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Predictability of northwest wind storms in Canterbury Part 2: Growth of errors in two numerical predictions

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Some idea of the relative magnitude of sources of error in predictions of wind storms on the Canterbury Plains, New Zealand, is gleaned by perturbing numerical weather prediction (NWP) model simulations in two cases where moderately strong winds were observed. This complements a previous study of uncertainty due to local effects (Purnell and McGavin 1999). Under 45 per cent of the total variance in gust maximum aerodynamic load and speed appears to be predictable several days ahead, rising to a limit under 60 per cent on the day of the event. In other words, the results suggest there would be little scope for improvements in any prediction service that was already nearly this accurate.

There is definitely some potential to improve the NWP model used here to provide predictions of maximum gusts via the statistical model of Part 1. The most significant predictors were the pressure-difference across the Southern Alps and its variation, but the model values of these were little better than half their observed magnitudes.

Introduction

Some idea of the relative magnitude of sources of error is essential for any rational investment intended to improve forecasting systems. However, there appears to be little literature on sources of error in forecasts of New Zealand weather. Possibly the most important studies of data sensitivity were carried out by NZ MetService Ltd, to determine how far they could reduce expenditure on observing systems and still provide an acceptable service. Other studies (e.g. Seaman 1994) have addressed the accuracy of NWP system components. However, forecasts of weather experienced on the ground may be unavoidably much less accurate than an NWP system because of locally generated errors, such as the eddy-cascades identified in Part 1 of the present study (Purnell and McGavin 1999). In practice, a lot of investment might rely on undocumented experience and personal perceptions as to what can be profitably improved.

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The present study is therefore intended as an exploratory investigation. One likely reason for the lack of previous exploration is its expense. Lack of resources has limited the present study to the pitifully small sample of just two cases where moderately strong winds were observed. However, this may at least give some feel for what might be expected, and might prompt a proper investigation. Although the only rational goal of such a study is to arrive at a lower bound for the uncertainty, the point is that a lower bound can be useful. The present work does at least produce an estimate of this sort. Further work could substantially tighten this estimate.

The technique used was to choose cases where at least moderately strong gusts were observed, and simulate these cases using the RAMS model, version 3b (Pielke et al. 1992) over as large an area as was practical. The selection of cases reflects the interest in storms, rather than calms, and is based on the proposition that forecasts have sufficient skill that a calm is not likely to eventuate when a storm is predicted. A more careful selection procedure may be desirable. Several simulations of each case were done, starting from perturbed initial states, so as to get some idea of the degree of uncertainty due to error in the initial and boundary conditions. A 'breeding' method was used to select perturbations of fast-growing amplitude. The alternative Monte Carlo ensemble forecasting procedure used by Speer and Leslie (1997) was well beyond the available computing resource.

Multiple prediction (ensemble forecasting) is now standard practice at the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP) (Toth and Kalnay 1993), as a way of both quantifying uncertainty and improving accuracy. This practice relies on the proposition that only a few error patterns are likely. The idea is that weather dynamics will admit only a few fast-growing error patterns, and a modern observing system will reduce the myriad of other patterns to negligible amplitude. Probably the simplest way of generating significant error patterns is the breeding method used by NCEP. This was the method used here. However the error patterns simulated here are valid for only a few days at most, because they were generated on a limited area. The range of model outcomes will be optimistically biased by artificial boundaries (Vukicevic and Errico 1990), so the experiments covered as large an area as was practical. What can still be claimed though, is that the resulting estimate of uncertainty will be a lower bound to the total uncertainty. There will always be unaccounted errors, even in a thorough study. The errors accounted for by the NWP runs done here are generated by synoptic-scale processes in the Australian region. Additional unaccounted errors include errors generated on a global scale. Unaccounted errors will result in a loose lower bound for total uncertainty, but do not invalidate it.

The experiments

Two cases where strong gusts were recorded on the Canterbury plains were studied. Several RAMS simulations of each case were computed. The first was a control run, started from ECMWF initial and boundary data. Other runs were started from small perturbations of the control run (see Table 2). In every case the regional model was nested in the ECMWF global model, with updating of the boundaries to match the global model except for a small perturbation. The perturbations were independently generated by a breeding method to select fast-growing error patterns. First, the initial and boundary temperatures and surface pressure of the control run were perturbed using a random-number generator, with a different seed for each perturbation. This was done by supplying the random data as 'observations' to a data-analysis tool which generated geostrophically balanced wind and temperature fields to be used as initial and boundary data for the RAMS model. Fast-growing error patterns were then bred by

Table 1. RAMS model configuration (Walko et al. 1995).

Model option	*Setting*
Basic equations	Compressible, nonhydrostatic
Vertical coordinate	Terrain-following sigma_z
Horizontal coordinate	Cartesian, Polar stereo-graphic projection
Grid structure	Fixed Arakawa C grids
Time differencing	Hybrid forward/leapfrog scheme
Advection scheme	2nd order
Turbulence closure	Prognostic TKE
Cumulus parameterisation	Modified Kuo, (Grid 1 only) Update 3600 s
Shortwave radiation	Update 1800 s
Longwave radiation	Update 1800 s
Surface treatment	Mixed woodland
Soil model	11-level, sandy loam
Nudging and initial data	12-hourly, 2.5x2.5 deg ECMWF analyses (at start of control run)
Upper boundary	Rigid lid at 25 km
Lateral boundaries	Nudging to ECMWF over 8 grid-points time-scale=1800 s.
Microphysics	
Cloud	Specify number density (3.0E8 /m^3)
Rain	Specify mean droplet diameter (1mm)
Pristine Ice	Prognose number density
Snow	Specify mean droplet diameter (1 mm)
Aggregates	Specify mean droplet diameter (1 mm)
Graupel	Specify mean droplet diameter (1 mm)
Hail	Specify mean droplet diameter (1 mm)

repetition of the following two steps at hours 0, 6,12, 18..., 120.

(a) Compute a six-hour predicted state S_{t+6} from the perturbed state S_t at hour t.

(b) Combine this six-hour prediction with data from the control run for the corresponding time according to the formula: $S_{t+6} = 0.9 \times S_{t+6} + 0.1 \times S_{CONTROL,\ t+6}$

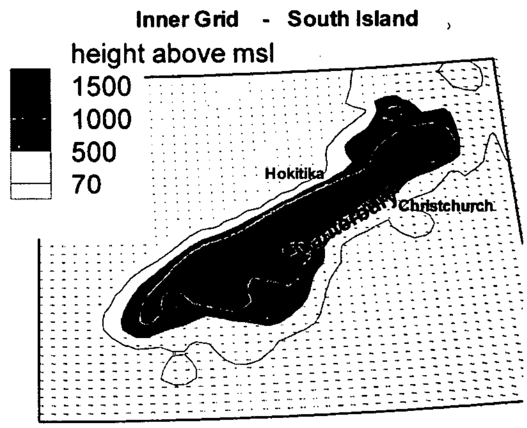
Step (b) was computed without any spatial interpolation by modification of the RAMS model to combine data from two 'restart' files, instead of reading just one. The resulting 'bred' states are rapidly growing but small perturbations of the control run. The final perturbed predictions were made starting from one of these 'bred' states as initial and boundary data for an unmodified RAMS model run covering a shorter period from $t + 36$ or $t + 51$.

The RAMS model was set up on a nested-grid configuration. The outer region was represented on a horizontal mesh, with an average node spacing of 76 km, over the region shown in Figs 2-4. There were 25 levels, with the lowest layer thickness from 137 m to 150 m. The nested inner region was represented on a horizontal mesh, with an average horizontal mesh spacing of 20 km, over the region covering the South Island of New Zealand as shown in Fig. 1. There were 25 levels matching the levels in the outer grid. The model options used in these experiments are briefly listed in Table 1. Note in particular that though the regional model was nested in the ECMWF global model, with updating of the boundaries, there was no interior nudging for the breeding and perturbed runs, or for any part of the control run that was compared to the breeding and perturbed runs. Interior nudging toward ECMWF data occurred only during the first six hours of each control run, to damp out gravity waves and other transients. The breeding runs were started from small geostrophically balanced perturbations of the control run, and forced by small geostrophically balanced perturbations of the lateral boundary conditions. The perturbed runs were started from the state of a breeding run at 36 and 51 hours from the start of the control run.

Results

To estimate the likely magnitude of the error that evolves from the initial-state errors due to data analysis in an operational NWP system, the bred perturbations should be scaled to a magnitude characteristic of an operational NWP system. The magnitudes of the bred perturbations of the control run shown in Table 2 and in Figs 2-4 were not normalised in any way. Characteristic error magnitudes could be found from statistics published by a proposed provider of NWP products. Observation error standard deviations are of the order of 1°C for temperature soundings and 1 hPa for surface pressure. For the present purpose it might be reasonable to assume a temperature error standard deviation of 2°C and a surface pressure error standard deviation of 4 hPa in the NWP initial state. Then perturbation 1, case 1, is probably too large, and perturbations 1 and 2, case 2, are too small by a factor of six. Since small perturbations give forecast differences that are nearly linearly additive, the forecast differences used to predict maximum gusts in case 2 are scaled by a factor of six to give realistic error magnitudes for an operational NWP system.

Fig. 1 The nested model inner region on a 20km mesh over the South Island of New Zealand.

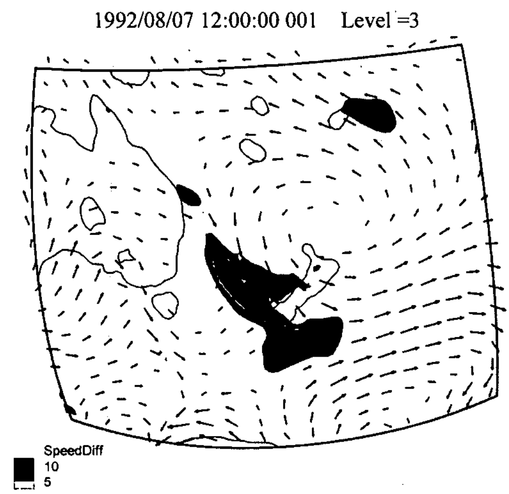


For case 1, Fig. 2 shows perturbation 1 at hour 12 on 7 August 1992, on the outer grid. It shows the predicted wind at level 3, together with shaded differences of wind speed between this perturbed prediction and the control run. Level 3 of the RAMS model is at an altitude of 370 m over the sea, rising to a maximum of 2425 m over the mountains. The main area of discrepancy is associated with the wind change that is advancing onto the south of the Island. This discrepancy between the control and perturbed run is more than just a timing difference, as is clear from its effect on the pressure difference shown in Fig. 5(a).

Table 2. Amplitude of bred perturbations of initial and boundary data.

Perturbation		*rms difference from control run*	
Start date	*Number*	*Temperature (°C)*	*Surface pressure (hPa)*
12Z 4 August 1992	1	2.0	6.2
00Z 17 April 1994	1	0.32	1.3
00Z 17 April 1994	2	0.32	0.83

Fig. 2 **Perturbation 1, level 3 at hour 12, 7 August 1992, showing predicted wind arrows and differences of wind speed between this prediction and the control run. Differences less than 5 m/s are not shaded, 5-10 m/s are light-shaded, and differences greater than 10 m/s are dark-shaded. Maximum predicted wind speed at level 3 over New Zealand is 20.6 m/s (at the southwest extremity of NZ: Fiordland).**



For case 2, Fig. 3 shows perturbation 1 at hour 12 on 20 April 1994, on the outer grid. It shows the predicted wind at level 3, together with shaded differences of wind speed between this perturbed prediction and the control run. Figure 4 shows the same information for perturbation 2. Though they differ, the outcome with respect to wind in Canterbury appears to be the same. This is borne out by the maximum gust estimates from statistical formulae shown in Figs 6(b) and 7(b). The location of the main area of discrepancy is south of the Island, where it has very little effect.

Figures 6 and 7 show maximum gusts observed at Christchurch and Kaikoura, and predictions made using the statistical formulae of Part 1, in which all the predictors are interpolated from data on the inner grid of the RAMS model. There is less difference between the perturbed predictions than between predicted and observed gusts, and all predictions tend to be too small. This is partly because the simulated pressure difference and its variation across the Alps is too small, as shown in Figs 5(a) and 5(b). To show, however, that a larger pressure difference will not eliminate these discrepancies, Figs 6(c) and 6(d) show the result of scaling the pressure difference and its variation by a factor of 2 in the statistical formulae of Part 1.

Fig. 3 **Perturbation 1, level 3 at hour 12 on 20 April 1994, showing predicted wind arrows and differences of wind speed between this prediction and the control run. Differences less than 0.5 m/s are not shaded, 0.5-1 m/s are light-shaded, and differences greater than 1 m/s are dark-shaded. Maximum predicted wind speed at level 3 over New Zealand is 21.5 m/s (at the centre of NZ: Cook Strait).**

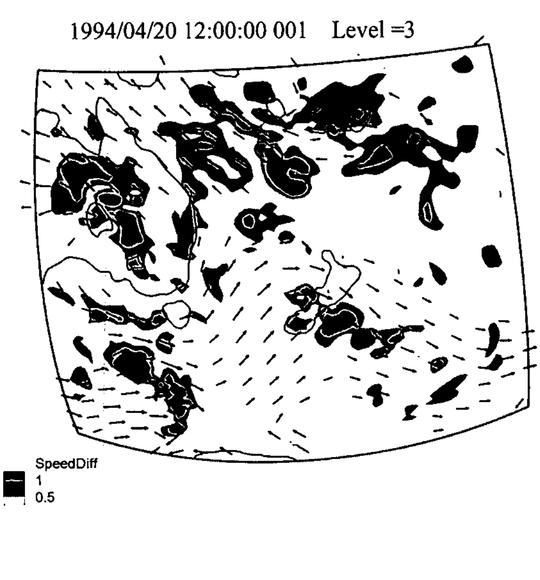
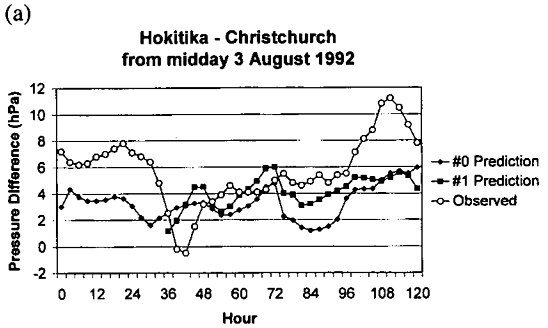


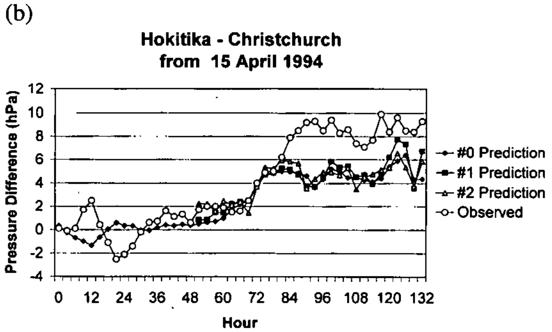
Fig. 4 **Same as Fig. 3 but for perturbation 2.**

Fig. 5 **Simulated and actual Hokitika-Christchurch difference of mean sea-level pressure across the Southern Alps. In Fig. 5(b) perturbations of the control run were scaled by a factor of 6 to a magnitude roughly characteristic of an operational NWP system (see text).**

(a)



(b)

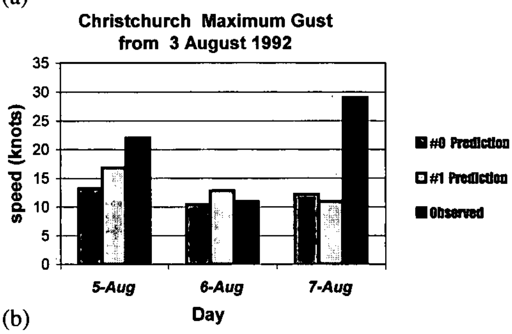


The divergence of the observations from predictions at 84 hours in Fig. 5(b) coincides with the arrival over the South Island of a strong frontal wind change. This is not necessarily an indication of the limitations of domain size because the regional model was nested in a global model, with updating of the boundaries to match the global model at all times except for a small perturbation. Of course the lack of global perturbations is significant, and it may be impossible for the model to track the observations without a suitable global perturbation. But a reasonable alternative explanation could be a deficiency in the regional model, such as inadequate resolution of the effect of the mountains.

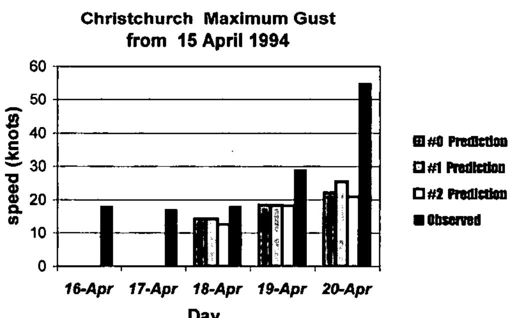
An estimate of the error variance attributable to synoptic-scale processes in the Australian region could be made from a carefully selected sample of at least 20 cases, with enough perturbations of each case to span the space of probable error patterns. These data were not available, but it might be useful to get some idea of what to expect using the experiments shown in Figs 6 and 7, especially if this prompts a proper study. Summing the squares of differences between the predictions of maxi-

Fig. 6 **Maximum daily gust at Christchurch Airport, as observed and as predicted by statistical formulae using RAMS model data. In Figs 6(a) and 6(b) perturbations of the control run were scaled by a factor of six to a magnitude roughly characteristic of an operational NWP system (see text). In Figs 6(c) and 6(d) the resulting pressure difference and its variation were further scaled by a factor of two before use in the formula for maximum gust (see text).**

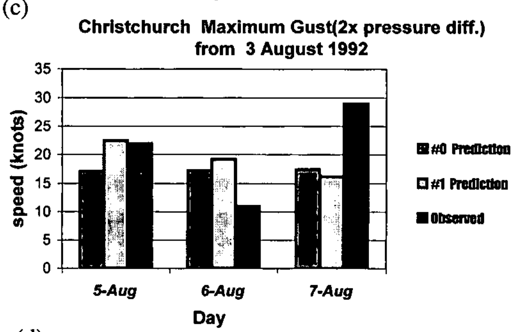
(a)



(b)



(c)



(d)

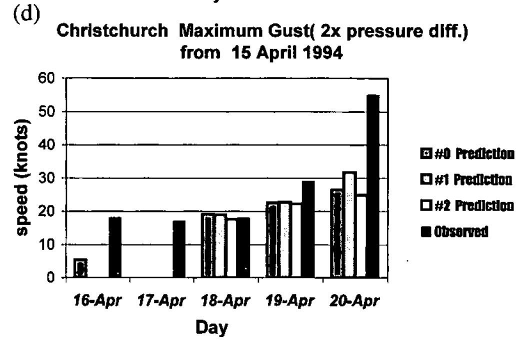
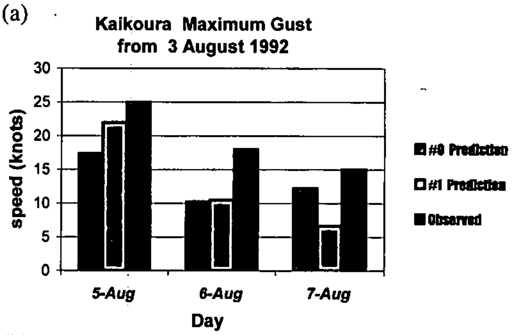
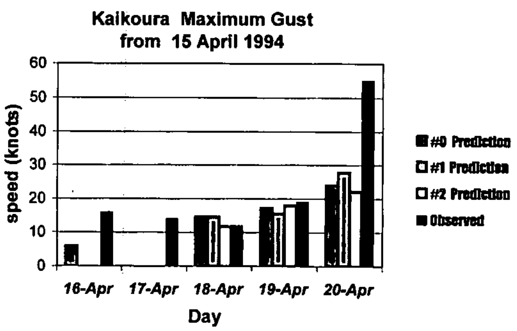


Fig. 7 Maximum daily gust at Kaikoura, as observed and as predicted by statistical formulae using RAMS model data. In (b) perturbations of the control run were scaled by a factor of 6 to a magnitude roughly characteristic of an operational NWP system (see text).

(a)



(b)



mum gust at both Christchurch and Kaikoura made by perturbed and control runs, for the last three days of both cases and all perturbations, gives an rms difference of 2.7 m/s. This difference is attributable to synoptic-scale errors generated in the Australian region. It corresponds to 13 per cent of the mean-square variation in the long-period records of northwesterly winds at Christchurch used in Part 1. This probably underestimates the uncertainty, because it omits several important sources of synoptic-scale error. These include boundary errors, errors from unexplored perturbations, and numerical dissipation in the regional NWP model.

Conclusions

There is a large irreducible uncertainty in forecasts of wind storms in Canterbury even using an estimate that is probably too small. There will be substantial additional uncertainty attributable to unaccounted error on a global scale, but even if this and other errors are ignored we still get a lower bound for the irreducible uncertainty. So even this poor estimate may be of interest, and might prompt a proper investigation.

Three categories of sources of error in predictions of maximum gusts using a NWP/statistical model are:

(a) Error resulting from uncertainty in the NWP model initial state. The spread of the perturbed three-day forecasts suggests that synoptic-scale processes in the Australian region will generate more than 13 per cent of the total variance in gust speeds. To this should be added substantial globally generated error in a three-day forecast, and other errors that will all contribute to a larger error in the initial state.

(b) Error due to deficiencies in the models.

(c) Error due to unpredictable local processes, such as the chaotic eddy cascades proposed in Part 1. The evidence there is that these dominate the production of strong gusts in Canterbury, and that this process therefore accounts for nearly 40 per cent of the total variance in gust maximum aerodynamic load and speed.

This estimate of errors (a) and (c) leaves at the most about 45 per cent of the total variance that could be attributed to error (b). Of these three errors, (a) is amenable to only slight improvement by global weather prediction institutions over a long period of time, error (c) cannot be fixed, and error (b) offers the only significant scope for improving forecasts. However, under 45 per cent of the total variance in gust maximum aerodynamic load and speed appears to be predictable three days ahead, rising to a limit under 60 per cent on the day of the event. In other words, there would be little scope for improvements in any prediction service that was already nearly this accurate.

There is definitely some potential to improve NWP predictions of maximum gusts using the statistical model of Part 1. The most significant predictors were the pressure-difference across the Southern Alps and its variation, but the model values of these were little better than half their observed magnitudes. A model with finer resolution than 20 km would represent higher and steeper mountains, leading to a greater pressure-drop across a larger mountain barrier. Whether the RAMS model would adequately approximate relevant processes such as form drag is another matter.

A survey of strong northwesterly events in Canterbury suggests that the two cases studied are reasonably typical, so that this balance of errors may be normal. However, the sample size is pitifully small, so that no more can be concluded without a more comprehensive sample. This was beyond the resources available, but the results presented here may be of sufficient concern to weather forecast providers in the region to prompt a proper study.

Acknowledgments

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