that the results were almost identical to correlations with model variables interpolated to the station locations. The correlation process was necessary to allow for biases in the model climate and because the local climate can vary considerably with topography and surface properties over a 50-km grid square. The difference in station height from the smoothed orography used by the model was 500–750 m in some locations near the South Island ranges, so that discrepancies of several degrees might be expected in the model temperature estimates. The question at issue here was not whether the model can represent the climate at an individual station exactly, but whether it provides the information that would allow the deviations in the climatic elements to be inferred more accurately than by a purely statistical approach.

For convenience in presenting the results, the variance reductions for each station were subjected to a Cressman-type analysis (Cressman 1959) to interpolate them onto a 28-km grid covering New Zealand. Four scans were used with radii decreasing from 196 to 49 km, preserving horizontal scales greater than ~100 km, in line with the 50-k spacing of the RAMS grid.

3. Model climate

While our concern here is directed at the model's ability to predict departures from the ''normal'' climate at New Zealand land stations, it is also of interest to see how well it is able to represent local variations in the pressure, temperature, and precipitation fields. The presence of these mesoscale variations is essential if the model estimates are to improve on those derived from the coarse resolution fields from the global model. It is less clear, however, whether an accurate representation of the local climate is necessary if departures from the seasonal means are to be predicted successfully.

a. Temperatures

Examples of the mean temperature computed from the RAMS model output and the mean of the 0000 and 1200 UTC 1000-hPa temperatures are shown in Fig. 4 for summer and winter months, January and July 1990. In January, both models show similar magnitude in their land sea contrasts, but the RAMS model fields have sharper gradients and the maximum temperatures are displaced to the east of the South Island mountains. The RAMS model has also been able to depict higher temperatures over the relatively narrow area of land in the north of the North Island. In July 1990 the land–sea contrasts in the RAMS output are much sharper than in the ECMWF fields and are similar in magnitude to those shown by both models in January 1990. In both months the RAMS surface temperatures corrected to mean sea level are 1°–2°C higher than those from the ECMWF data, but because the methods to obtain them differ, the absolute values are not strictly comparable.

The model's mean maximum and minimum temperatures are both strongly linked to the surface elevation, decreasing at ~0.5°/100 m. To verify these against the corresponding station values, the model temperatures were adjusted by applying the optimum lapse rates determined by Zheng and Basher (1996) over the height difference between the station and the interpolated model surface elevation. The height difference ranged from 250 m over much of the coastline (Fig. 3a), due to the relatively coarse grid, to 500–750 m for some South Island stations in mountainous regions.

The model's maximum temperatures were 0°–4°C lower than those observed for the mean of January 1990–94, while its July maxima were close to that observed for much of the country. In January the model's minimum temperatures were too high by 4° in the north of the North Island; elsewhere they were up to 2°C too high. In July the RAMS minima were generally too high by 0°–4°C. Over the whole country, the observed diurnal temperature range of 6°–14°C, depending on location and season, typically exceeded the model's temperature range by 2°C.

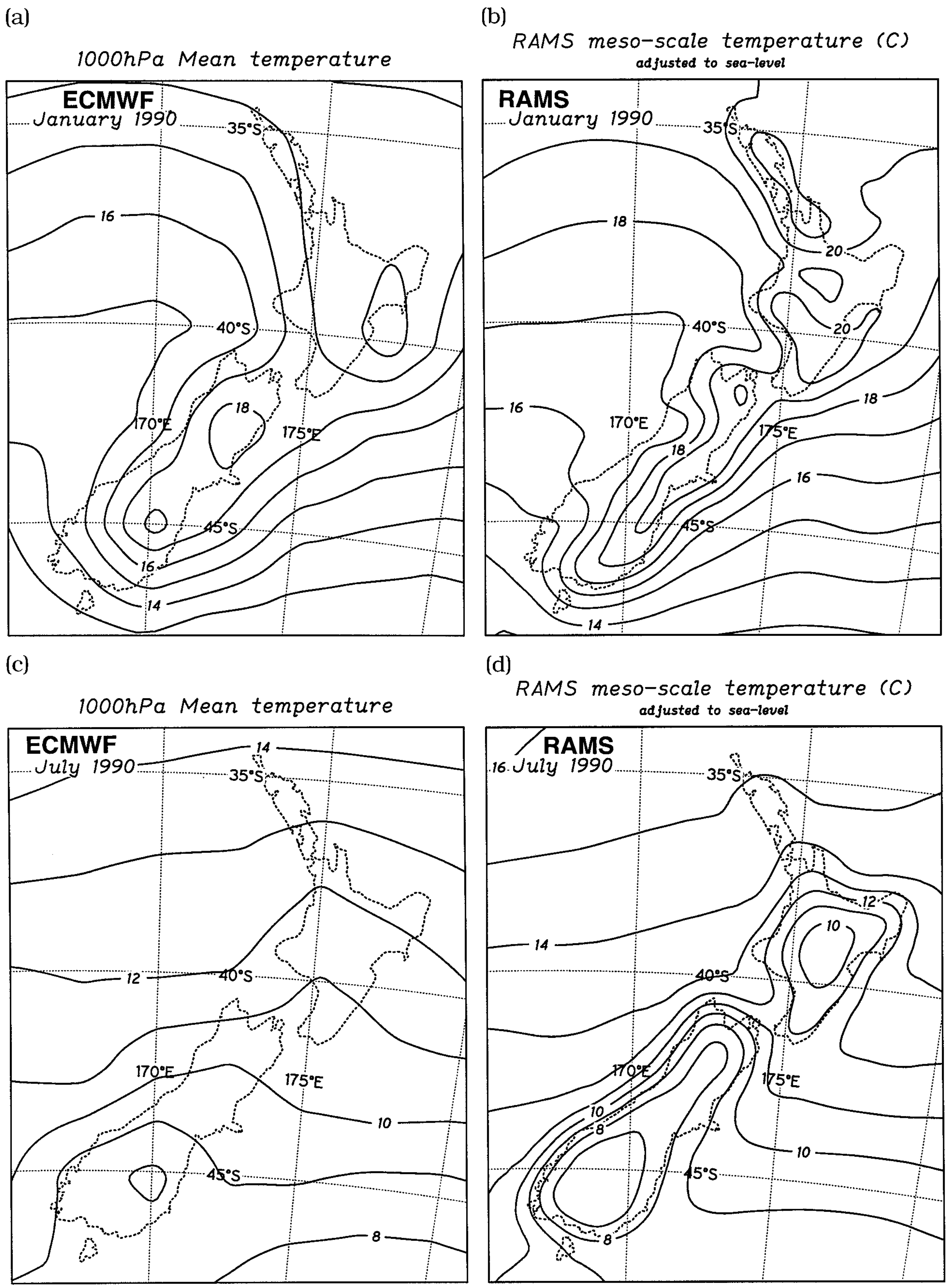
The mean diurnal cycles at Auckland Airport (37.0°S, 174.8°E) and Christchurch Airport (43.5°S, 172.5°E) were also compared for the January and July means over the 1990–94 period. Comparisons of hourly values (Fig. 5) at these stations with contrasting climates show that the model gives a realistic simulation of the observed diurnal cycle in January with an amplitude of ~2°C greater than observed at Christchurch. In July the mean model temperatures are higher than the observed values by 1°–2°C, while the range is approximately 1°C smaller in Auckland.

b. Precipitation

The 78-station network is unable to represent detailed variations in precipitation around the country, particularly in the west of the South Island, but the major features are revealed by Fig. 6. The largest annual means are observed on the west coast of the South Island, where the prevailing west-southwest winds impinge on the Southern Alps (e.g., Sturman and Tapper 1996). The analyzed values exceed 7000 mm, in contrast to the areas in the lee of the mountains where they are typically less than 1000 mm.

In the North Island, the annual totals are on the order of 1000 mm, somewhat more on the west coast in areas exposed to southwesterly flow, and rather less along the east coast. The mean annual precipitation from the RAMS model follows this same pattern, with the highest values along the west coast of the South Island. The annual totals in Fig. 6b are down by about a factor of two to three compared to the observed values in Fig.

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC



Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

6a. The resolved or synoptic-scale component in Fig. 6c is responsible for most of the South Island precipitation and is the major contributor in the central North Island. The convective precipitation[1] (Fig. 6d) is the main contributor in the north of the North Island and is comparable with the resolved precipitation on part of the east coast of the South Island.

Part of the reason for the systematic underestimation of total precipitation is likely to be the smoothed orography and the weaker vertical motions that result. Previous results from the RiMM[2] mesoscale model over New Zealand coupled to the precipitation scheme of Sinclair (1994) have shown that rainfall is strongly influenced by the slope of the terrain. Peak precipitation rates in Sinclair's model increase threefold as the grid resolution is reduced from 50 km to its optimum spacing of 10–15 km. For one case study over the South Island using the RAMS model at resolutions from 80 to 1.25 km, Revell et al. (1995) found that 12-hourly precipitation totals doubled as the resolution increased from 80 to 20 km. A further doubling resulted from a reduction in grid spacing to 5 km. Renwick et al. (1998) also showed when running the CSIRO DARLAM model over New Zealand that increasing the terrain height led to more spatial and temporal variability and higher mean precipitation.

c. Stability of monthly runs

The daily series of mean maximum and minimum temperature departures from the model's mean annual cycle at each station location for each day of the month have been averaged over the 1990–94 period and are shown in Fig. 7. None of the mean deviations exceed 0.9°C and they are not significant at the 5% level. Time series of daily precipitation totals plotted by day of the month also show no obvious trend.

These series show that the regional model's climate is essentially stable throughout the course of a 1-month run with little evidence for an initial ''settling-in'' period or a subsequent drift. Model runs for longer than 1 month appear to be possible but are presently ruled out by the technical requirement that the sea temperature and surface roughness be held at their initial values.

[1] The convective rainfall was not computed at boundary points influenced by the ''nudging'' process and is not available over the extreme north and east of the North Island.

[2] The RiMM mesoscale model was developed by Dr. Roger Ridley of NIWA. It was based on the Pielke model, which was a forerunner of RAMS and had no radiation or microphysics components.

4. Regression analysis

a. Daily predictions

The variance reductions achieved in estimating daily station anomalies for the entire 15-yr period by the screening regression technique are shown in Fig. 8. For maximum temperature, T_x, the predictor sets described in section 2c were made available to the regression routines at local noon (0000 UTC) and the following midnight, to bracket the afternoon period in which the maximum usually occurs. The largest variance reductions, some in excess of 70%, are found down the east coast of both islands in the lee of the mountain ranges where the temperatures are most variable. The effect is to produce a standard error of around 2°C over most of the country, regardless of the initial temperature variance. The 1000–500-hPa thickness at local noon was the principal predictor over most of the country but, east of the ranges in both islands, indicators of westerly wind strength were also important and became the leading predictor at a number of South Island stations. On the northwest coast of the South Island the 500-hPa EOF corresponding to westerly flow was the only major predictor. In these cases where high variance reductions were achieved, up to 80% of the overall variance reduction came from the first predictor.

For minimum temperature, T_n, the regional and local predictor sets were specified at local midnight (1200 UTC) and noon, preceding and following its most probable time of occurrence by a few hours. The variance reductions are relatively uniform across the country, ranging generally between 40% and 55%, except for the southeast of the South Island where the weather is most changeable. The principal predictors chosen were all from 1200 UTC. In all but seven cases the 1000–500-hPa thickness anomaly was the principal predictor, explaining up to 48% of the variance, but this relation breaks down in the southeast of the South Island where it drops to below 20%. In the remaining seven stations, located in the southern North Island, a predictor representing northerly flow was the first choice. The second predictor selected after the thickness anomaly was typically an indicator of the anomalous northerly flow or of the surface wind speed.

Several power-law transformations were applied to the daily rainfall to try to improve the performance of the regression equations (e.g., Katz and Acero 1994). The use of a cube root (i.e., $R^{0.33}$) transform gave slightly better results than were obtained for a square root or fourth-root transform and these are presented in Fig. 8c. The regional and local predictors were specified at local noon (0000 UTC) 3 h after the start of the daily ac-

←

Fig. 4. Mean 1000-hPa temperatures from the ECMWF model for January and July 1990, and the mean surface temperature from the RAMS model for the same months, adjusted to sea level (units °C).

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

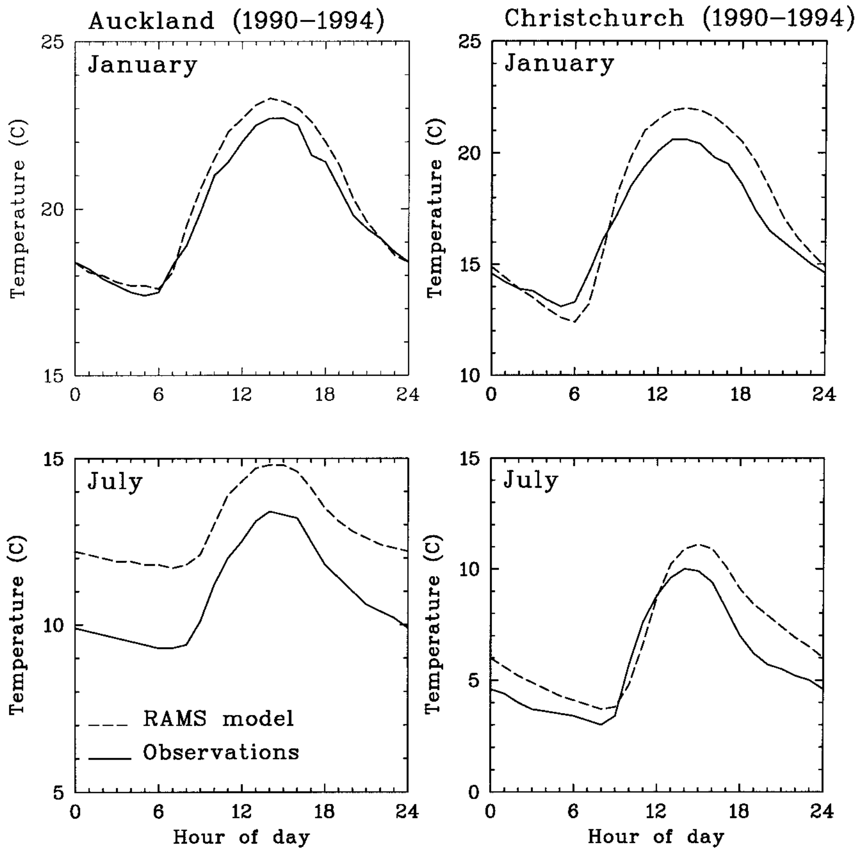


FIG. 5. Mean observed and model diurnal temperature cycles at Auckland and Christchurch airports for January and July 1990–94.

cumulation and for the following two 12-h observation times. The best predictions are found along the west coast of the South Island where variance reductions are ~40%. A similar figure is obtained in the far north of the country. In the east of the North Island, the reductions fall to around 30%, while some reductions below 20% are found in places along the South Island's east coast. Inspection of the regression equations showed that the most useful predictors were a local meridional wind component at either 1000 hPa or, less frequently, 500 hPa in the north of the country, an EOF component representing northerly flow over the west of the South Island, and a zonal wind component at 1000 or 500 hPa on the east coast of the North Island. As little as 30% of the total explained variance came from the first predictor.

In summary, northerly flow is the key predictor west of the mountain ranges, while easterlies also have a small influence east of the North Island ranges. These are not very good results and little was able to be done to improve them. Stratifying the synoptic situations into the seven categories defined by Kidson (1997) and deriving separate regression equations for each class led to only a slight improvement. The overall mean variance reduction was increased in this way from 29% to 34%, but this corresponds to a mean decrease in the standard error of only 3.6%.

While skill in forecasting daily rainfall amounts is very small, using the regression technique, the results of predicting the probability of daily rainfall exceeding a particular threshold were a little better. In this case, the predictand was set to have a value of 1 if this limit was equaled or exceeded and 0 otherwise. The variance reductions were found to increase as the threshold decreased. For the conventional climatological threshold of 0.1 mm that defines a ''precipitation day'' (WMO 1983), explained variances were 2.4% higher than for rain amount. The patterns were generally similar.

b. Regression analysis for 1990–94

Since the model interpolations were limited to 1990–94, regression estimates of daily values were also made for this period only but using the same equations derived for the 1980–94 period. The overall patterns of variance reduction were similar to those for 1980–94 and the difference in mean explained variance for the 75 stations reporting temperatures and the 74 with precipitation data over this period was not significant. The variance ex-

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

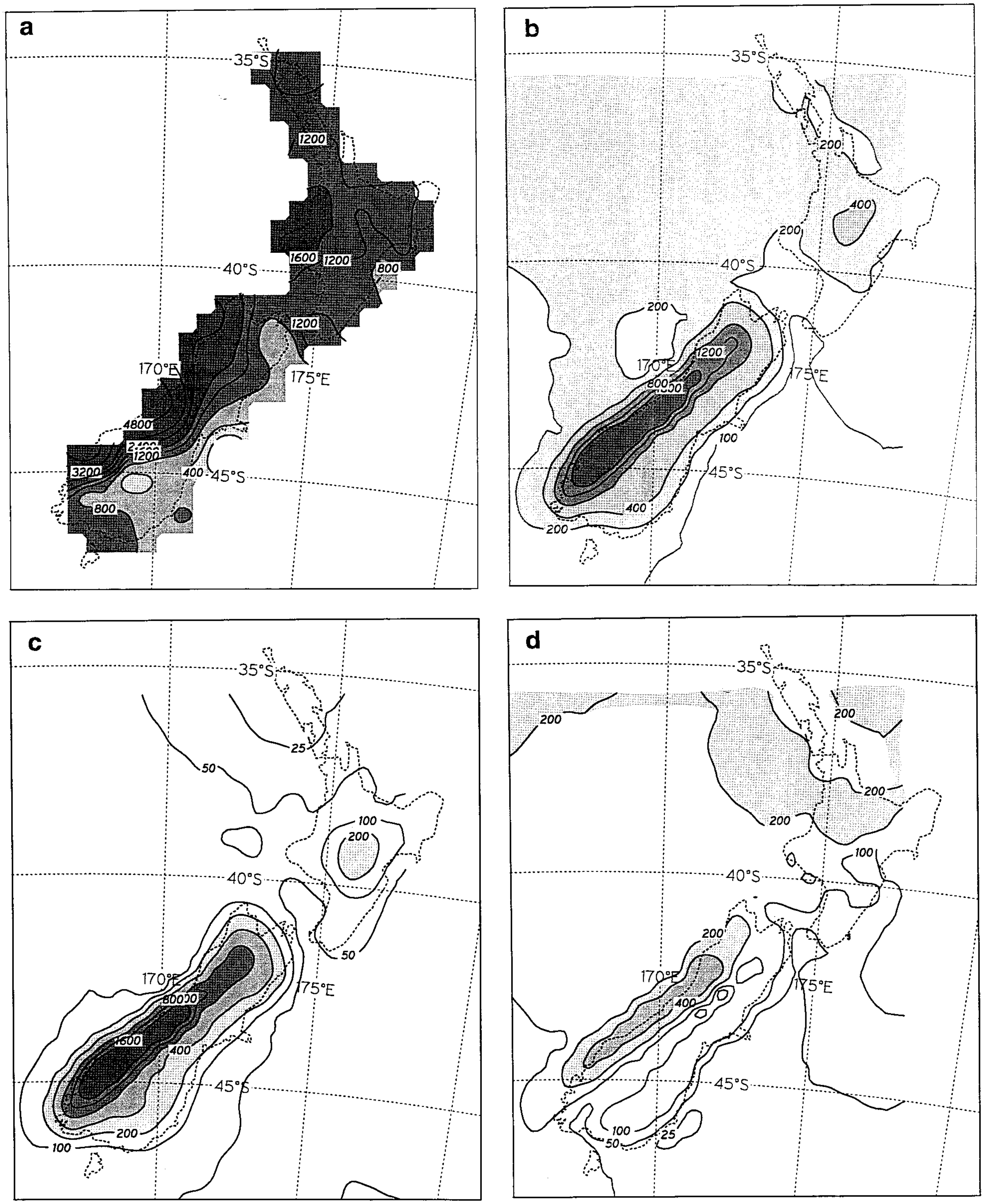


Fig. 6. (a) Mean annual precipitation for New Zealand derived from the 78-station network. (b) The mean annual precipitation derived from RAMS output for 1990–94, and its synoptic-scale (c) and convective (d) components (units mm, contours at 200, 400, 800, 1200, 1600, 2400, 3200, and 4800 mm).

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

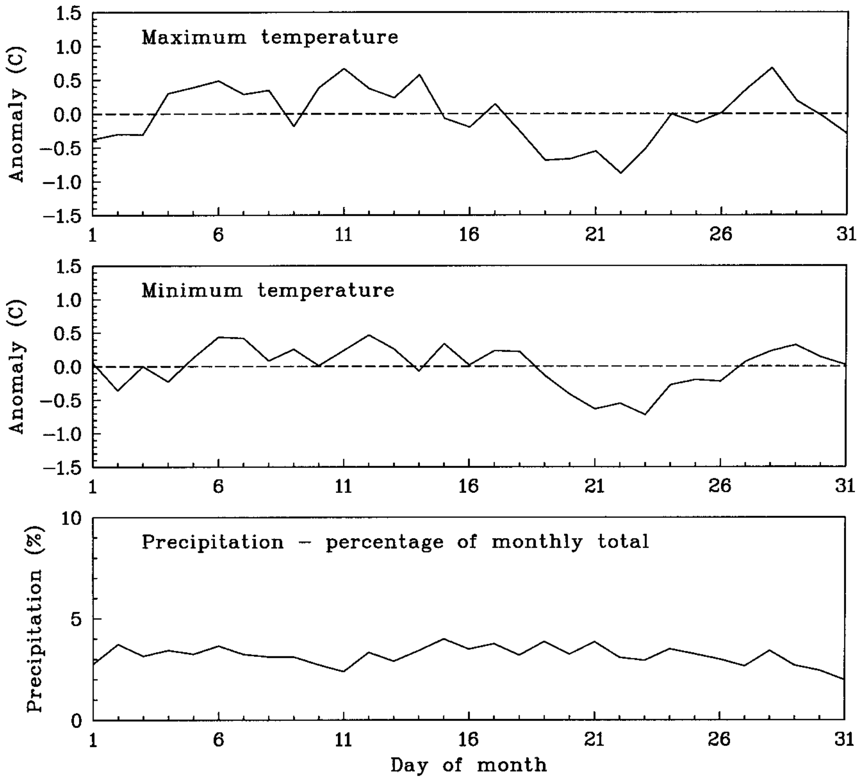


FIG. 7. Mean maximum and minimum temperature anomalies and percentage of monthly precipitation from the RAMS model averaged over all stations for each day of the month between 1990 and 1994.

plained for T_x rose from 48.9% to 49.4%, for T_n from 44.3% to 45.4%, and for $R^{0.33}$ from 29.2% to 31.0%.

c. Monthly means

Two techniques were tried: 1) averaging or summing, as appropriate, the daily estimates obtained from the regression technique above, and 2) direct estimation of the monthly mean or total using predictors derived from the mean circulation. In the latter case, the predictors chosen were the monthly means of the 1000- and 500-hPa EOFs and the local surface and upper-air predictors derived from the monthly mean fields rather than from daily values. As seen in Table 1, the mean variance reductions achieved from direct prediction of the monthly means/totals exceeded those from combining daily values by 6%–15%. The patterns of explained variance from combining the daily values were generally similar to those in Fig. 9.

In Fig. 9 we see that for T_x, the monthly pattern of variance reduction is similar to the daily pattern. The maximum values of ~70% along the east coast of both islands are comparable, but increases of 5%–20% occur over the remainder of the country. The mean variance reduction for all stations is 61.1% compared to the 48.9% for daily values. The monthly T_n variance reductions, like their daily counterparts, are fairly uniform over the whole country apart from the southeast of the South Island. The mean variance reduction is 58.5% compared to the 44.3% for daily values.

Specification of the monthly precipitation is also improved over that for the daily $R^{0.33}$ values, with mean variance reductions up from 29.2% to 36.4%. The patterns are broadly similar with minimum variance reductions in the monthly mean again experienced on the south and east coast of the South Island and in the southern North Island. A bigger increase is shown in the skill of specifying the mean probability of precipitation exceeding 0.1 mm, which corresponds to the number of precipitation days in the month. The variance reductions are relatively uniform over the North Island and northern part of the South Island although they are still low over the east coast of the South Island. The mean explained variance is 54.8% compared to the 31.5% for daily estimates.

5. Regional climate model predictions

As noted earlier, a simple linear regression was used to adjust the RAMS model's estimates of daily and monthly maximum and minimum temperatures and precipitation amounts at each station to give the best match

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

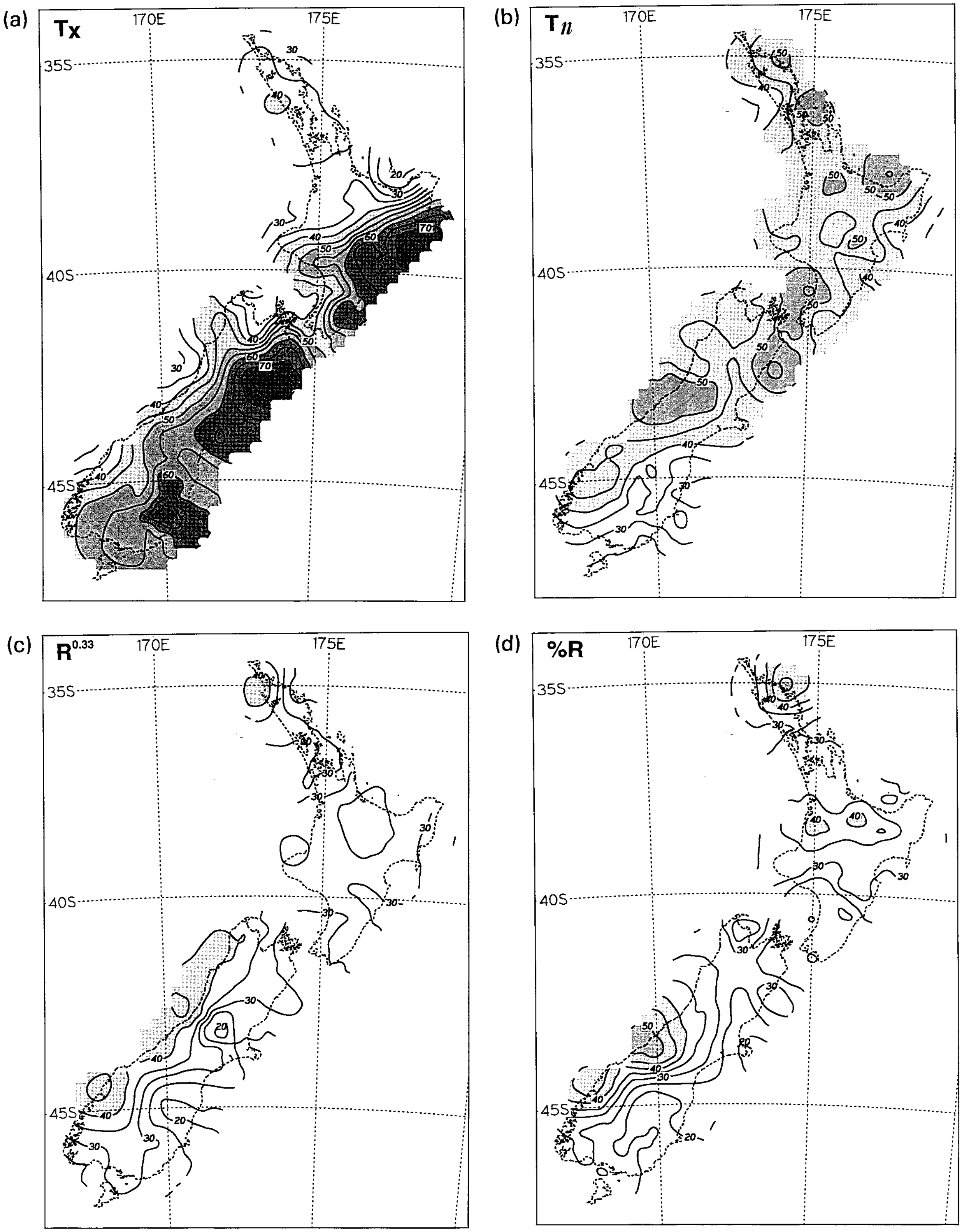


FIG. 8. Percentage variance reductions obtained by screening regression analysis for daily values of (a) maximum temperature T_x, (b) minimum temperature T_n, (c) cube root of precipitation $R^{0.33}$, and (d) probability of precipitation exceeding 0.1 mm (%R), for the period 1980–94.

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

TABLE 1. Mean percentage variance reductions in monthly mean maximum and minimum temperature, precipitation total (RA), and number of precipitation days (RT) for all 78 stations from 1980 to 1994. Direct monthly estimates were obtained using monthly mean predictors to predict monthly means/totals and are compared against the sum/mean of daily estimates.

Method	T_x	T_n	*RA*	*RT*
Direct monthly estimates	61.1	58.5	36.4	54.8
Sum of daily estimates	55.0	52.8	24.0	40.2

with observed values over the 1990–94 period. A cube root, $R^{0.33}$, transform was again used for the daily model precipitation values and regressed against the cube root of the daily measured precipitation. The square of the correlation coefficient provides the variance reduction, which is compared to the results from the screening regression approach, for a subset of 59 or 60 stations.

a. Maximum temperatures

The variance explained in the daily maximum temperatures (Fig. 10) by the RAMS model estimates is generally similar to that for the regression estimates in Fig. 8. Values exceeding 60% are found down the east coasts of both islands. The model-based estimates are not quite as good in the west and north of the South Island but verify better in the north of the North Island. The daily and monthly variance reduction patterns are similar but the monthly values are noticeably higher. The model does least well in the north of the North Island, and the north and west of the South Island.

b. Minimum temperatures

The corresponding variance reductions for daily and monthly mean minimum temperature are shown in Fig. 11. The daily variance reductions show a broadly similar pattern to those in Fig. 8, with generally better performance in the north of the North Island and some improvement in the south of the South Island. The monthly variance reductions show the most skill in the same areas and are comparable to those achieved by the statistical scheme.

c. Precipitation

The model estimates of daily values of $R^{0.33}$ in Fig. 12 show comparable skill to the regression estimates in Fig. 8 but outperform them in the central and northern North Island where the model's convective precipitation makes a larger contribution to the daily totals. The decline in skill in the northern and eastern extremities of the North Island probably results from the absence of a convective component near the edge of the grid, noted earlier. The improvement in skill over the North Island is also seen in the estimates of total monthly precipitation, and the skill of the monthly estimates is also good over the north of the South Island. There is a significant difference in the patterns for the daily and monthly variance reductions over the remainder of the South Island. While daily RAMS model specifications and both daily and monthly statistical estimates are best on the west coast, the model's monthly predictions are better on the east coast. The reasons for this are not known, although it might be noted that the major contribution to the model's resolved rainfall occurs on the west coast of the South Island. The statistical routines are able to relate this to variations in the strength of the prevailing winds but the model apparently cannot. Scatterplots of the observed and model-predicted monthly totals for west coast stations showed no obvious reason for this weak relationship, and it was not possible to improve the correlations by applying a variety of transforms to the monthly values.

d. Mean variance reductions

The mean variance reductions averaged over all stations for daily and monthly estimates from the RAMS model and from the statistical procedures for both the full period and the 5-yr period matching the model runs are shown in Table 2. For daily estimates, the RAMS model gives values that are slightly higher for each variable but the differences are probably not significant. On the monthly time frame, the RAMS model has a clear lead in estimating maximum temperature, the mean skill for minimum temperature forecasts is similar, while the statistical routines perform better for monthly rainfall.

In practical terms, the differences in daily predictions are small, with reductions in the mean standard error ranging from 1% to 4% over the 15-yr statistical estimates. For the monthly estimates the standard error of the model's maximum temperature is reduced by 5% over the regression result, while for mean precipitation there is a corresponding increase of 12%. While the variance reduction patterns tend to be similar, the RAMS model performs better for maximum temperatures in the north of the country and is less successful for precipitation on the South Island west coast.

6. Discussion and conclusions

The results described above have compared a simple regression approach to the use of a nested climate model for downscaling climate variables over a mountainous country with strong regional variability. With ''perfect'' large-scale forcing from daily analyses there is little difference in skill between the two techniques for daily or monthly predictions. This suggests that both have performed well and that the predictive skill is limited by the response of local climate to circulation variations. Nevertheless, we need to consider whether the optimum

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

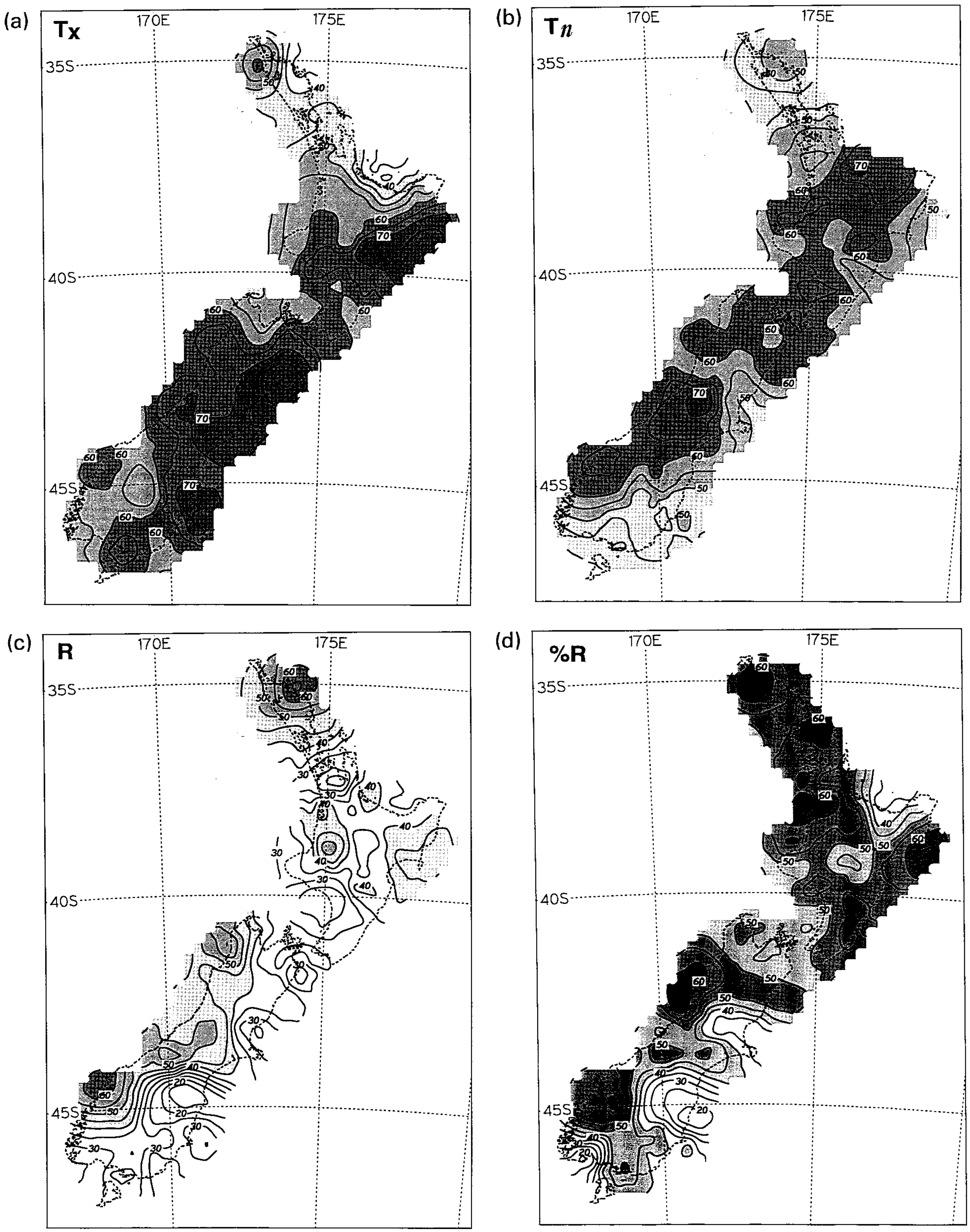


FIG. 9. Percentage variance reductions obtained by screening regression analysis for monthly values of (a) mean maximum temperature T_x, (b) mean minimum temperature T_n, (c) mean daily precipitation R, and (d) mean probability of precipitation exceeding 0.1 mm $\%R$, for the period 1980–94.

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

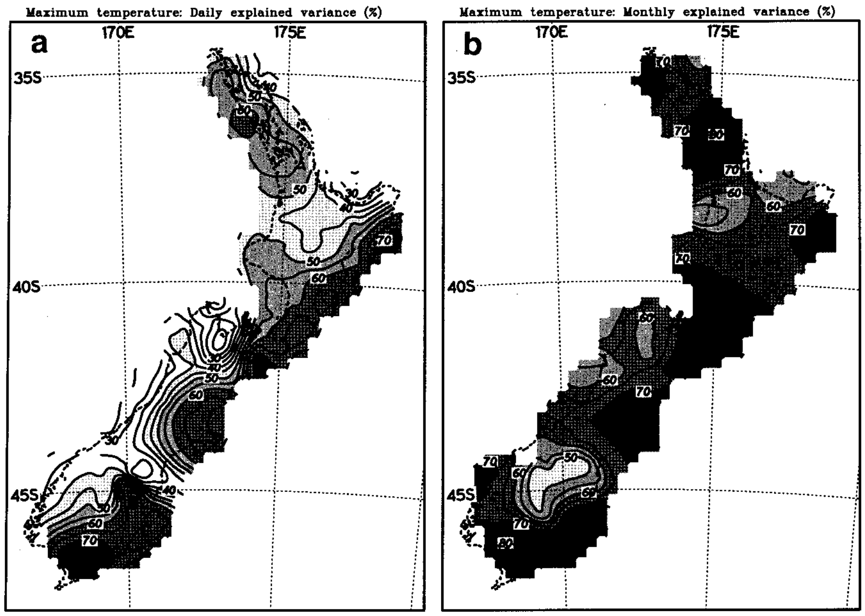


FIG. 10. Percentage of daily and monthly variance in maximum temperature explained by model predictions of maximum temperature.

results have been obtained for each technique and whether this result is a fair reflection of their relative performance.

The screening regression approach used for the statistical estimates took a fairly conservative approach to predictor selection, with the explained variances reducing by a few percent on independent data. Predictors relating to both large-scale and local flow were derived from the 1000- and 500-hPa geopotential height fields but no attempt was made to incorporate data from other levels or the relative humidity and vertical motion fields. These additional predictors would not be expected to add much independent information as both synoptic-scale vertical motion and humidity are linked to the local thermal and vorticity advection predictors, which, in any case, were seldom chosen. Partitioning the dataset by synoptic class implies corresponding mean synoptic-scale patterns of vertical motion and precipitation, but

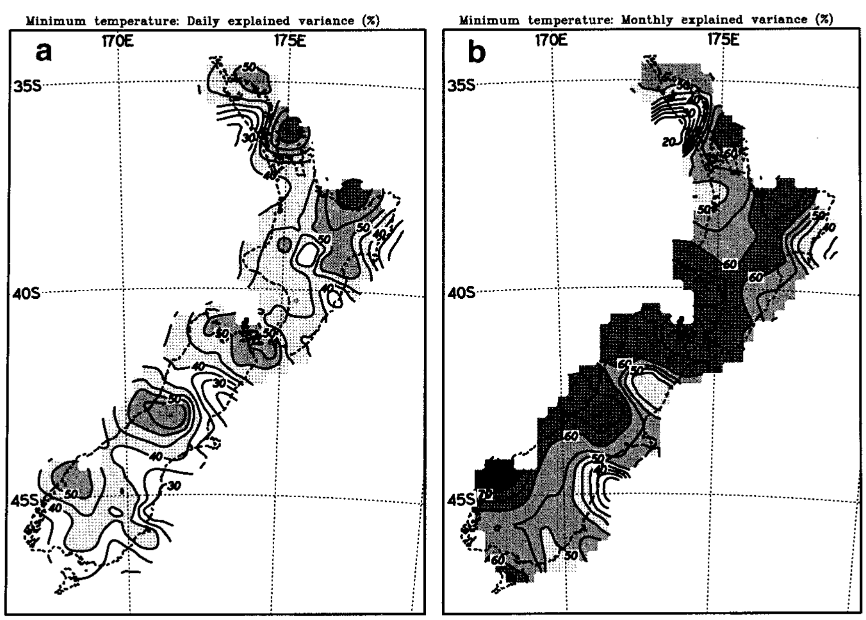


FIG. 11. Percentage of daily and monthly variance in minimum temperature explained by model predictions of minimum temperature.

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

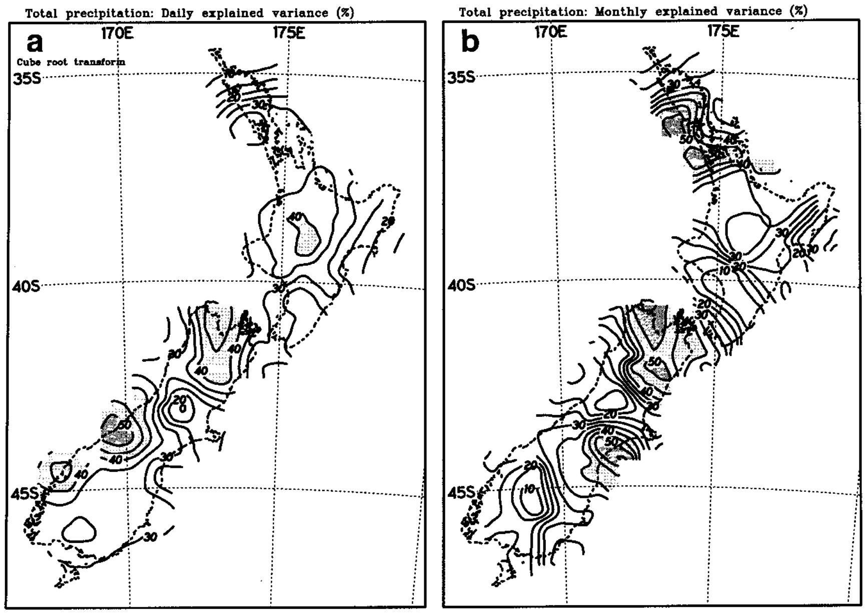


FIG. 12. Percentage of daily variance in $R^{0.33}$ and monthly variance in precipitation total explained by the corresponding model predictions.

locally there is only a few percent increase in the variance reduction for hourly temperature predictions (J. W. Kidson 1996, unpublished manuscript) through the variance contributed by the class means. While we chose not to use humidity variables as predictors in this study, recent work by Hewitson (1997) shows that they made an important contribution to the accuracy of his downscaling technique over South Africa. We would expect further improvements in the regression technique by the inclusion of better quality humidity information from future datasets (McNally and Vesperini 1996). Further small improvements would also result from stratifying the data by season before developing the regression equations.

It was not expected that estimates of monthly precipitation or mean temperature departures from the sum of daily predictions would be less accurate than direct estimates of the monthly values from monthly mean predictors. The higher skill of the direct monthly estimates may be due to the particular predictors selected in the daily regression equations and the reduction in standard error from averaging the daily values of predictors and predictands. The principal predictors express, in most cases, linear relationships between the predictand and, for example, thicknesses or wind components that would apply equally well between monthly means. Previous results for New Zealand stations (Kidson 1997) have also indicated that monthly estimates using the relative frequency of the synoptic classes or mean departures for each class weighted by class frequency are also less accurate than direct estimates. If this result were to be generally true it would considerably reduce the volume of model output required to generate monthly statistics, though estimates of daily variability would still be needed for climate impact studies.

In using the RAMS model our goal was not necessarily to obtain an accurate simulation of regional climate variations but rather to see if daily and monthly departures of climatic elements were better estimated than by the purely statistical approach. On the whole, this has not been demonstrated and we need to consider whether the model's performance might be improved. We specified the full set of physics options and realistic lower boundary conditions and, while these may be capable of further improvement, the quality of the simulation is likely to be strongly influenced by the domain size and resolution. The grid resolution of 50 km, while comparable to those used in the investigations referenced earlier, has evidently limited the peak precipitation rates in the model, although the spatial distribution is generally satisfactory. This is in line with the findings

TABLE 2. Percentage variance reductions in maximum (T_x) and minimum temperature (T_n) for 59 stations, and precipitation from 60 stations ($R^{0.33}$ for daily values, R for monthly totals) obtained from interpolated RAMS model predictions and statistical regression.

Selection	T_x	T_n	$R^{0.33}/R$
Daily			
RAMS (1990–94)	51.3	48.6	35.3
Stat. (1980–94)	48.3	44.5	29.2
Stat. (1990–94)	48.6	44.7	31.4
Monthly			
RAMS (1990–94)	70.4	59.1	32.4
Stat. (1980–94)	61.7	59.3	37.7
Stat. (1990–94)	61.8	56.8	36.4

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

of Pielke et al. (1997), who used a 60-km grid over the coterminous United States. The results of Revell et al. (1995) suggest that a reduction in the grid spacing by a factor of 3, with an increase in computer time by a factor of 27, would be necessary to obtain similar daily or annual precipitation totals to those observed. We cannot say whether this would lead to better estimates of year to year variability. The area covered by the grid size (28° long × 18° lat) is relatively small compared to the smallest area used by Jones et al. (1995) but the monthly mean fields in Fig. 7 contain an appropriate amount of mesoscale detail and show no evidence of distortion near the boundaries. The situation for daily fields is rather different in that the coarse-scale forcing does not indicate where, or indeed if, mesoscale features should develop. When working with current data, we have the opportunity to assimilate local fine-resolution data to delineate mesoscale features. For climate model output we anticipate that the mesoscale detail that develops should improve on estimates of daily variability and result in realistic long-term averages, even if ''correct'' daily values are not predicted.

While the simulation of regional climate is an interesting problem in its own right, the results here suggest that for downscaling applications the considerable extra effort involved is not matched by an improvement in performance over statistical techniques. Both may be used in forecasting of climate variability where the daily variations lie within the range for which the statistical estimates have been optimized. As discussed earlier, it seems likely that regression equations apply without much loss of accuracy over the full year because of the physical relationships they express. If these linear relationships persist beyond the range of observed values it may be possible to apply the regression approach to small changes from the present climate. However, as argued elsewhere, model-based interpolation may be preferred where significant climate change is involved and, for example, increased atmospheric water vapor content may change the intensity of storms (e.g., Trenberth and Shea 1997). It is not known whether either technique is more likely to be affected by incorrect specification of the large-scale forcing.

The comparison of daily predictions also has implications for regional weather services that have access to products from the global centers but would like to improve local forecasts. Effort put into developing and running local mesoscale models is likely to be unrewarded unless assimilation schemes can be developed to incorporate local mesoscale features.

In summary, the main points are the following.

- Interpolations using the RAMS model (with subsequent scaling) are generally comparable to those from a regression scheme for a small country with highly variable terrain.
- The skill of both techniques generally follows similar patterns on both daily and monthly timescales, suggesting that the results are more dependent on the characteristics of the station than the methods used to forecast them.
- Nevertheless, there are some intriguing differences. The RAMS model is able to do better with daily precipitation over parts of the country because of its convective contributions. While it does well with resolved precipitation to the west of the South Island mountains on the daily timescale, it fails to match this on a monthly basis.
- The small margin of skill coupled with the extensive computing requirements makes the use of a nested model unattractive unless there is a need to deal with climate change outside the range of previously recorded values.

Acknowledgments. Thanks are due to Drs. Mike Revell and Kip Marks of NIWA, and Craig Tremback of Aster Corp. for assistance with the RAMS model, and to Jim Renwick for help with specification of boundary values and with statistical issues. Thanks are due to the reviewers whose suggestions helped clarify a number of points. This research was supported by the Foundation for Research, Science and Technology Contract CO1522.

REFERENCES

Bardossy, A., and E. J. Plate, 1992: Space-time models for daily rainfall using atmospheric circulation patterns. *Water Resour. Res.,* **28,** 1247–1259.

Bates, G. T., S. W. Hostetler, and F. Giorgi, 1995: Two-year simulation of the Great Lakes region with a coupled modeling system. *Mon. Wea. Rev.,* **123,** 687–701.

Copeland, J. H., R. A. Pielke, and T. G. F. Kittel, 1996: Potential climatic impacts of vegetation change: A regional modeling study. *J. Geophys. Res.,* **101** (D3), 7409–7418.

Cressman, G. P., 1959: An operational objective analysis system. *Mon. Wea. Rev.,* **87,** 367–374.

Dorman, J. L., and P. J. Sellers, 1989: A global climatology of albedo, roughness length and stomatal resistance for atmospheric general circulation models as represented by the Simple Biosphere Model (SiB). *J. Appl. Meteor.,* **28,** 833–855.

Draper, N. R., and Smith, H., 1981: *Applied Regression Analysis.* 2d ed. Wiley, 709 pp.

Giorgi, F., and L. O. Mearns, 1991: Approaches to the simulation of regional climate change. *Rev. Geophys.,* **29,** 191–216.

——, C. Shields Brodeur, and G. T. Bates, 1994: Regional climate change scenarios over the United States produced with a nested regional climate model: Spatial and seasonal characteristics. *J. Climate,* **7,** 375–399.

Glahn, H. R., 1985: Yes, precipitation forecasts have improved. *Bull. Amer. Meteor. Soc.,* **66,** 820–830.

Hewitson, B., 1994: Regional climate in the GISS general circulation model: Air surface temperature. *J. Climate,* **7,** 283–303.

——, 1997: GCM derived climate change impacts on regional climate variability. Preprints, *Fifth Int. Conf. on Southern Hemisphere Meteorology and Oceanography,* Pretoria, South Africa, Amer. Meteor. Soc., 24–26.

Hirakuchi, H., and F. Giorgi, 1995: Multi-year present day and 2 × CO_2 simulations of monsoon climate over eastern Asia and Japan with a regional climate model nested in a general circulation model. *J. Geophys. Res.,* **100,** 21 105–21 126.

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC

IPCC, 1995: *Climate Change 1995: The Science of Climate Change.* Cambridge University Press, 572 pp.

IRI, 1995: International Forum on Forecasting El Niño: Launching an international research institute. Executive Summary, NOAA, 65 pp. [Available from NOAA Office of Global Programs, 1100 Wayne Avenue, Suite 1225, Silver Spring, MD 20910.]

Jones, R. G., J. M. Murphy, and M. Nouger, 1995: Simulation of climate change over Europe using a nested regional climate model. Part I: Assessment of control climate, including sensitivity to location of lateral boundaries. *Quart. J. Roy. Meteor. Soc.,* **121,** 1413–1449.

——, ——, ——, and A. B. Keen, 1997: Simulation of climate change over Europe using a nested regional climate model. Part II: Comparison of driving and regional model responses to a doubling of carbon dioxide concentration. *Quart. J. Roy. Meteor. Soc.,* **123,** 265–292.

Karl, T. R., W.-C. Wang, M. E. Schlesinger, and R. W. Knight, 1990: A method of relating general circulation model simulated climate to the observed local climate. Part I: Seasonal statistics. *J. Climate,* **3,** 1053–1079.

Katz, R. W., and J. G. Acero, 1994: Sensitivity analysis of extreme precipitation events. *Int. J. Climatol.,* **14,** 985–999.

Kida, H., T. Koide, H. Sasaki, and M. Chiba, 1991: A new approach to coupling a limited area model with a GCM for regional climate simulation. *J. Meteor. Soc. Japan,* **69,** 723–728.

Kidson, J. W., 1997: The utility of surface and upper air data in synoptic climatological specification of surface climatic variables. *Int. J. Climatol.,* **17,** 399–414.

Kim, J. W., J.-T. Chang, N. L. Baker, D. S. Wilks, and W. L. Gates 1984: The statistical problem of climate inversion: Determination of the relationship between local and large-scale climate. *Mon. Wea. Rev.,* **112,** 2069–2077.

Klein, W. H., 1982: Statistical weather forecasting on different time scales. *Bull. Amer. Meteor. Soc.,* **63,** 170–177.

——, and H. Bloom, 1989: An operational system for specifying monthly precipitation amounts over the United States from the field of concurrent 700-mb heights. *Wea. Forecasting,* **4,** 51–60.

Kowalcyk, E. A., J. R. Garratt, and P. B. Krummel, 1991: A soil-canopy scheme for use in a numerical model of the atmosphere—1D stand-alone model. CSIRO Div. of Atmos. Res. Tech. Paper 23, 56 pp. [Available from CSIRO, Division of Atmospheric Research, Private Bag 1, Mordialloc, Victoria 3195, Australia.]

Maunder, W. J., 1971: The Climate of New Zealand—Physical and dynamical features. *World Survey of Climatology,* Vol. 13, *Climates of Australia and New Zealand,* J. Genhlli, Ed., Elsevier, 213–227.

McNally, A. P., and M. Vesperini, 1996: Variational analysis of humidity information from TOVS radiances. *Quart. J. Roy. Meteor. Soc.,* **122,** 1521–1544.

Mearns, L. O., R. W. Katz, and S. H. Schneider, 1984: Extreme high-temperature events: Changes in their probabilities with changes in mean temperature. *J. Climate Appl. Meteor.,* **23,** 1601–1613.

Mitchell, J. F. B., C. A. Wilson, and W. M. Cunnington, 1987: On CO_2 climate sensitivity and model dependence of results. *Quart. J. Roy. Meteor. Soc.,* **113,** 293–322.

Phillips, N. A., 1990: *Dispersion Processes in Large-Scale Weather Prediction.* WMO, 126 pp.

Pielke, R. A., and Coauthors, 1992: A comprehensive meteorological modeling system—RAMS. *Meteor. Atmos. Phys.,* **49,** 69–91.

——, T. J. Lee, J. H. Copeland, J. L. Eastman, C. L. Ziegler, and C. A. Finley, 1997: Use of USGS-provided data to improve weather and climate simulations. *Ecol. Appl.,* **7,** 3–21.

Podzun, R., A. Cress, D. Majewski, and V. Renner, 1995: Simulation of European climate with a limited area model. Part II: AGCM boundary conditions. *Contrib. Atmos. Phys.,* **68,** 205–226.

Renwick, J. A., J. J. Katzfey, K. C. Nguyen, and J. L. McGregor, 1998: Regional model simulations of New Zealand climate. *J. Geophys. Res.,* in press.

Revell, M. J., M. R. Sinclair, and D. S. Wratt, 1995: The storm of November 1994—Numerical simulation of a heavy rain event over the Southern Alps of New Zealand, using the RAMS model at very high resolution. Preprints, *Workshop of GEWEX Cloud System Study Working Group 3,* New York, NY, Goddard Inst. for Space Studies, 47–51.

Reynolds, R. W., 1988: A real-time global sea surface temperature analysis. *J. Climate,* **1,** 75–86.

Richman, M. B., 1986: Rotation of principal components. *J. Climate,* **6,** 293–336.

Sasaki, H., H. Kida, T. Koide, and M. Chiba, 1995: The performance of long term integrations of a limited area model with the spectral boundary coupling method. *J. Meteor. Soc. Japan,* **73,** 165–181.

Semazzi, F. H. M., N.-H. Lin, Y.-L. Lin, and F. Giorgi, 1993: A nested model study of the Sahelian climate response to sea-surface temperature anomalies. *Geophys. Res. Lett.,* **20,** 2879–2900.

Sinclair, M. R., 1994: A diagnostic model for estimating orographic precipitation. *J. Appl. Meteor.,* **33,** 1163–1175.

Sturman, A. P., and N. J. Tapper, 1996: *The Weather and Climate of Australia and New Zealand.* Oxford University Press, 476 pp.

Trenberth, K. E., and J. G. Olson, 1988: An evaluation and intercomparison of global analyses from the National Meteorological Center and the European Centre for Medium-Range Weather Forecasts. *Bull. Amer. Meteor. Soc.,* **69,** 1047–1057.

——, and D. J. Shea, 1997: Atmospheric circulation changes and links to changes in rainfall and drought. Preprints, *13th Conf. on Hydrology,* Long Beach, CA, Amer. Meteor. Soc., J14–J17.

von Storch, H., E. Zorita, and U. Cubasch, 1993: Downscaling of climate change estimates to regional scales: An application to winter rainfall in the Iberian Peninsula. *J. Climate,* **6,** 1161–1171.

Walko, R. L., W. R. Cotton, M. P. Meyers, and J. Y. Harrington, 1995a: New RAMS cloud microphysics parameterization. Part I: The single-moment scheme. *Atmos. Res.,* **38,** 29–62.

——, C. J. Tremback, R. F. A. Hertenstein, 1995b: *RAMS, The Regional Atmospheric Modeling System.* Version 3b, users guide. Aster Division, Mission Res. Corp.

Wallace, J. M., S. Tibaldi, and A. J. Simmons, 1983: Reduction of systematic forecast errors in the ECMWF model through the introduction of an envelope orography. *Quart. J. Roy. Meteor. Soc.,* **109,** 683–717.

Wilks, D. S., 1992: Adapting stochastic weather generation algorithms for climate change studies. *Climate Change,* **22,** 67–84.

Wilson, L. L., D. P. Lettenmaier, and E. Skyllingstad, 1992: A hierarchical stochastic model of large-scale atmospheric circulation patterns and multiple station daily precipitation. *J. Geophys. Res.,* **97,** 2791–2809.

WMO, 1983: *Guide to Climatological Practices.* 2d ed. WMO.

Zheng, X., and R. E Basher, 1996: Spatial model of New Zealand temperature normals. *Int. J. Climatol.,* **16,** 307–319.

Zorita, E., J. P. Hughes, D. P., Lettenmaier, and H. von Storch, 1995: Stochastic characterization of regional circulation patterns for climate model diagnosis and estimation of local precipitation. *J. Climate,* **8,** 1023–1042.

Unauthenticated | Downloaded 08/06/21 04:42 AM UTC