Assessing the site-scale effects of climate variability in New Zealand: developments with the CLIMPACTS integrated model system

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Abstract Site-specific and/or regional scale assessment is increasingly becoming an important component in studies of climate variability and change impact. This is partly because of the development of climate change research itself, but is also due to the growing demand for policy-relevant information related to climate change for vulnerability and adaptation at this spatial scale. Linking the large-scale analyses to small-scale experiments hence becomes critical. As it is still not practical to use large-scale physically-based climate models for such purposes, a stochastic approach using weather generators, has the potential to be applied effectively for assessing the impact of climate variability and change at the site scale. This approach, however, requires that the key statistical characteristics of the historical climate variables are accurately represented by the weather generation model used. So far, many inadequacies exist in various weather generators and have limited their application in site-specific impact assessments. A modeling strategy has thus been developed and incorporated into an integrated assessment model system (CLIMPACTS) to provide the end-users with the flexibility to compare and select the most appropriate weather generator for their particular site. In this paper, Kiwifruit is used as an example to demonstrate within the CLIMPACTS system the capacity for selecting and applying weather generators at two sites in New Zealand.

1. Introduction

Variations in climate can have significant adverse influences on the New Zealand economy through direct effects on primary production (agriculture and forestry), and indirect effects through its influences, for example, on water resources. Thus, there is an immediate need for policy decision on how to prevent or adapt to climate change based possible future climate changes. Enhanced knowledge of the possible effects of climate variability and change will contribute significantly to the management of risk, locally, regionally, and nationally in both the near-term and future. One important aspect of climate change impacts is the occurrence of extreme events. Along with the predicted changes in average conditions in connection with global climate change, the frequency of occurrence of such extreme events can also be expected to change.

Given this context, a multi-disciplinary research team was formed in 1993 to study on the CLIMPACTS programme. The objective is to develop an integrated model system that can be updated to account for scientific advances and be used as a flexible tool for conducting sensitivity analyses of effects on important sectors of the New Zealand economy. After the first stage of national assessment capacities completed which involves mainly the studies on the agricultural sector focusing on the national, regional, and local scales (Kenny et al., 1995; Warrick et al., 1996), the research has been moved to the site-scale capacities development recently.

Integral to the site-scale studies in CLIMPACTS necessitates the development of tools to examine effects of climate variability and change, and subsequent effects on climate-related risk. The climate variability and change have the greatest direct effect on the New Zealand economy, particularly at site specific and regional scale. However, questions of what climate variability and change might occur, and what the effects might be, largely remain unanswered.

Therefore, recent studies of the CLIMPACTS programme has been focused on the capacity building to examine the effects of climate variability and change for site-scale assessment. In this paper, we demonstrate the methods being used and their application on a specific horticultural crop (kiwifruit).

2. The Methods

Climate impact assessment in many areas such as crop-climate relationships and water resources management require a sufficient long climate time series, which almost in every assessment studies far beyond the scope of the current historical records. Therefore the interest in possible climate variability and change and in the assessment of their impacts have led to increased attention to methods for simulating climate variables. Physically based general circulation models

(GCMs) are able to produce enough long time sequence of climate variables, under both current or changed climate conditions, but their inability to reproduce the climate on a finer resolution limit their direct use in site-scale impact studies. Furthermore, at present, GCMs are unable to provide reliable information regarding the possible changes of climate extremes. Continuing studies have been done by atmospheric scientists in order to keep with the physically consistent manner of GCMs (Young, 1994). However, techniques based on synthetically generated time series are "not now practical" because "a physical, not just statistical structure of many important variables is not well known or easily expressed" (Robock et al., 1993).

As an alternative, stochastic approaches, i.e., weather generators have been used as computationally inexpensive tools to produce multiple-year climate change data at a daily time sequence for site-scale impact assessment purposes. The philosophy behind such approaches is the expectation of generating climate variables that, at least, have consistent statistical characteristics with their historical records. Moreover, regarding the possible changes in extremes, which have not been coped well in its physical manner, a statistical approach could also be adopted with a stochastic model.

However, the existing stochastic models have many inadequacies which caused their limited use in climate impact assessment (Wilks, 1992). After the first stochastic model which could generate a whole suite of climate variables became available at the early 1980s (Richardson, 1981), great efforts have been made to refine the model performance and resulted in numerous stochastic models with different approaches. The fundamental questions remain to the model end-users: how reliable a stochastic model is or, for a certain climate variable which is of the most interest for a specific impact study purpose, how well a stochastic model represents its statistical characteristics. Without the statistical characteristics of a climate variable being sufficiently represented compared to its historical records, the reliability of any following assessments would be questionable, either for more detailed climate variability analysis, or for greenhouse gas induced climate change impact assessment.

Given the statistical complexity involved in a time series of climate data and numerous stochastic models at hands, it may be unrealistic to single out a certain stochastic model that performs better than all other models in various climate variables simulating. The key point here is then how to distinguish the model that is best fit into a modeler's particular impact assessment interests. In order to provide as much as possible of the modelling flexibility, a model system that is developed for a site-scale impact assessment purpose should incorporate, at least, the typical weather generators with their necessary statistical characteristics being easily available. Hence, in CLIMPACTS model system, four different weather generators and an extreme event analysis tool based on general extremal distribution function have been built-in. Each of the selected four generators represents a general approach in the weather generator development history.

The first model is the Richardson's weather generator as normally termed as WGEN. In WGEN, the precipitation occurrence is described by a two-state (wet or dry day), first-order Markov chain wherein the transition probabilities for a given location are allowed to vary through an annual cycle. The variation of precipitation amounts on wet days is characterized as gamma distribution with the shape and scale parameters were determined from the historical daily precipitation data. The daily temperature and solar radiation is defined conditional on the wet/dry state of a particular day. To allow day-to-day dependence of temperature and solar radiation, the maximum, minimum temperatures and solar radiation components are represented as a first-order, trivariate autoregressive process. The annual cycle of the mean and standard deviation of temperature and solar radiation are modeled by single Fourier harmonics with fixed phase angles. Further details of the WGEN model could be found at Richardson (1981).

The second and third models, as termed as WG-SERIES and WG-LARS, are using a series approach to simulate the precipitation occurrence based on the distribution of the length of continuous sequences, or series, of wet and dry days. WG-SERIES uses a geometric distribution to fit the observed sequences of wet and dry days and uses the same method as WGEN in estimating the precipitation amount. A non-parameteric approach was adopted in the WG-LARS to estimate the distribution of sequences of wet and dry spells and the precipitation amount at wet days. Readers are referred to Racsko et al., (1991) and Semenov and Barrow (1997) for details of the WG-SERIES and WG-LARS models.

The fourth model, which is termed as WG-COND, has the daily precipitation amount conditioned on the monthly precipitation totals. In WG-COND, the precipitation amounts are stratified into subsets of months according to the low, near-normal and high precipitation categories. Again, precipitation on wet days is modeled as independent gamma variates. Wilks (1989) discussed the detail of the WG-COND models.

The extreme event analysis tool based on the theory of extreme values (Leadbetter et al, 1983). As expressed by the theory, for sufficiently large parent sample size, the probability distribution of the standardized (or "reduced") maximum value can be approximated by the general extremal distribution function as described by Jenkinson (1969). The probability weighted moments method was used in this study to estimate the generalized extremal distribution function parameters. In order to have a general application, the extreme event analysis tool was built to have the capability to analysis various extreme event types, such as extreme event of a fixed date, or in a user-defined period. The extreme analysis tool was then further incorporated directly with impact models, so that the extreme events that have most significant effects on that particular crop, such as kiwifruit, can be easily addressed.

3. The Kiwifruit Application

Considerable knowledge exists for kiwifruit with its economic importance to New Zealand. Salinger and Kenny (1995) used average climate data to describe kiwifruit distribution for New Zealand, which provided a valuable first-order assessment. Three important climate factors were identified as being important for kiwifruit: winter chilling; growing season thermal time; and annual rainfall. Winter temperature conditions are important for winter chilling of vines (Brundell, 1976). Warm spring and early summer conditions are important for subsequent development (McPherson et al. 1992). In the autumn months it is evident that lower mean temperature enhance final fruit maturity (Seager et al. 1991). The availability of water for vine growth is one of the main determinants for adequately sized fruit (Prendergast et al. 1987; Judd et al. 1989). Insufficient moisture leads to smaller fruit. Kerr et al. (1981) suggested a minimum annual rainfall of 1250 mm was required with 100mm/month or more between December and March. In addition, extreme climate events, minimum temperature in particular, can damage or even kill the crop at sensitive growth stages. Frosts in spring are most harmful because this is the period when there is new season's growth. The crop may be damaged if there is an insufficient frost-free period (the period between the last frost in spring and the first frost in autumn).

Table 1: Long-term mean historical and weather generators simulated monthly precipitation (mm)

Month	Historical	WGEN	WG-SERIES	WG_COND	WG-LARS
Te Puke					
Jan	101.43	133.60	149.13	150.02	75.27
Feb	89.04	117.89	129.36	121.03	91.09
Mar	174.41	141.98	155.74	138.12	139.10
Apr	123.63	142.09	150.29	152.71	77.65
May	99.89	150.09	160.41	181.79	193.82
Jun	162.22	147.71	155.25	193.82	155.99
Jul	179.93	173.28	152.45	216.30	206.76
Aug	149.13	178.26	153.46	223.73	228.31
Sep	144.74	171.36	143.61	218.48	183.16
Oct	155.52	164.72	157.03	228.24	207.60
Nov	129.74	142.61	151.97	211.37	188.84
Dec	141.31	127.53	151.88	191.43	241.47
Ann	1650.99	1791.11	1810.58	2227.03	1989.08
Lincoln					
Jan	54.25	58.97	66.19	64.63	44.72
Feb	48.67	52.04	60.57	57.11	35.55
Mar	60.30	56.74	69.73	63.60	53.08
Apr	58.23	60.55	68.83	67.55	53.92
May	61.68	66.38	70.33	71.66	56.56
Jun	58.88	64.64	66.52	65.66	57.62
Jul	65.92	66.64	67.05	64.91	69.96
Aug	59.31	58.01	63.21	59.40	56.06
Sep	42.60	51.71	59.08	50.59	35.89
Oct	48.73	50.82	57.76	53.11	40.64
Nov	53.29	51.13	56.91	53.91	47.08
Dec	56.22	58.11	60.45	62.55	47.50
Ann	668.06	695.76	766.63	734.69	598.56

Based on the above description, the following statistics were used to compare and choose the appropriate weather generator for kiwifruit. They are annual total rainfall, with monthly amount from December to March in particular; the mean temperature for all months; the distribution of the extreme low temperature after crop budburst; the distribution of the extreme low temperature before crop maturation. Two sites, namely Te Puke of the North Island and Lincoln of the South Island of New Zealand, were used in this study. For each of these two sites, thirty years of historical climate records are available. However, the solar radiation data is incomplete, thus sunshine data was used to calculate the solar radiation and was then used as the surrogate of the observed solar radiation data. Five hundred years daily time series of rainfall, maximum, minimum temperature and solar radiation were simulated to eliminate the influences of a short-term simulation result on the statistical characteristic representation. Tables 1 and 2 show the long-term mean monthly historical and the four weather generators simulated rainfall and temperature for Te Puke and Lincoln respectively.

In terms of the December to March and annual rainfall, none of the models simulate well for Te Puke, with WGEN performs marginally superior than the other three. However, recall the minimum rainfall that the kiwifruit phenologically required, the annual and March rainfall is generally sufficient, no matter is historically recorded or simulated, i.e., larger than 1250 mm annually and 100 mm on March. That leaves WG-LARS the possible best candidate for the rainfall impact assessment study, as it produces better simulation results on January and February rainfall. For Lincoln's rainfall simulation, WGEN performs significantly better than the other models. In terms of temperature, Table 1 and Table 2 show that all models perform reasonably well and give similar statistical results for both sites, though almost all of them generate a slight higher temperature than their corresponding historical records.

Table 2: Long-term mean historical and weather generators simulated monthly temperature (°C)

Month	Historical	WGEN	WG-SERIES	WG-COND	WG-LARS
Te Puke					
Jan	16.95	18.13	18.14	18.17	18.18
Feb	17.17	18.39	18.46	18.33	18.38
Mar	15.81	17.13	17.16	17.10	17.14
Apr	13.51	14.63	14.70	14.57	14.53
May	10.83	11.82	11.84	11.78	11.62
Jun	9.04	9.77	9.76	9.74	9.68
Jul	8.42	9.17	9.14	9.17	9.00
Aug	9.14	9.93	9.91	9.93	9.88
Sep	10.63	11.48	11.42	11.41	11.41
Oct	12.36	13.25	13.27	13.20	13.23
Nov	13.96	15.08	15.06	15.11	15.04
Dec	15.52	16.88	16.94	16.88	16.87
Lincoln					
Jan	15.99	16.39	16.34	16.38	16.44
Feb	15.83	16.36	16.37	16.42	16.42
Mar	14.20	14.83	14.89	14.84	14.97
Apr	11.50	12.02	12.03	12.06	12.00
May	8.46	8.76	8.87	8.91	8.89
Jun	6.28	6.61	6.53	6.62	6.61
Jul	5.76	6.09	6.09	6.08	6.06
Aug	6.73	7.09	7.08	7.11	7.14
Sep	8.64	8.95	8.97	8.99	9.02
Oct	10.94	11.16	11.12	11.08	11.13
Nov	12.54	13.27	13.12	13.17	13.41
Dec	14.40	15.22	15.01	14.95	15.12

Based on both historical and generated data, the extreme event analysis tool that was incorporated into the kiwifruit impact model was used to assess the frost risk. Figures 1 and 2 show the results of extreme analysis of minimum temperature for a user defined periods of 'after-budbreak' and 'before-maturation' (in this study, they were set as default from budbreak to January 1st and from January 1st to maturation) for Linclon. As figures 1 and 2 indicated, none of the models performs well in representing the statistical feature of the low temperature extreme events, with WG-LARS producing marginally better result than other models in before-maturation minimum temperature event.

4. Discussion and Conclusion

Although weather generators have the potential to be used as an inexpensive tool for site-scale impact assessment purposes, it is critical that the statistical characteristics of the historical climate variables have been represented well in the generated time series data. In addition, if extreme events are also of concern the statistical feature of the extreme event need to be accurately addressed which has its particularly importance, since in most circumstances the impact of the extreme events has much more significant consequences than the long-term means. During the past, great efforts have been made to achieve such a simulation sufficiency and resulted in a number of weather generators. However, the result of this study has shown it is still not possible to single out one method that performs better than all others in various site-scale climate change impact assessment studies. As for kiwifruit at Lincoln, if the influence of the rain were under focus, we may need to use WGEN result for such a study purpose, while if the effect of frost risk before-maturation were the matter, WG-LARS would be the best candidate to assess its consequences.

Given the reliability is always under concern in climate change research, carefully selecting a suitable weather generator hence has the first importance in site-scale climate variability and change impact assessment studies. An impact assessment model need provide end-users the flexibility to choose the most appropriate model in their particular study interests. In CLIMPACTS system, this was achieved by providing an easy to select options with a user-friendly interface showing all the necessary output statistics. The CLIMPACTS has built in such a way that future development of weather models and extreme analysis tools can be easily added in, as well as various plant models from which the impact studies need to be carried out.

Future development of the system will be to incorporate the greenhouse gas induced climate change into the weather generator results, so that the impact assessments could be extended to various climate change scenarios. It will also include a research to selecting a appropriate method for CLIMPACTS system to scale-up the site-scale impact assessment result to regional level.

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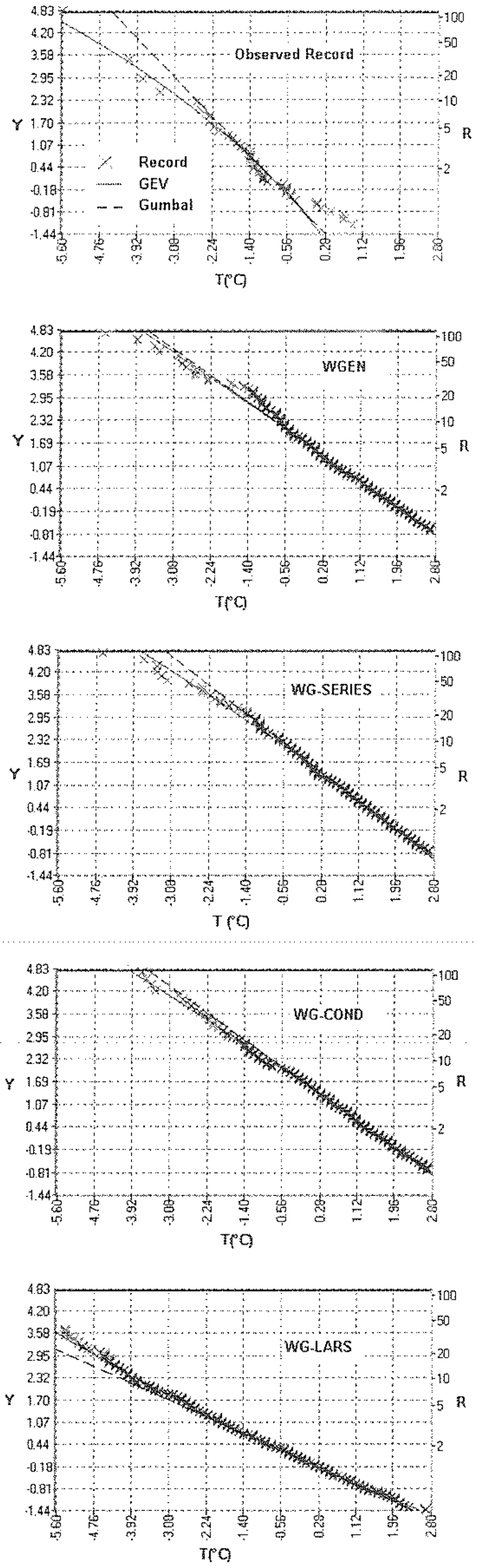

Figure 1 Extreme low temperature analysis after budbreak for Lincoln, Y – Reduced Gumbel variable; R – Return years.

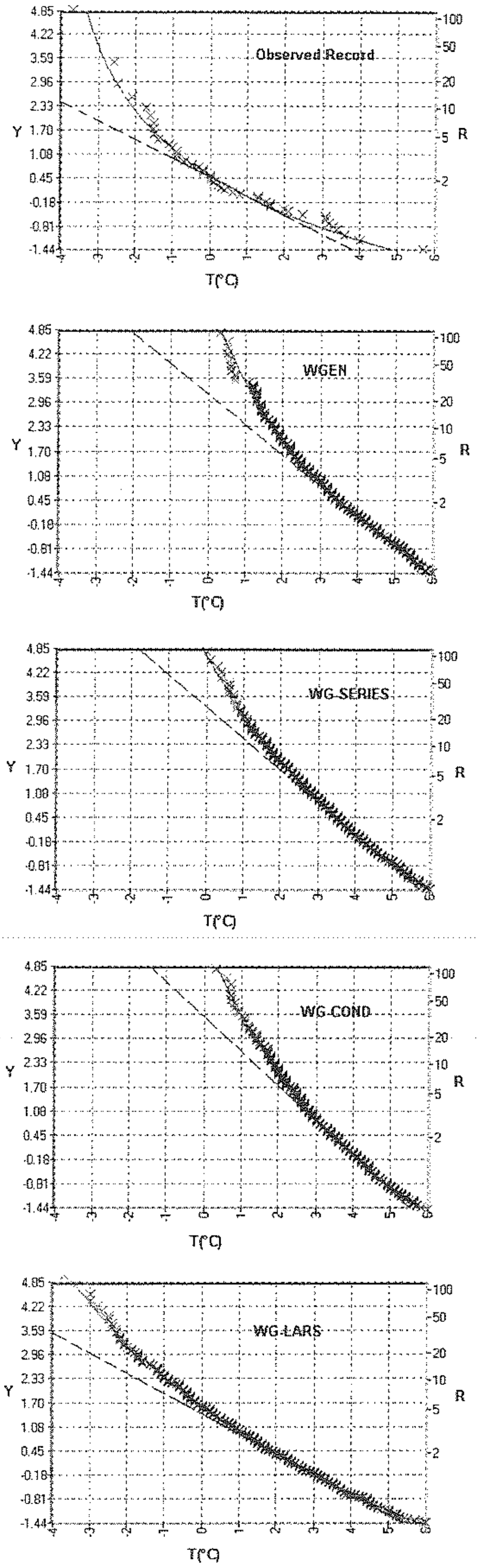

Figure 2 Extreme low temperature analysis before maturation for Lincoln, Y – Reduced Gumbel variable; R – Return years.