Recent frost trends for New Zealand

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Executive Summary

This study aimed to detect trends in frost across New Zealand for the period 1972-2008 using all the suitable minimum screen temperature observations from NIWA's climate monitoring network. The observations were quality controlled and steps taken to ensure they were suitable for trend detection. This yielded a larger number of sites than previous studies so as to provide enough data for a regional analysis but a shorter timeframe.

The study provides strong evidence of a national warming trend as the number of frosts was found to be decreasing since 1972 when examined annually and aggregated across New Zealand. Increasing minimum temperatures and increasing (less negative) frost temperatures were also detected. This is consistent with previous national level analyses for New Zealand and the Pacific, and while no formal attribution analysis is undertaken it is also consistent with the process of global warming. When the agricultural growing season (October-April) was examined weak increasing trends in frost occurrence were found, but they were not significant. At the monthly level particularly for April and October-November when some agricultural crops are vulnerable no consistent trends were detected.

When regions within New Zealand were examined both warming and cooling were detected as negative and postive trends in frost occurrence. The most pronounced increases in frost occurance (cooling) were detected in the Wairarapa and the south east of the South Island in an area extending from Ashburton to Dunedin. Strong decreases in the number of frosts (warming) are evident in high altitude zones for both Islands, extending to the agricultural zone in the north of the South Island. For the most part neutral to slightly decreasing (warming) frost occurrence trends were detected for the major agricultural regions. This study addressed detection of recent trends, and it did not assess how trends and regional patterns might change in the future under the combined influences of projected anthropogenic global warming and decadal natural variability in regional climate.

This study highlights the influence of New Zealand's maritime climate and topography on the formation of frost and its interaction with larger scale global forcing. While the national aggregate results were consistent with global warming, the study provides evidence that global and national warming trends do not translate directly to all regions in New Zealand. Hence regional and local level analysis are needed to ensure that risks are well characterised when developing adaptation responses to climate change like modification to frost risk management.

1. Introduction

1.1 Frost

In agricultural and forest landscapes frosts occur when the surface of plants are cooled to below the dew point of the surrounding air. This creates conditions where ice crystals grow either on the surface of the plant or within plant cells. Two distinct meteorological settings give rise to frosts. First, when clear still evenings create heat loss from the ground to the atmosphere creating inversion layers and the plant canopy becomes cooler than the earth below and air column above. In most New Zealand landscapes such ‘radiation frosts’ also result in katabatic flow of cold air from higher to lower altitudes. Second, ‘advection’ or wind frosts occur when a very cold air mass moves across the plant canopy as part of a broader weather system. Such frosts are relatively rare in New Zealand.

The full definition of frost risk is the climatic frequency of these events in combination with the impact on production. Frost can have direct impact on production volumes and quality in crops, pastures and forests for example: the blistering or bursting of fruit in orchards and vineyards; yield loss when frost damages flowers in broadacre or horticulture crops; the abrupt cessation of growth in some pasture species; and scalding of soft stems, new growth or juvenile plants during advection frosts. However, the occurrence of a meteorological frost does not necessarily result in a production or quality loss, as direct impacts can be modified by the timing of an event as well as mitigation actions and planning (Ireland 2005). Site and species selection, frost insurance, production diversity, timing of planting to avoid the frost window, and physical actions to disturb inversion layers are all effective frost risk management actions. Therefore frost mitigation has an indirect impact of the farm business through additional costs, and for more extensive production systems some of these options may not be financially viable.

Climate change brings the prospect of reduced frost risk because of the global process of warming that has been observed over the last century. In New Zealand, increasing trends in minimum temperature have been reported that are consistent with global climate change. Zheng et al (1997) report a significant warming trend in air temperature of 0.11 °C per decade from 1896-1994. Salinger and Griffiths (2001) report significant increases in minimum temperature, reduction in cold nights and reduced frost days for the period 1951-1998, in a study that used 37 stations from 1930-75 and 51 stations from 1951-98. Both these studies were constrained to the national level using a small number of sites across New Zealand where data quality can be assured. Withers et al. (2007) found a more complex regional picture, identifying around one third of a national data set where temperatures were decreasing for the period 1900-1998 (mostly in the South Island). While Withers et al. (2007) used data from more sites, the time series are of poorer quality than those used by Salinger and Griffiths (2001) and Zheng et al (1997). There are also perceptions of both increasing and decreasing frost risk reported by agricultural practitioners around New Zealand.

1.2 Project scope

Given this background there is significant interest, particularly in the agricultural sector, in determining whether there have been any trends in frost occurrence and/or intensity around the country over the past 30-40 years. The Ministry for Agriculture and Forestry (MAF) have asked NIWA to prepare a report examining this issue. Specifically the work was commissioned to:

- interrogate existing frost records for the last 30-40 years to see if changes have occurred in frequency, severity and timing of frosts;

- produce maps which represent these trends and statistics over the whole country;

- undertake an analysis to determine trends in soil temperature, matching it to the frost analysis; and

- provide comment on the possible drivers of trends, including recommendations on the best way to incorporate climate change into future work examining the incidence of frost.

Hence this study is an initial detection analysis of recent frost trends in New Zealand, drawing on readily available data held at NIWA and using standard analytical methods. As a result there are a number of limitations surrounding the work, which are discussed in section 2 and 4.2.

2. Methodology

2.1 Frost definition

The definition used in this study follows the standard meteorological characterisation of a frost, temperatures below 0°C measured in a Stevenson screen at 1.2 m above the surface. However, meteorological frost is a partial definition and it does not fully describe frost risk for the primary sector. Whether or not ice crystals form and vegetative tissue is damaged when temperatures fall below 0°C depends on a range of factors that characterise the freezing point of a substance or the critical temperature of a crop, for instance:

- the humidity of the surrounding air mass, where generally lower humidity promotes the formation of ice within plant cells;
- temperature gradients through the soil and plant canopy;
- the frost hardiness of plants, where generally cells with higher lignin and or saline content have a much lower critical temperature. Some plants have a physiological response, ceasing the production of new growth when they experience the first frost of a season.

Full analysis of frost risk requires more detailed process based models and or production data than available for this study or able to be practically implemented for a large number of sites across New Zealand. Despite this, the meteorological definition used has a practical advantage in that it supports more widespread analysis of frost using the climate monitoring network.

2.2 Study timeframe

A choice was made to confine the analysis period to recent climatology (1972-2008). The assumption was that by constraining the analysis to this period, there would be sufficient data to undertake a spatial analysis of trends and determine if there is any regional structure in frost occurrence. This period also matches the temperature series available for the virtual climate station network, which provides a nationally comprehensive coverage, but there are also some concerns about its use in frost trend analysis (described below). The thirty six year period is around the minimum time frame that the World Meteorological Organisation recommends for climate determination.

It is necessary briefly to explore the study time frame in a longer historical context so as to clarify the limitations that this choice has on the study . Figure 1 shows trends fitted to the New Zealand national composite long term temperature series for the full period (starting 1853, black line) and the chosen study period (red line). There is a small difference between the long term linear trend compared to 1972-2008, but in this series the differences are negligible. The anomalies, which are deviations from the 1865-2008 mean, are used to remove the seasonal fluctuation and are one way of treating climate series so that they reflect long term changes. The low pass filter in Figure 1 (blue line) highlights that there are also shorter term oscillations in the series, or inter annual variability. Closer inspection of the filter suggests that the variability in these oscillations differs between the study period (1972-2008) to the previous 30 years (1950-1972). This corresponds to the hypothesis that there are detectable decadal scale signals around the long term trend.

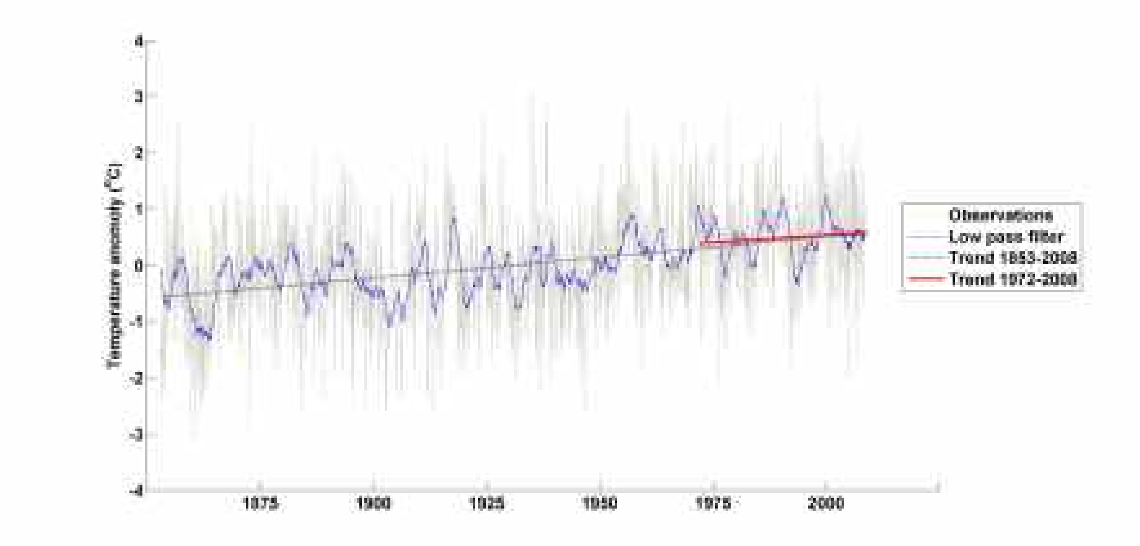


Figure 1. New Zealand's national composite long term average temperature series (Salinger et al 2001).

A different approach to trend detection is needed to explore the decadal scale signal in temperature time series than the low pass filter in Figure 1. One such approach, wavelet decomposition, is presented in Figure 2 for an index describing decadal oscillation in sea surface temperature (the Pacific Decadal Oscillation (PDO) index Mantua et al 1997), the mean temperature series and the mean temperature anomaly. The decomposition removes all of the short term noise in the data, in this case fluctuations associates with weather, seasons and inter annual variability (ENSO). Similarity between the decomposed PDO and temperature series is evident (correlation of 0.78). The long term trend was all that remained in the New Zealand temperature anomaly series using the same decomposition procedure, which has already had some of the short run variability removed by seasonal normalisation.

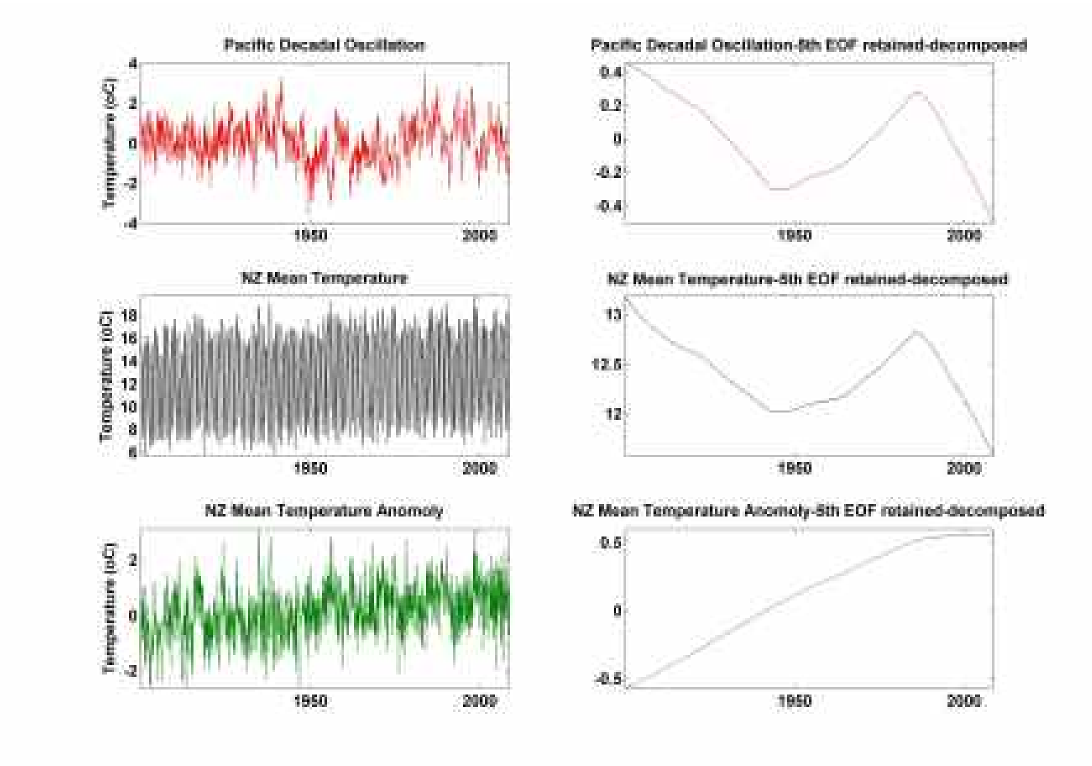


Figure 2. **Wavelet decomposition of the Pacific Decadal Oscillation index (Mantua et al. 1997), New Zealand's long term mean temperature series and the temperature anomaly for the temperature series.**

The decomposition analysis in Figure 2 re-affirms the work of Folland et al (2002) and Salinger et al (2001), who found detectable decadal scale signals in Pacific and New Zealand temperatures, with a background of longer term warming trend. For this study it illustrates some key principles for correctly interpreting scale and understanding limitations:

- because of the restricted time period (1972-2008) it will not be possible to discern the relative contribution of decadal scale oscillations and longer term processes like global warming in this study. It is confined to a time frame which represents one climatic period, mich of which was in one phase (approximately 1972-2002) of the PDO;

- as a result it will not be possible from this study alone to assign any degree of confidence in terms of the expected future persistence of frost trends;

- metrics and methods that are suitable for detecting climate change are more spatially and temporally aggregated than those that are sensitive to other processes like ENSO, and synoptic forcing (weather).

2.3 Climate data

The data flow for this study is summarised in Figure 4. Primary station level observations were sourced from CLIDB (NIWA's climate data base), constrained to those sites that record daily minimum temperatures with at least 60 percent complete records from 1972-2008. This timeframe was chosen because of the relatively large amount of data available compared to other times in the historical record. As mapped in Figure 3, 88 New Zealand stations met this criterion out of a possible 690 where minimum air temperatures have been observed over the past century. On average 30 percent of observations are missing through the period 1972-2008 at these stations. This provided a national coverage of station level observations, with enough sites to represent each meteorological district, (Figure 3 and Table 1).

It needs to be stressed that there are insufficient data to characterise frost at sub regional and micrometeorological scales using the set developed from CLIDB. Therefore the analysis undertaken with this data set will provide a broad regional picture only. Analysis of frost at finer resolution than this scale requires additional support, such as information from remote sensing (Tait and Zheng, 2003) and is beyond the scope of this study.

In the form they are extracted from CLIDB the data are incomplete time series that also contain a range of potential problems due to instrument changes, station changes, influences of the landscape surrounding recording stations (urban development or vegetation change) or recording faults. As a result they are not suitable for trend analysis without additional quality control and treatment (data homogenisation).

Interpolated minimum daily air temperature series from the Virtual Climate Station Network (VCSN) were also sourced for the closest grid point to each station. The VCSN is a national level daily climate data series, where all observations from the period 1972-2008 are interpolated to a regularised 5km^2 grid. Minimum temperature is interpolated using a three dimensional laplacian thin plate spline (sourced from the ANUSPLIN package), using geographic location and altitude as a covariate. A technical description of the methodology is provided by Tait (2008).

While the VCSN data provide complete series from 1972-2008, they can have an inherent bias when compared to station level observations. Although the nature and degree of bias varies significantly between stations, typically the tails of the distribution (including frost risk) exhibit greater departure from observations. This is because of the need to trade-off the smoothness of national level surfaces against the station level observations as part of interpolation. As a result data from the VCSN network are not assured for trend analysis in primary form, although an analysis is pursued here to investigate landscape influences on trends. As described below, a bias correction procedure was implemented so that the VCSN series could be used to patch missing station observations, and also replace those that were removed during quality control.

Table 1. Number of sites, mean percent of data missing and descriptive statistics for minimum air and earth temperature data sourced for this study. IQR is the interquartile range

Region	Minimum air temperature				Minimum earth temperature			
	Number	*% Missing*	*Mean*	*IQR*	*Number*	*% Missing*	*Mean*	*IQR*
A	9	29	11.2	5.4	18	61	14.6	6.5
B	10	36	9.2	7.2	19	62	12.7	7.7
C	9	14	9.2	6.5	23	52	12.9	7.2
D	9	38	8.1	6.8	27	62	12.2	7.8
F	12	24	8.4	6.2	28	56	12.1	7.0
G	11	20	7.3	6.0	11	50	11.5	7.4
H	8	35	7.6	6.7	15	62	11.0	9.1
I	20	28	5.3	7.1	22	59	10.0	8.8
National	88	29	7.3	6.6	218	59	12.7	7.5

Minimum daily earth temperature observations, soil surface temperature readings with the probe at less tan 5cm from the surface, were also sourced from CLIDB. This was done with less rigorous criteria and quality control than air temperature—data were obtained for stations which had at least a 25 percent continuous record between 1972-2008. This is because the network for measuring earth temperature in New Zealand became more nationally comprehensive in the early 1990’s. Typically data had 60 percent missing records for the period 1972-2008 (Table 1). Hence the analysis of minimum earth temperature trends undertaken in this study should be considered exploratory, providing at best a broad comparison for the analysis undertaken with air temperature.

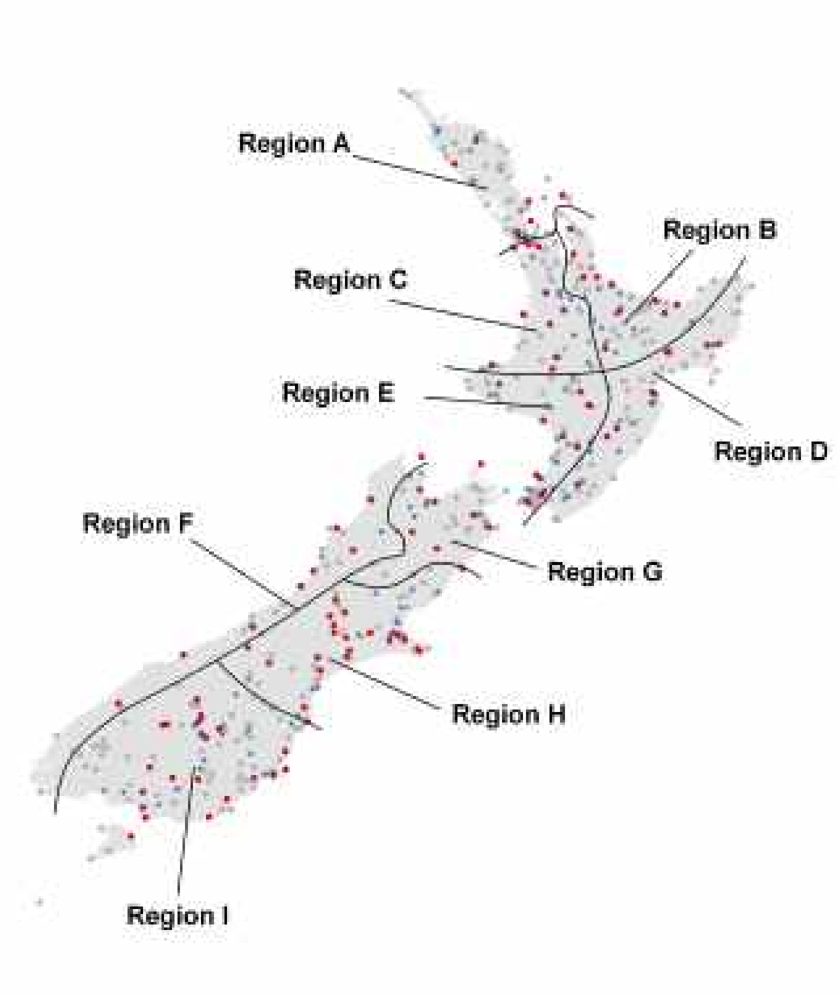


Figure 3. New Zealand's 9 meteorological regions showing: ● air temperature observation stations; ● stations meeting the selection criteria (station open between 1970-2008 with > 60 percent minimum air temperature records complete); ● earth temperature observations stations.

2.3.1 Quality control

An automated and objective quality control procedure was devised to screen station level air temperature observations for potential errors (Figure 4), with the aim of identifying and removing observations that would make the final analysis of frost trends suspect. Quality control of climate time series for trend and other analyses can take many forms (Peterson et al 1998): direct methods that rely on metadata; manual inspection; internal consistency testing that rely on statistical analysis; through to external verification that compare series with an independent set.

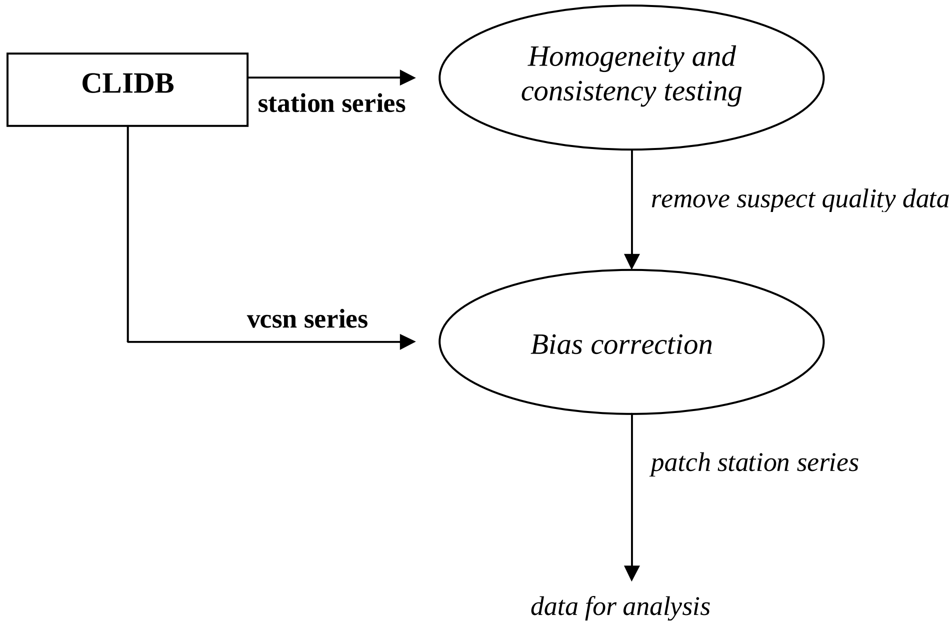


Figure 4. Quality control and patching procedure used to build the minimum air temperature dataset.

Five levels of quality screening are used in this study based on different approaches to homogeneity and consistency testing. They were adapted for use in this study from methods described by Thompson (1984), Rhodes and Salinger (1993), Alexandersson and Morberg (1997), Brunet et al (2002) and the review of Peterson et al. (1998). The five tests implemented are:

1. Suspect detection: suspects are those observations greater than 3.5 standard deviations away from the monthly mean.

2. Internal consistency: observations failing the internal consistency tests are those where the change from the previous observation is greater than 3.5 standard deviations from the mean monthly change.

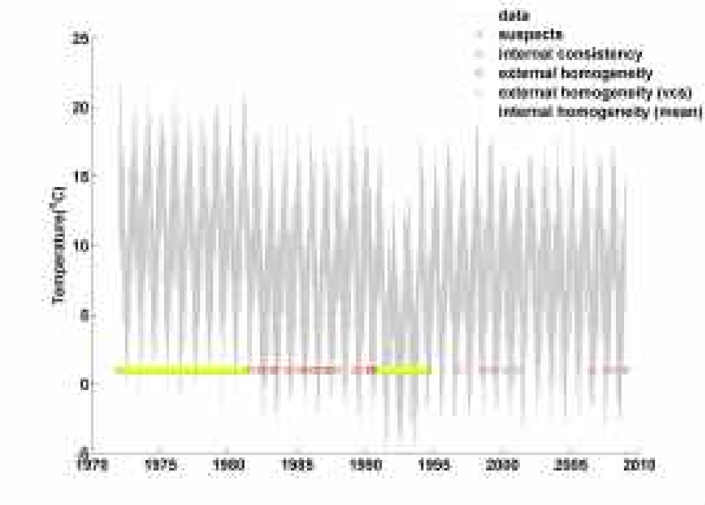
3. External homogeneity: Observations that fail the external homogeneity test have a Z series deviation greater than 1.5 standard deviations from the monthly mean. The Z series is based on a modification of the Standard Homogeneity Test (Alexanderson 1996), and are anomalies (between the observed and a reference set), normalised by seasonal and total variance. For the external homogeneity test the reference set is the distance weighted mean of the three closest stations.

4. External homogeneity (vcs): this test repeats the Z score procedure and uses the same criteria described for 3, but the reference set is taken as a distance weighted mean of the VCSN time series across on a 5-by 5 grid box ($25km^2$) over the observation station.

5. Internal homogeneity (mean): this test repeats the procedure used in 3 and 4, but uses the internal seasonal mean as the reference series.

Examples of two time series screened using these tests are in Figure 5. Both time series have been modified to illustrate a range of potential problems, such as break points, systematic shifts and changes in variance. The original signal for the station is from 1982-2008. Both series have been infilled (prior to 1982) with a biased data series using station observations taken upslope from this site. The period from 1991-1995 in series A has been shifted by subtracting 1.5°C to introduce an unusual shift with two definite breakpoints. The period 1990-2008 in series B has a negative exponential trend imposed.

The symbols in the figures identify which observations fail a particular screening test. As shown the tests clearly identified suspect data introduced into the series. The external homogeneity tests identified both the artificial bias and in filled elements of the series in Figure 3a. In Figure 3b the homogeneity tests identified multiple break points, including those associated with the introduced negative exponential trend. In both of these examples, a small number of observations failed the internal consistency test, while very few failed the suspect detection test.



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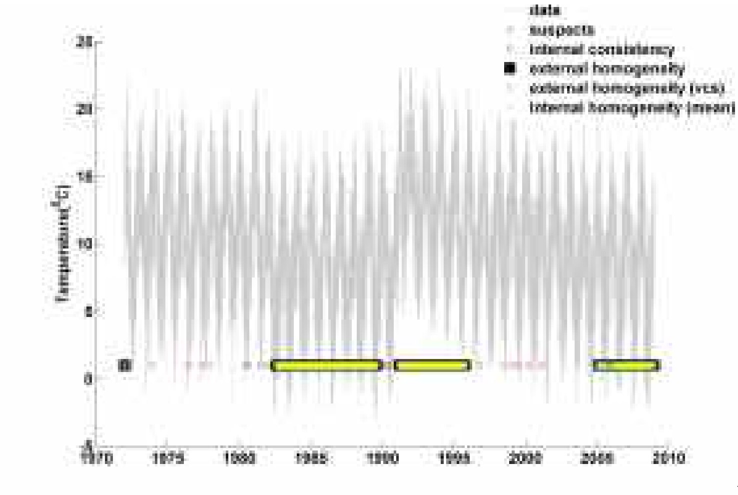

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Figure 5. **Examples of time series screened using the homogeneity and consistency testing procedure.**

The quality control procedure was applied to both the air temperature and earth temperature station data sourced from CLIDB. The number of suspect observations identified is summarised at the regional and national level in Table 2. Typically around 15-20 percent of observations were suspect for air temperature (with some sites as little as 2-3%). There were more quality concerns in the earth temperature data with around 30 percent of observations identified on average. For the air temperature data the suspect observations were removed and replaced with bias corrected VCSN series (described below).

Table 2. National and regional summary of percent observations removed in quality control.

	Minimum air temperature			Minimum earth temperature		
	Mean	*Max*	*Min*	*Mean*	*Max*	*Min*
A	17.1	39.5	4.3	34	48.9	10.2
B	13.6	42.1	5.1	23.1	45.8	15.2
C	25.2	39.1	8.3	34.2	51.1	9.1
D	16.8	35.1	5.3	19.9	39.5	5.8
F	22.9	39.3	2.3	35.7	43.5	4.3
G	20.0	37.0	9.2	31.1	39.1	6.7
H	12.1	35.9	4.4	34.2	41.8	8.9
I	20.2	41.4	2.1	34.3	45.2	9.1
J	17.7	41.4	2.9	23.4	54.1	12.6
National	18.4	39.0	4.9	30.0	45.4	9.1

2.3.2 Bias correction for patching

The bias correction procedure used for the VCSN is based on methods described by Ines and Hansen (2006) for correcting daily time series derived from global and regional models for use in crop simulation. It involves truncating the cumulative distribution function of the VCSN series to the cumulative distribution function of the observed series, where:

$$P_{(n)} = V_{(n)} \times a_{(n)}$$
$$a_{(n)} \cong A \quad where \quad V.cdf = V_{(n)} \qquad \textbf{Equation 1}$$
$$A = \frac{O.cdf}{V.cdf}$$

where P is the patch series on day n, V is the virtual climate station observation, and a is an adjustment factor taken form the adjustment vector A, where V corresponds to the VCSN cumulative distribution function (*V.cdf*). *O.cdf* is the observed cumulative distribution function for data where data flagged in quality control have been removed. The bias corrected VCSN data is then used to patch missing data or observations that had been removed in quality control.

A cross validation was undertaken by partitioning the VCSN and station data into fitting and evaluation subsets, where the former is used to determine the adjustment vector *A*. Data from the evaluation subset is used to compare the untreated and bias corrected VCSN data by correlation with the observed station data. The results of the cross validation are shown in Table 3, where generally the bias correction yielded higher correlations across all the meteorological regions.

Table 3. Summary of cross validation results (correlation coefficients) for the bias correction procedure.

	Region								
	A	B	C	D	E	F	G	H	I
VCSN	0.52	0.47	0.57	0.46	0.49	0.56	0.60	0.40	0.52
Bias corrected VCSN	0.78	0.76	0.75	0.71	0.79	0.83	0.76	0.72	0.89

2.4 Frost trend analyses

A range of methods can be used to detect the presence, strength and statistical significance of trends in climate time series. Linear models can be fitted using parametric (least squares regression) and non-parametric (for example pair wise slope) methods. Polynomials and auto regressive moving average models (ARMA) can also be considered if the series is non-monotonic. Extreme value analysis can be used to examine trends in rare events such as heat waves. Non linear time series analysis methods are also used for higher order problems, for example decomposition of series to examine non-stationary components (example Figure 2). Common methods used to detect and estimate the strength of trends in climate series are the Spearman Rank Correlation Coefficient, the two sided Mann-Kendall test which is non parametric and the Student t-test.

Trend detection in this study is carried out in a relatively straight forward way, using ordinary least squares linear regression. This is an appropriate method for the problem and level of analysis required in an initial study of trends, given the assumptions that the relatively short series (36 years) is monotonic and the metrics analysed are normally distributed. The slope parameter (trend) of the fitted linear model is obtained for a number of metrics describing frost risk (detailed below), and reported along with the F ratio and p value which characterise the strength of the linear fit to the underlying data.

A number of metrics are used to characterise frost risk and intensity that aggregate occurrence either in space or time so as to be suitable for characterising climatology. The following describes the general approach to the calculations, while the full range implemented in this study is listed in Table 4.

The ***frequency of frost*** is calculated by determining the number of days in each year minimum air temperature is below a critical threshold:

$$\begin{array}{lll} if & O_{(n)} = T_{(n)} & f_{(n)} = 1 \\ else & & f_{(n)} = 0 \end{array}$$

Equation 2

$$F_{(Y)} = \frac{\sum_Y f}{\sum_Y n}$$

where O are observed minimum air temperatures on day n. T is the critical threshold in this case 0°C. f is a frost score being either zero for no frost or one for a frost day F is the frost frequency in year Y. Growing season (September-April) and monthly (excluding summer) analyses are undertaken by sub setting the observations to the relevant time period each year. Thus Equation 2 is the total number of meteorological frost days in a prescribed period divided by the total number of days in that period.

A metric describing the ***average temperature of meteorological frosts*** when they occur was also calculated. Mean frost temperature (FT) for the year (Y) is taken as:

$$FT_{(Y)} = \frac{\sum v_{(Y)}}{\sum n\left(v_{(Y)}\right)} \quad where \quad v_{(Y)} = O_{(Y)} \leq T$$

Equation 3

where v are air temperature observations (O) that are equal or less than the critical threshold T (0°C). n denotes the number of observation for v. Thus Equation 3 is the average temperature of observations for a specified time period (in this case a year) when temperatures are below 0°C.

The ***first frost day*** (S) each year (Y) is determined as:

$$S_{(Y)} = \min\left(Fd_{(Y)}\right) \quad where \quad Fd_{(Y)} \cong doy \cong O_{(Y)} \leq T$$

Equation 4

where Fd is the day of the Julian year (doy) that air temperatures are below a critical threshold T (0°C). The ***last frost day*** (E) is taken as the maximum of Fd, while the length of frost window L is E-S. Thus Equation 4 defines the first and last recorded frost for a given year or season.

National and regional composite time series are also produced by aggregating across a meteorological zone, for example frost frequency is calculated as:

$$\begin{array}{lll} if & O_{(r,n)} \leq T_{(n)} & f_{(n,r)} = 1 \\ else & & f_{(n,r)} = 0 \end{array}$$

Equation 5

$$FR_{(Y)} = \frac{\sum_{Y,r} f}{\sum_{Y,r} n}$$

where r is the meteorological region (A-I, see Figure 1) and FR is the regionally aggregated frost frequency. All other procedures are the same as for Equation 2. Regional aggregation for mean air temperature, frost intensity and the first or last frost dates differs in that the mean across the meteorological region is taken.

Table 4. Frost risk analyses undertaken in this study. Growing season period is October-April. N is national composite, R is regional composite, S is station level analysis.

Indicator	Units	Annual	Growing season	Monthly	Scale
Frost frequency	Probability/time period Or Days/time period	*	*	*	N,R,S
Frost temperature	Mean °C	*	*	*	R,S
First Frost	Julian day	*			R
Last frost	Julian day	*			R
Frost window length	Days	*			R
Minimum temperature	Mean °C	*	*		R
Earth temperature	Mean °C	*	*		R

2.5 Spatial analysis

Two strategies are pursued for spatial analysis to address perceived limitations in the sample of data: either its quality through time through time or across the country.

2.5.1 Calculate then interpolate

Station level trends are interpolated using a bi-variate thin plate smoothing spline from the ANUSPLIN package (Hutchinson 1995, 1998a, 1998b). This strategy is pursues to ensure that the quality of data is assured through time, but the approach does not yield a large spatial sample for modelling. The general objective when fitting a spatial interpolation function to sparse data is to find an appropriate balance between signal and noise, thereby finding information about spatial variability at a broad scale while not over or under fitting to the data at the individual site. In the thin plate spline this is governed by selection of the smoothing parameter. The technical details of the spatial analysis are as follows:

- all fitted spline surfaces were realised at a 5km^2 resolution;
- all fitted spline functions were of second order
- for frost frequency analyses the most appropriate surfaces were obtained by a square root transformation of the data, and estimating the smoothing parameter by minimising the Generalised Cross Validation (GCV);
- for frost intensity analyses no transformation was required and minimising GCV yielded an appropriate fit;
- for all trend analyses the data were truncated to a 1:5 range, a logit transformation applied and the signal to noise ratio of 1:1 used;
- data for frost intensity trends was too sparse for valid surface fitting, so no results are presented for this variable.
- in some cases individual station results were found to have high leverage, and were removed from the data set. The influence of this procedure is shown in Figure 6, where data from Dunedin Aerodrome is removed to provide a more appropriate surface given the underlying data for mean annual frost frequency.

2.5.2 Interpolate then calculate

The metrics and approaches to trend fitting described in section 2.3 are fitted to minimum temperature on a grid-by-grid basis for the VCSN network. There are some questions about the strength of trends detected in this approach because of known biases in the current data, for example because of poor sampling in the high altitude zones it is known that above snowline temperatures have a warm bias (*pers comm*. Tait 2009). In the lower lying and upland regions of the country, the sampling is more comprehensive and independent validation demonstrates no discernable bias outside of expected measurement error. While bias problems exist, this approach provides an improved representation of the spatial variability across New Zealand, particularly the role of the landscape in controlling trends. This is because the VCSN minimum temperature set is based on all available observations from 1972-2008 and uses a three dimensional spline providing additional support from digital elevation model.

High leverage data included **High leverage data removed**

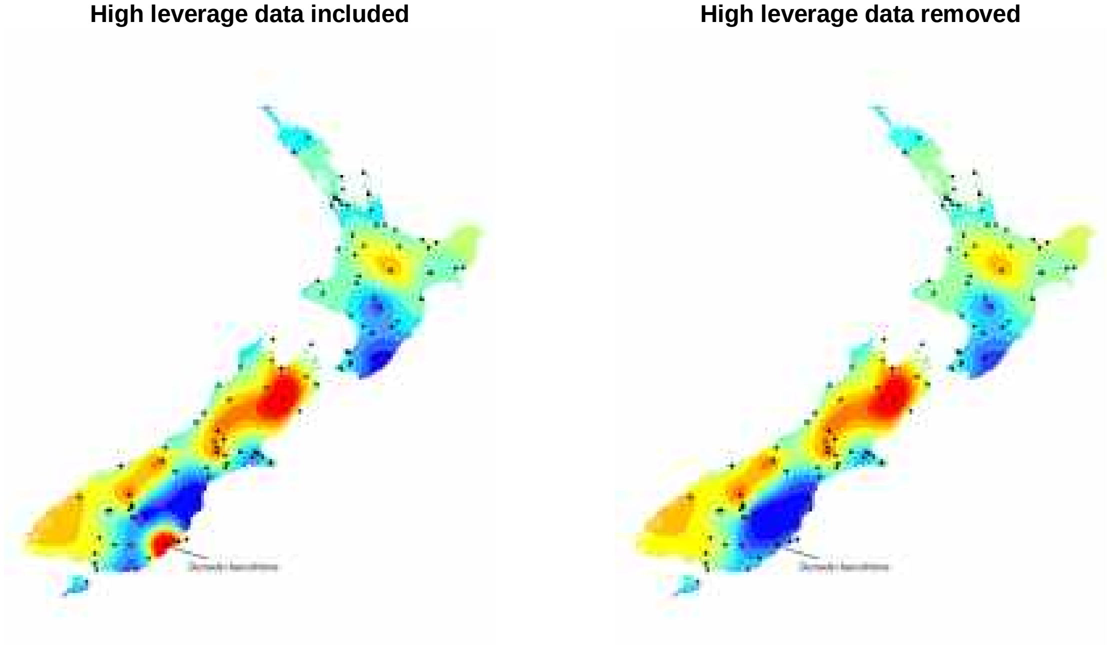

Figure 6. Effect of removing high leverage stations from the interpolation of mean annual frost frequency.

3. Results

3.1 National composite analysis

The national composite analysis (Figure 7) shows an overall decrease in frost probability for the period 1972-2008 (-0.003 probability/decade), with corresponding increases in frost temperature (+0.02°C/decade) and minimum temperature (+0.07°C/decade). This equates to an on average decline of around 1 frost day per decade. All the trends were significant at the 5 per cent confidence level. As illustrated by the cumulative distribution plot (CDF) in Figure 8 approximately 70 percent of stations had negative trends, ranging from -0.1 to -1.5 days per decade.

Annual **Growing season**

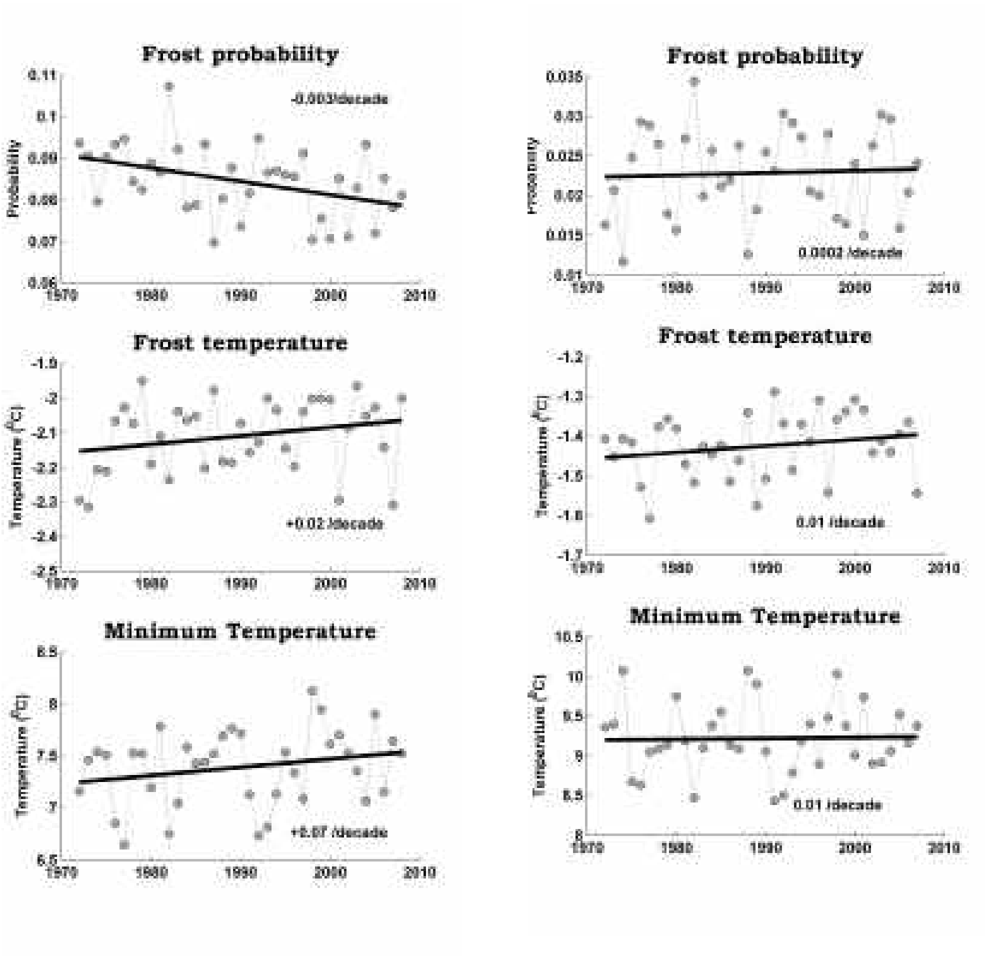

Figure 7. National composite annual and growing season frost probability, intensity and minimum temperature trends.

When examined for the growing season the trends are not as strong (Figure 7) nor were they statistically significant at the five or ten percent confidence levels. The sign of the frost probability trend also changes from a negative trend for the annual time period to a very weak positive trend (+0.0002 P/decade) for the growing seasonl time period (Figure 7, right hand side). This result is also evident in Figure 8, where the dominant signal in the national composite is a neutral trend, with between 50-60 percent of stations having no change in the number of frost days for 1972-2008.

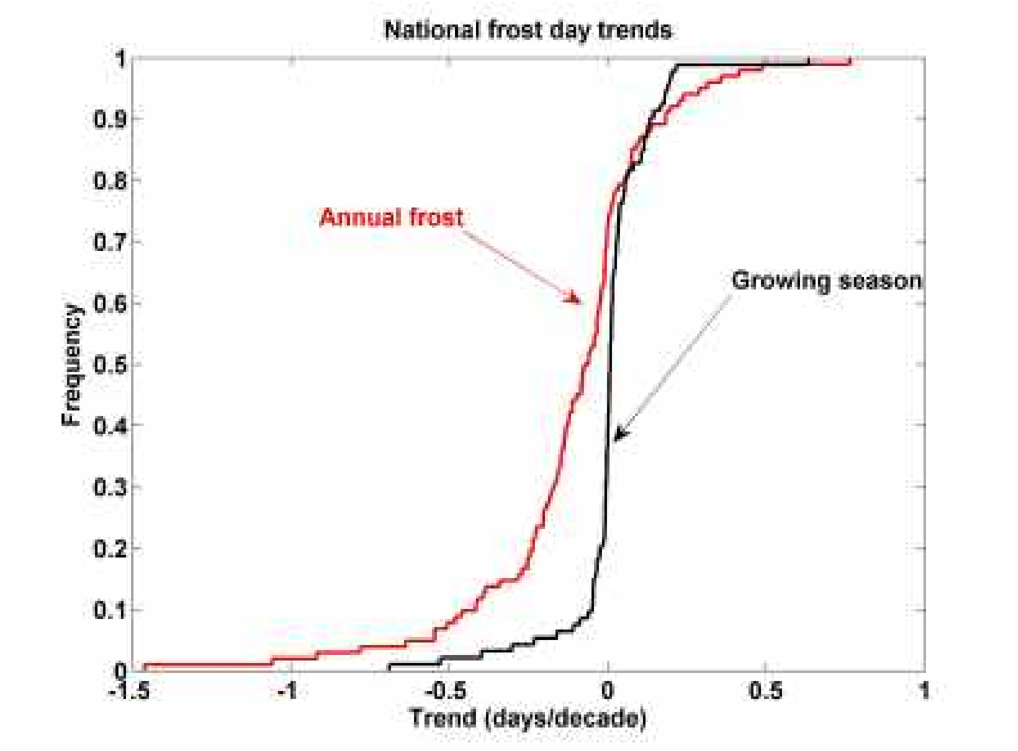

Figure 8. Empirical cumulative distribution functions showing the frequency of station level trends for the growing season (October-April) and annual time periods.

3.2 Regional composite analysis

The overall direction of trends found for the national composite analysis were also found for the regional analysis—frost risk was found to be decreasing in most regions and minimum temperature and frost intensity were found to be increasing for all regions for the annual time period. The exception to this result was for Meteorological Region E where a positive trend in frost risk was found. All the trends reported for the annual time period at the regional level were significant to at least the 10 percent confidence level (Table 5).

Table 5. Regional composite trends (unit/decade). Numbers in bracket are F test probabilities. * is significant where P>0.1 and ** is significant where P>0.05.

	Frost risk (P)	Frost temperature (°C)	Minimum temperature (°C)
Annual			
Region A	-0.0008 (3.0)*	0.12 (9.8) **	0.2 (12.1)**
Region B	-0.004 (8.3)**	0.009 (1.0)**	0.06 (1.0)*
Region C	-0.003 (4.7)**	0.04(6.2)**	0.08 (1.8)*
Region D	-0.0005 (2.2)*	0.06(12.1)**	0.04 (0.4)*
Region E	0.0004 (2.3)*	0.02(0.8)*	0.08 (1.7)*
Region F	-0.003 (5.2)**	0.05 (2.2)*	0.09(2.3)*
Region G	-0.011 (6.1)**	0.107(13.2)**	0.2 (12.0)**
Region H	-0.004 (3.6)*	0.1 (12.5)**	0.04 (0.6)*
Region I	-0.003 (3.1)**	0.01(2.1)	0.02 (0.2)
Growing season			
Region A	-0.00001(0.2)	0.07 (3.1)**	0.04 (1.7)*
Region B	-0.0004 (0.7)	0.04 (4.2)**	-0.03 (0.3)
Region C	-0.0001 (0.03)	0.07 (3.5)**	0.05 (3.2)**
Region D	0.0005 (0.9)	0.07 (1.3)**	-0.04(3.0)**
Region E	0.0005 (0.6)	0.05 (1.3)	-0.07(3.0)**
Region F	-0.0003 (0.1)	0.09 (4.1)**	-0.04(2.6)
Region G	-0.003 (12.4)	0.09 (4.3)**	0.03(1.3)
Region H	-0.002 (1.03)	0.15 (12.1)**	-0.01 (3.4)**
Region I	0.003 (2.1)	-0.3 (3.1)	-0.03 (2.1)

Like the national analysis the growing season time period did not have the same trend direction and strength as the annual time period. None of the frost probability trends were statistically significant for the seasonal analysis. However at this scale differences between regions do emerge (Table 5). Regions D, E and H exhibited a significant cooling trend in growing season minimum temperature of the order of -0.03 °C/decade, B and F had negative trends that were not significant, and A, C and G had a warming trend. Most of the regions had a significant positive growing season frost temperature trend (warming), with the exception of region I.

3.3 Frost seasonality

Trends in dates defining the opening and closing of the frost season (as well as season length) are in Table 6 for the regional scale of analysis. At this scale the reported metric is the 5^{th} percentile of opening frost date across the region and the closing date the 95^{th} percentile. For opening frost date both positive and negative trends were detected but these were not statistically significant at either the 5 or 10 percent confidence level , except for the positive trend in region A. All of the end of season (last) frost day trends were positive (i.e. the last day was becoming later), with significant trends found in regions C, D, E and I. Both positive and negative trends were found for the season length, with the positive trends in regions D, E and I being significant.

Table 6. Trends in frost start date, end date and season length for New Zealand Meteorological regions. Start date is the 5^{th} percentile of observations and end date the 95^{th} percentile. Numbers in brackets are F test probabilities. * is significant where P>0.1 and ** is significant where P>0.05.

Region	Mean (date)	Trend (days/decade)
Start of frost season		
A	10 June	6.5 (9.7)**
B	20 May	2.1 (1.7)
C	16 May	1.1 (0.5)
D	21 May	0.4 (0.06)
E	2 May	-1.0 (0.3)
F	9 May	0.7 (0.1)
G	27 April	-1.1 (0.5)
H	30 April	1.2 (0.5)
I	1 May	-1.5 (1.3)
End of frost season		
A	14 August	2.6 (0.67)
B	13 September	0.2 (0.01)
C	10 September	5.4 (5.5)**
D	17 September	6.0 (5.8)**
E	2 October	3.9 (2.2)*
F	24 September	2.2 (1.0)
G	1 October	0.5 (0.07)
H	11 October	0.7 (0.1)
I	23 September	4.0 (6.5)**
Length of frost season		
A	65	-3.8 (1.2)
B	116	-2.3 (0.5)
C	118	4.2 (2.4)
D	119	5.6 (3.5)**
E	152	4.9 (2.1)*
F	138	1.5 (0.3)
G	157	0.5 (0.03)
H	163	-0.5 (0.05)
I	145	5.6 (7.5)**

3.4 Threshold sensitivities

To provide more information about the influence of the temperature threshold on the results sensitivity analyses were undertaken at the national level. Figure 9 show responses of the national average frost frequency, temperature and frost season length trends to changes in the threshold between -2 and + 4 °C. The results show that trends in frost frequency were not sensitive to the critical temperature used. As the critical temperature selected becomes warmer the magnitude of the trend increases. A similar result was also found for frost temperature, although there is a lot more irregularity in the sensitivity tests, for example the large spike at -1.7 °C. For frost season length changing the threshold results in a directional change in the national trend—it remains neutral to positive (increasing seasonal length) up to a threshold around 0°C and becomes negative (decreasing seasonal length) above this level. This result, and also the irregularities in both frost temperature and frost season length are indicative of the process control on these metrics—synoptic patterns have a greater influence on these metrics when compared to frost frequency.

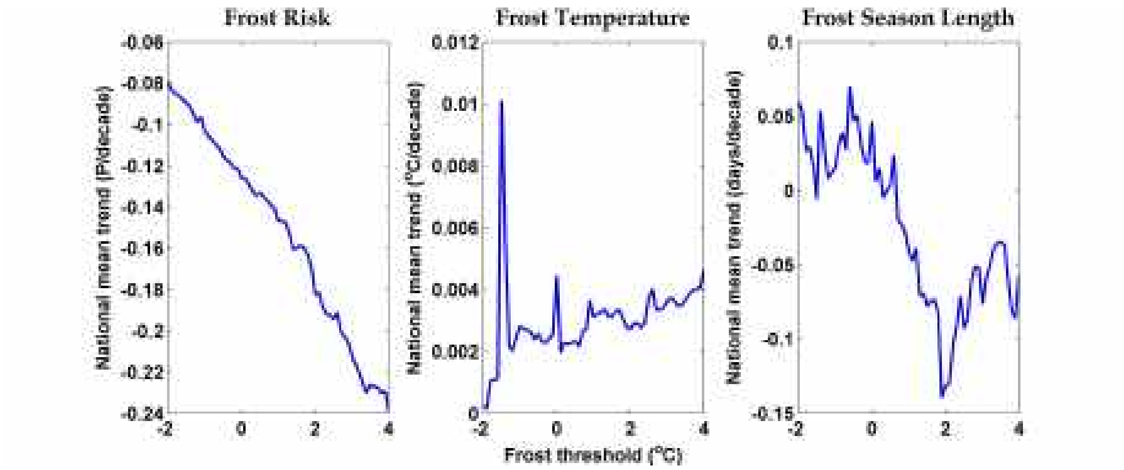

Figure 9. Sensitivity tests of the national mean trend to changes in the frost threshold.

3.5 Earth temperature

The earth temperature results are summarised for the regional level in Table 7. Similar to the frost risk analysis, earth temperature trends exhibited region-to-region variability in terms of their direction and strength. Significant positive (warming) trends were detected for the annual period in regions A, B, and F. Positive trends were also found for regions G and H but these were not significant at the 10 or 5 per cent confidence level. Negative (cooling) trends were detected in regions C and I, with the F-test not significant. For the growing season analysis a weak negative (cooling) trend was detected that were not statistically significant.

Table 7. Trends (units/decade) in annual and seasonal earth temperature. ( ) are F test probabilities. * is significant where P>0.1. ** is significant where P>0.05.

Annual	
Region A	0.01 (2.5)**
Region B	0.002 (10.5)**
Region C	-0.0001(5.1)
Region D	-0.001(5.3)
Region F	0.02(4.1)**
Region G	0.0081(1.2)
Region H	0.004 (0.3)
Region I	-0.0008 (1.7)
Region J	0.02(4.9)**
Seasonal	
Region A	-0.003 (0.1)
Region B	-0.005(1.6)
Region C	-0.001(5.8)
Region D	-0.008(4.4)
Region F	-0.006(2.6)
Region G	-0.006(2.9)
Region H	-0.006(3.1)
Region I	-0.007(3.7)
Region J	-0.0004(4.2)

3.6 Spatial analysis

The spatial interpolation of station level results are provided as a series of national maps in Appendix 2. The map of frost climatology (Appendix 2, Maps1-10) highlights that the station data set used in this research was able to be used to build interpolated surfaces broadly representing frost risk across the country. They reflect the very broad landscape and coastal processes that control frost climatology. The spatial distribution of frost risk produced in these maps is in broad agreement with the frost climatology produced by Goulter (1981). However the data are not densely sampled and interpolation methods not sensitive enough to map the finer landscape modification of frost which were detected in the Goulter study.

The key results for this work are the annual and seasonal frost risk analyses (Maps 11-12, Appendix 2), also shown as Figure 10. This highlights a strong spatial signal in direction of trends in frost risk across New Zealand found in this study. That is both the negative and positive trends detected in the national composite analysis (section 3.1) are concentrated in regions. That is there appear to be more frosts in a few regions than rather than a random distribution over the country. The spatial analysis also re-enforce the results obtained in the composite analyses, that a clearer signal is evident in the annual analysis compared with the seasonal analysis. The results also provide a better examination of the spatial distribution of trends within New Zealand than the regional composites which were structured according to pre defined zones.

The spatial analysis suggests that the increase in frost frequency (cooling) is concentrated in two areas both on the eastern sea board of New Zealand. The first is the south east of the North Island encompassing the agricultural zone in the Wairarapa. The second is a larger zone on the south east of the South Island, from Ashburton to Dunedin. Interpolated trends in these zones are strong (+0.2 to +0.3 °C/year). Strong negative trends in annual frost frequency (warming) are located in the alpine regions of both islands.

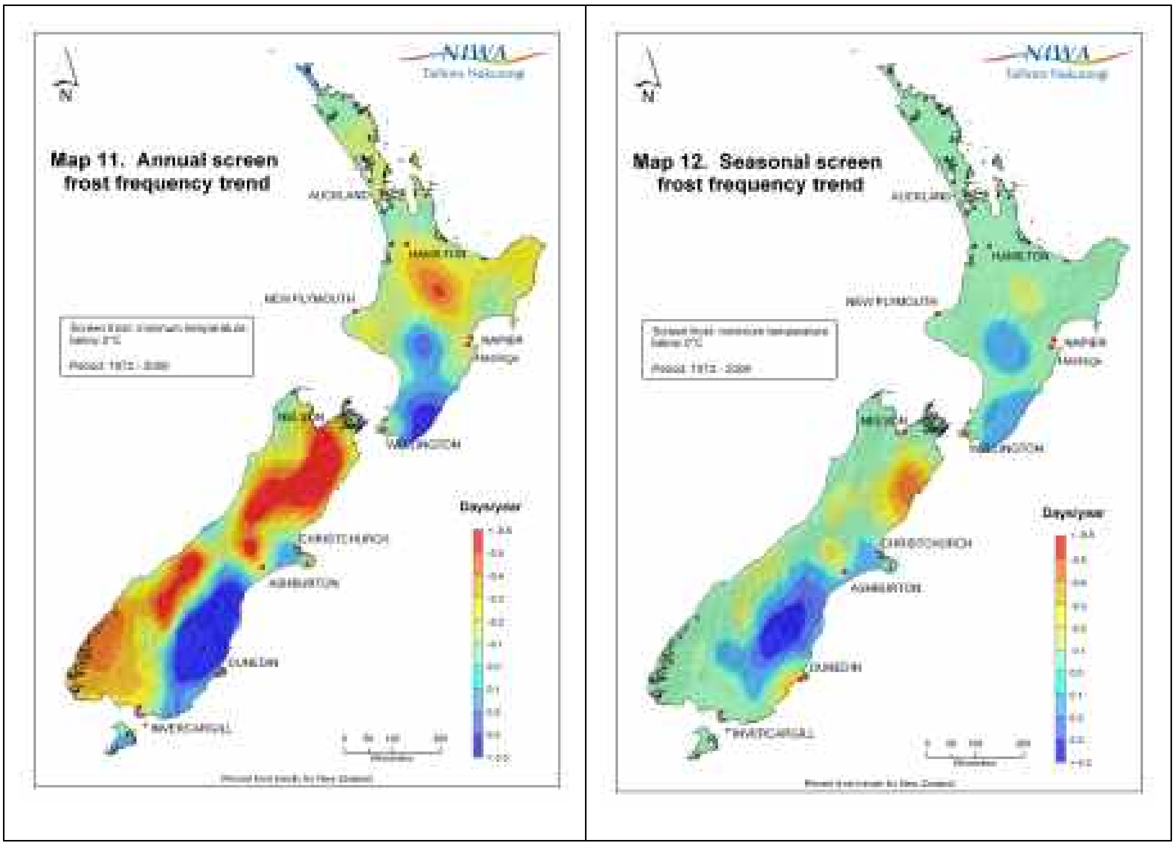

Figure 10. Interpolation of station level trends for seasonal (growing season) and annual frost frequency.

There was little spatial structure when frost frequency trends were interpolated at the monthly level and the signal to noise set at half the number of data points (Maps 13-20). This is evidence that the trend signal was relatively weak when examined at the monthly time period, particularly for the late and early season months of April (Map 13) and November (Map 14). Similarly little coherent spatial structure was evident in the interpolation of trends for the frost seasonality indices (maps not provided).

When the interpolate then calculate approach was used the same broad spatial structure in frost trends was found (Figure 11, Map 31). The most pronounced positive trends in frost frequency remain the region of the Wairarapa, and the area below Ashburton on the South Island. Additional areas of moderate increases in frost frequency were also detected using this approach, including a part of the Canturbury plain, Nelson hinterland and western Southland on the South Island, and the Ruaukumara Range on the North Island. The area of large positive decrease in frost frequency centred on the Southern Alps and Tongariro—evident as a smooth region in Figure 10—appears to be topographically controlled when this approach to spatial analysis is used. The strength of the trend in the higher altitude zone should be questioned because of known data availability limitations in these zones. Notably, most of the remaining major agricultural regions exhibit a neutral to slightly negative trend in frost frequency.

Importantly, an increase in frost frequency was detected in the Tasman and Nelson hinterland districts using interpolate then calculate (Figure 11, Map 31), whereas when trends were interpolated from individual stations this feature was smoothed and a decreasing trend was found (Figure 10, Map 11). Closer inspection of the spatial distribution of the station data used to produce Map 11 (Figure 6) highlights that in the Nelson region the stations were located on the coast, and there is a poor sample in the Tasman. It is likely that these sampling features have biased the fitted surface in these regions for the calculate then interpolate approach. Hence, it is advised to give more weight to the increasing frost frequency trend found by the interpolate than calculate approach (Figure 11, Map 31) for the Tasman and Nelson districts. Further ratification of these trends may be warranted by analysis of individual station series in these districts.

It was also possible to examine if any spatial patterns were evident in the significance tests of trends using the interpolate then calculate approach (Figure 12). Generally areas that have been identified as being either strongly positive or negative in terms of frost frequency trend were significant at either the 5 or 10 percent level, and there is a degree of spatial coherence in these results.

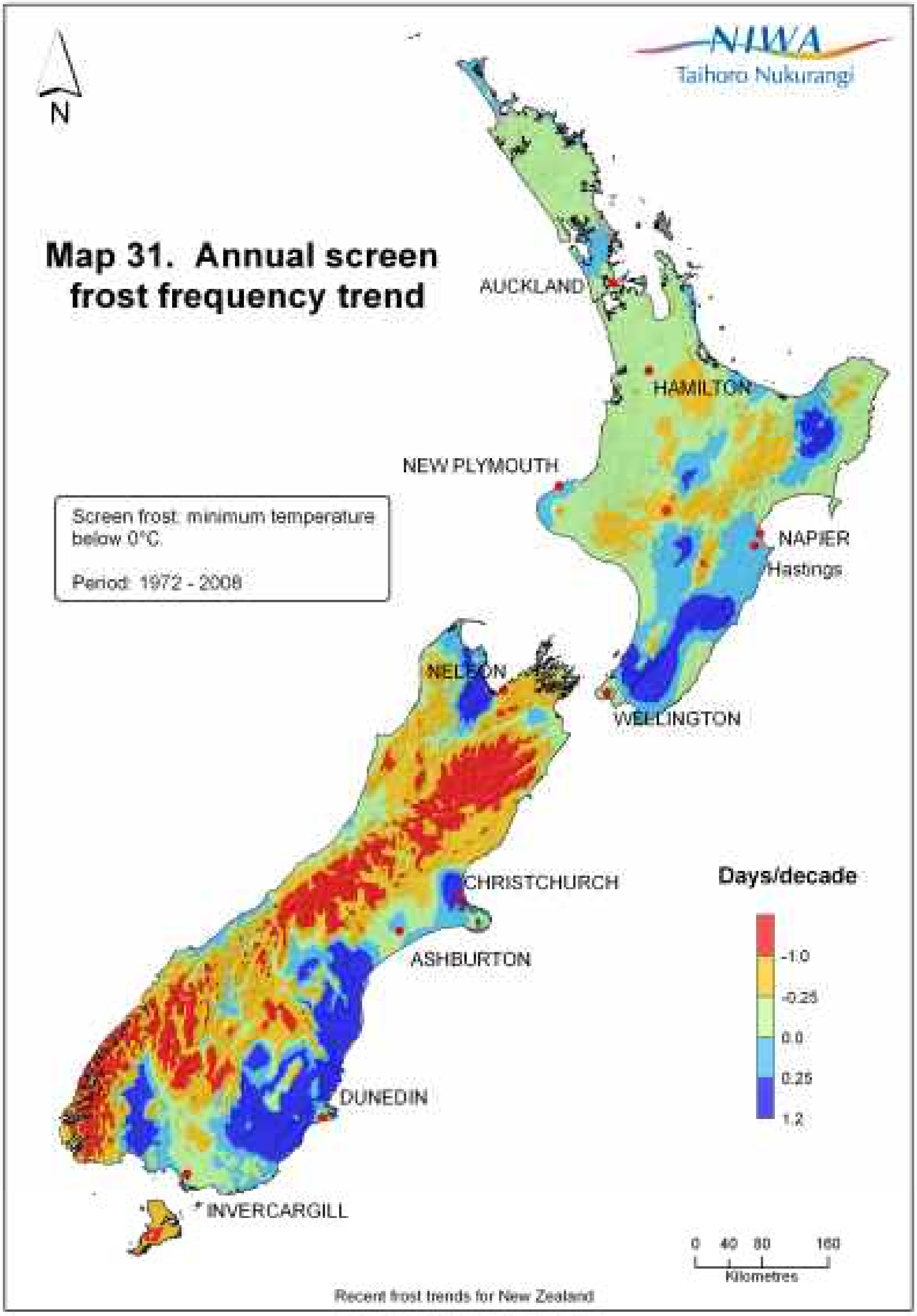

Figure 11. Frost trends detected when using the interpolate then calculate approach.

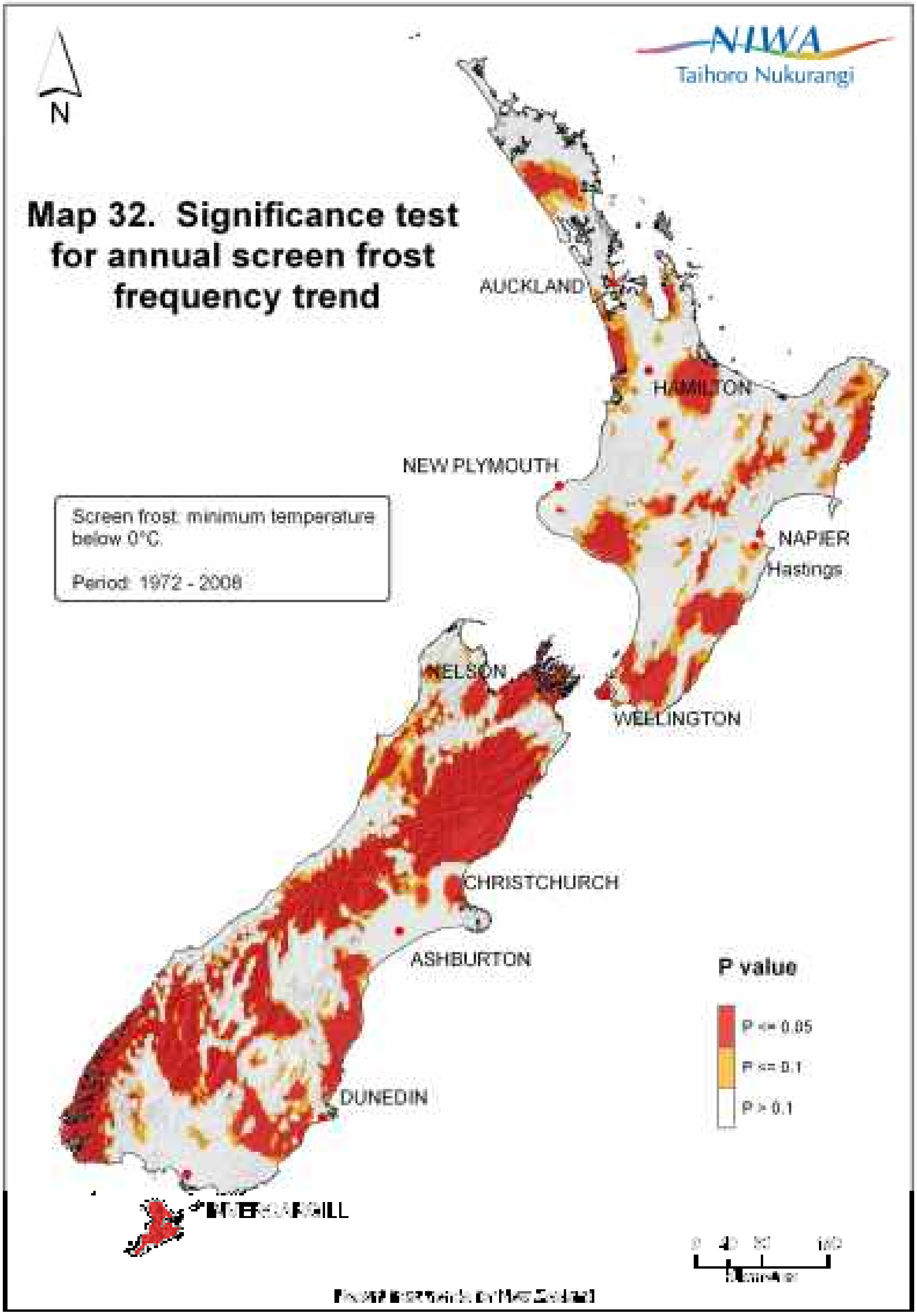

Figure 12. **Significance test for frost frequency trends using the interpolate then calculate approach.**

4. Discussion

4.1 Interpretation

Interpretation of the results obtained in this study relies on understanding the different scale of process that control frost in New Zealand. Detection of reduced frost frequency at the national composite level and for the annual time period is consistent with a decadal scale warming of the global atmosphere. The methodology underlying the national composite analysis is well suited to detecting trends at these broad scales, but not as sensitive to local scale variability. This is consistent with the results obtained by Zheng et al (1997) and Salinger and Griffiths (2001), and also the global level climate change reported by the IPCC (IPCC 2007).

As the time and spatial scales of the frost trend analyses became finer, the greater the influence of inter annual, seasonal and weather processes. New Zealand's maritime climate has potential to modify the overall global signal, and as found in this study, it is plausible that regional and sub regional trends can run counter to the direction of those detected at the national and global scale. Regional variability of this type is also evident when global climate change projections are downscaled for New Zealand (Mullan et al. 2007). Frost occurrence at the regional and growing seasonl level is largely controlled by the stability of weather systems, and trends driven by the persistence of certain weather types. It is possible to form a starting hypothesis about the process controls on the results, as the spatial distribution of annual and growing seasonstation trends is consistent with a more persistent southerly flow and north westerly winter flow influencing New Zealand (pers comm. Mullan 2009).

It is also important to recognise the potential drivers of frost influencing the results found at the finer monthly time scale and for the frost season indices. At this level the occurrence of frost is more strongly influenced by the nature of individual weather events, rather than broader signals from atmospheric warming and circulation (weather type persistence). This is particularly the case for the occurrence of out of season frosts (April and November analyses)—the empirical results in this study showed that no linear trend could be detected at the monthly level and that the thirty year time series have an almost random like nature. At the empirical level, the frost indices at these finer time scales and outside of the higher elevation zones can be considered as being more responsive to the noise driven by weather rather than the signal driven by a shift in large scale climate forcing.

As described in the introductory sections, the study has been confined to one climate period 1972-2008, where there is sufficient data to examine the regional variation in frost occurrence across New Zealand. Most of this time slice was in one positive phase of the Interdecadal Pacific Oscillation, which has been observed in long run series and identified as a significant source of climate variation at decadal time scales throughout the South West Pacific (Salinger et al. 2001, Folland et al 2002). It was not possible with the 1972-2008 time series and methods used here to estimate the relative contribution of the decadal and longer term global signals to the trends reported, particularly if the spatial distribution found is part of decadal or longer term variability. Hence, it is plausible, given a decadal scale oscillation in the Pacific's climate, that the magnitude and or spatial pattern in the direction of the trends detected in this study could change in the future despite the expected continuation and strengthening of global scale warming.

For primary production, frost is both a climatic feature and weather event that can be managed to some extent, depending upon the viability of mitigation options. This study detected a trend that is consistent with global warming, so it might be tempting to conclude that it is possible to lower frost mitigation standards and reduce costs in the coming years. However, extension of the national trend found in this study to form such a conclusion is invalid. The regional variability created by New Zealand's maritime climate, means that in some regions frost trends may be increasing rather than decreasing on decadal time scales in a background of global warming. On the shoulders of the growing season, where a frost event has potentially severe impacts because of increased exposure, frosts are strongly controlled by the weather and these show little persistent signal through time. For management of production systems in the next decade, damaging frost should continue to be considered a natural hazard, where diligent monitoring of day to day weather information and matching actions to long term climatic frequency analysis is the best pragmatic approach.

4.2 Limitations

The analyses undertaken in this study were limited by the amount of data available, both across New Zealand and through time. Additional series through time would allow a more thorough examination of decadal scale influences such as the Interdecadal Pacific Oscillation or changes in the persistence of Kidson weather regimes on trends and support alternative analytical methods (see below). This has already been completed to some at the empirical level in the studies of Zheng et al (1999), Salinger and Griffith (2001) and Withers et al (2007), but more work is warranted in terms of attribution of trends. While some interpretation about the consistency of the detected trends with climate processes has been made, there was insufficient observation series to complete a formal attribution study.

Similarly, increasing the number of sites across New Zealand would build more confidence in the spatial modelling of trends. It is important not to over interpret fine level geographic detail from the maps produced in the appendices and in Figure 10 and Figure 11—that is, it is not possible to identify trends at specific locations from these maps. Given the data and methods used, the maps convey the broad regional structure of frost occurrence and trends, but there is insufficient network to support detailed landscape scale spatial modelling of frosts. Hence, localised variability that producers are fully aware of, such as the gradient in frost frequency experienced across a valley, or from one paddock to the next, are not evident in the analysis.

Given the length of the series available and scope of the study, a choice was made to use linear least squares regression techniques to detect trends. Other non-linear methods may have provided different insights, particularly when examining longer run series and studying the contribution of decadal processes. There is also scientific debate surrounding the usefulness of significance testing in analysing climate trends. For example Nicholls et al. (2000) advises that a trend should not be dismissed out of hand if it does not pass a significance test, particularly if there is strong confirmatory evidence from other data and a process explanation. Similarly it is wise to question a trend even if it is statistically significant and there are no reasonable process explanations or confirmatory analyses.

The analyses pursued here use a meteorological definition of frost, simplifying its occurrence definition so that its implied risk may be assessed with standard Stevenson screen observations. As discussed in the introductory sections, the meteorological definition of a frost does not always correlate directly with an event that causes damage to crops and trees having a production impact, and is therefore only a partial measure of frost risk for the primary industries. Full frost risk analysis is usually only possible at a very localised scale, with more refined data and information about the sensitivity of a given crop and variety to freezing. It was not possible to pursue this level of detail and provide a national coverage for this study.

4.3 Further work

This initial study of recent frost trends highlights a number of areas that may be addressed by further research. Of particular importance is understanding the regional direction of trends in frost risk under a changing climate through formal attribution studies of both the global climate change signal and its modification by synoptic processes. Further ratification of the trends detected in this study is required using improved data sets, supplemented with output from climate models and remote sensing. We advise that this is necessary step, along with formal attribution, before any decisions are taken to change frost risk management, or focussing changes reducing mitigation standards at certain regions. It is also now possible to project frost risk into the future using global climate change scenarios and analyse its regional variability using output from NIWA's Regional Climate Modelling Programme in combination with targeted empmpirical-statistical downscaling. The study also highlights the value in at least maintaining current levels of environmental monitoring over the current decades, so that detailed regional risk analysis may be pursued under a changing climate.

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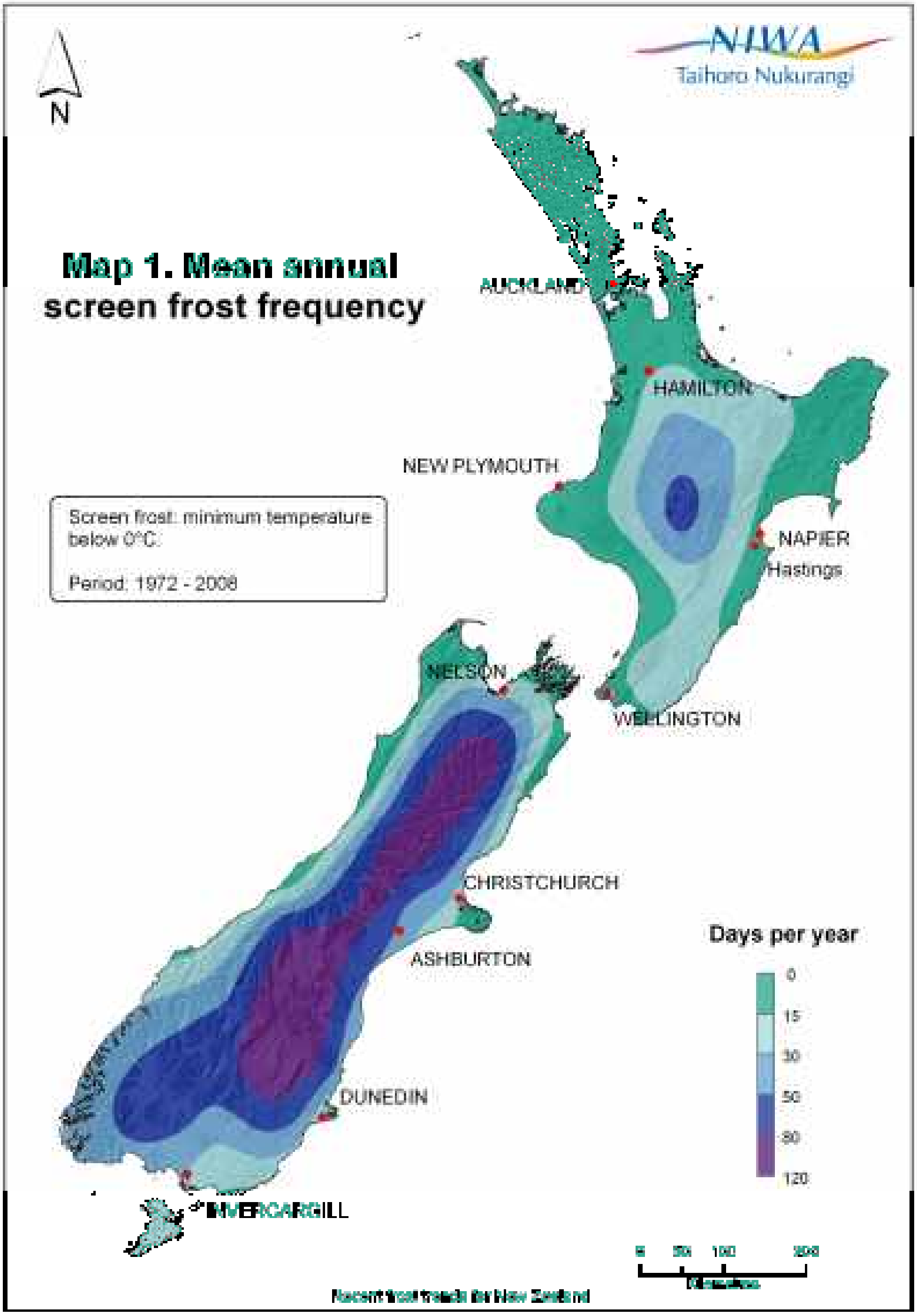
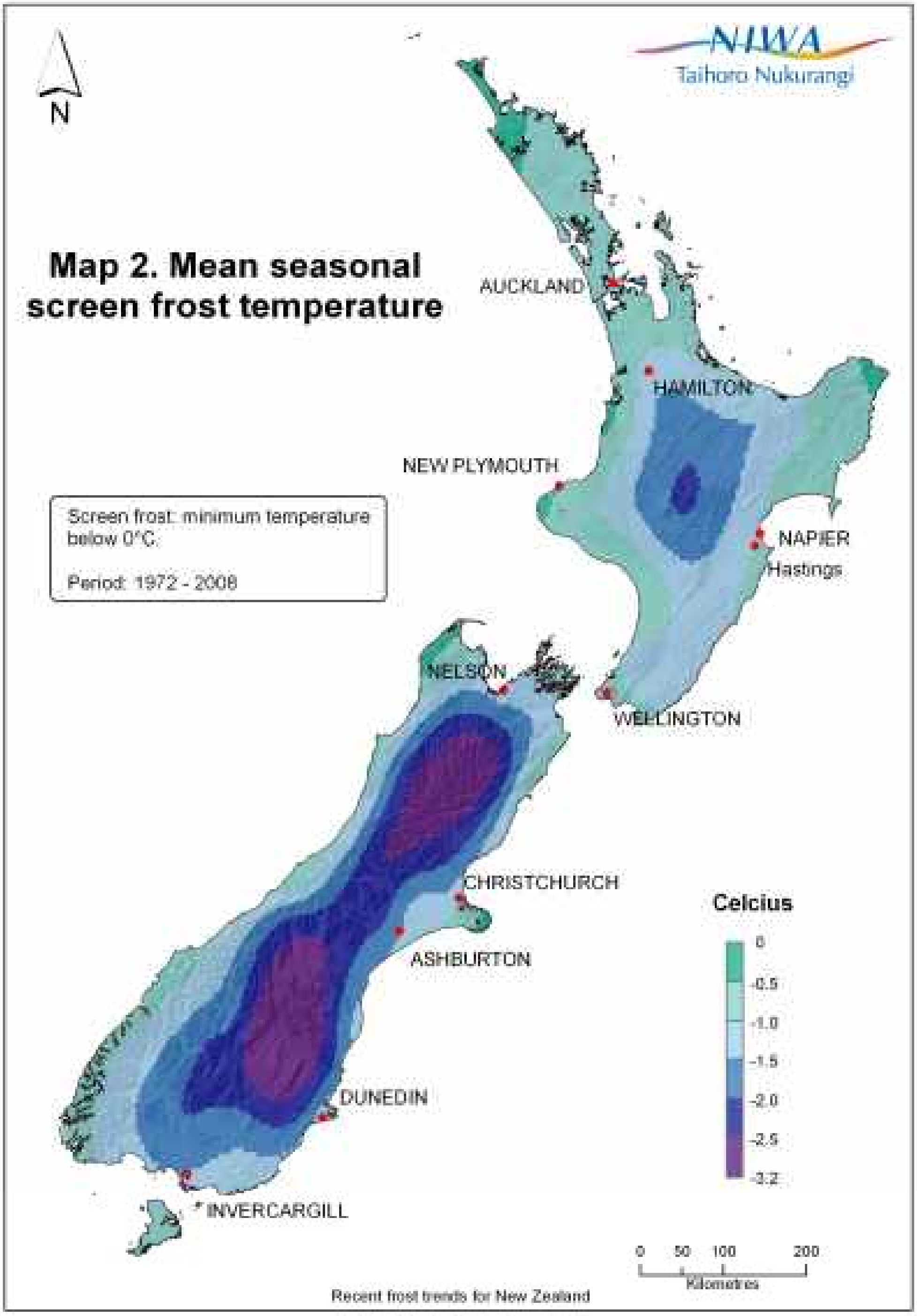
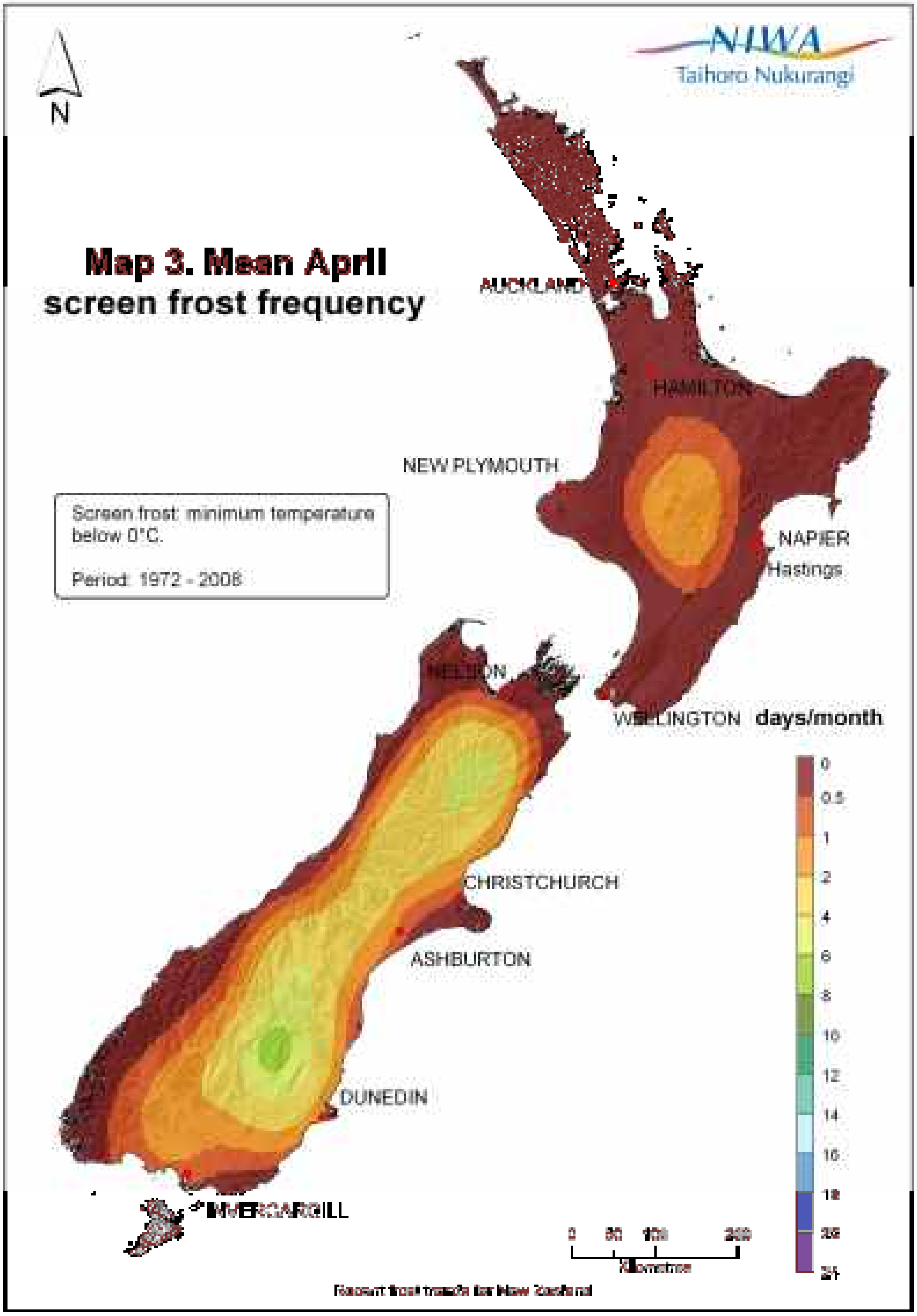
Appendix

The appendix contains maps describing frost climatology for 1972-2008 and linear trends detected in key periods. Maps 1-30 are based on the calculate then interpolate approach, and maps 31-32 are based on the interpolate then calculate approach.

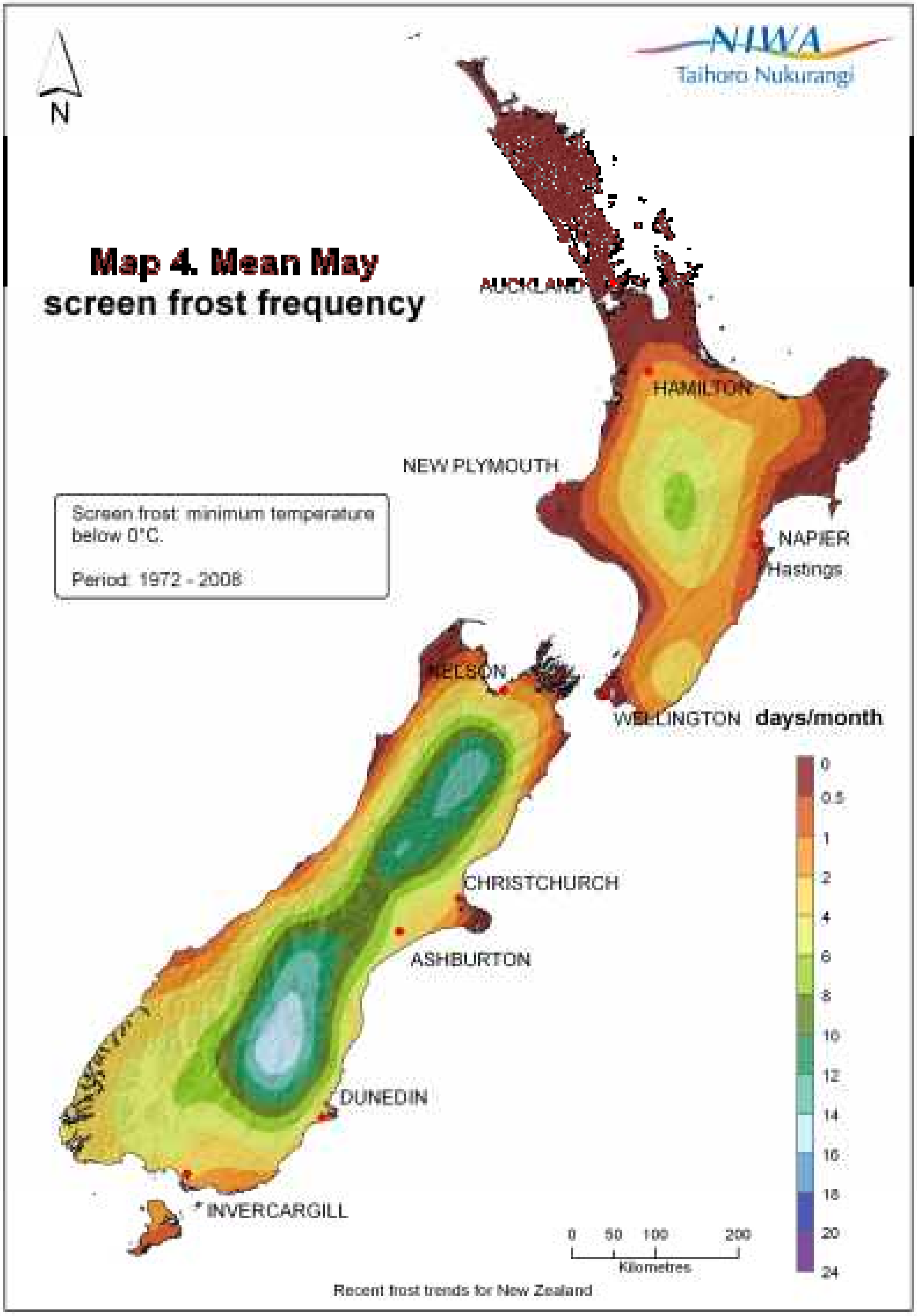


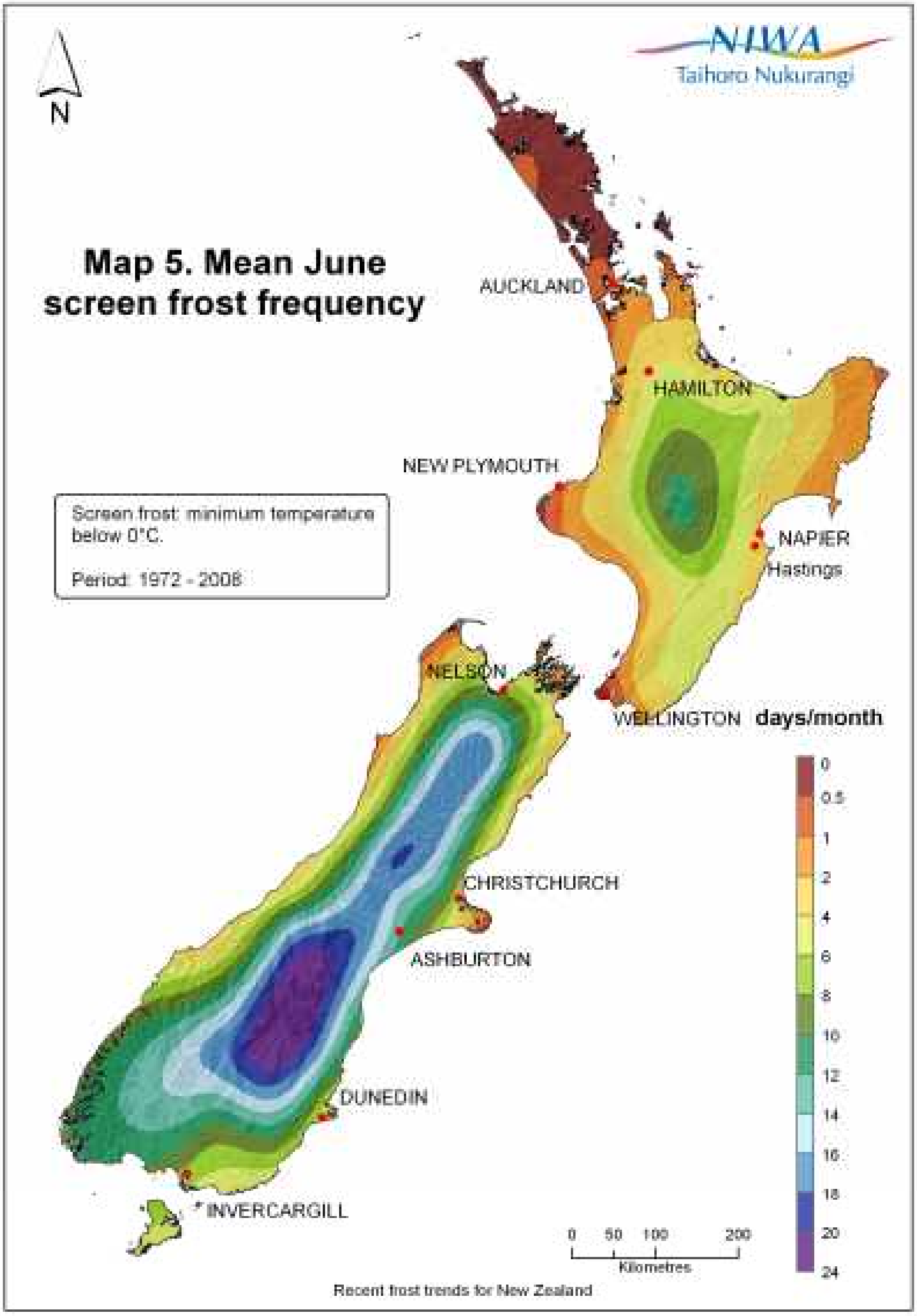


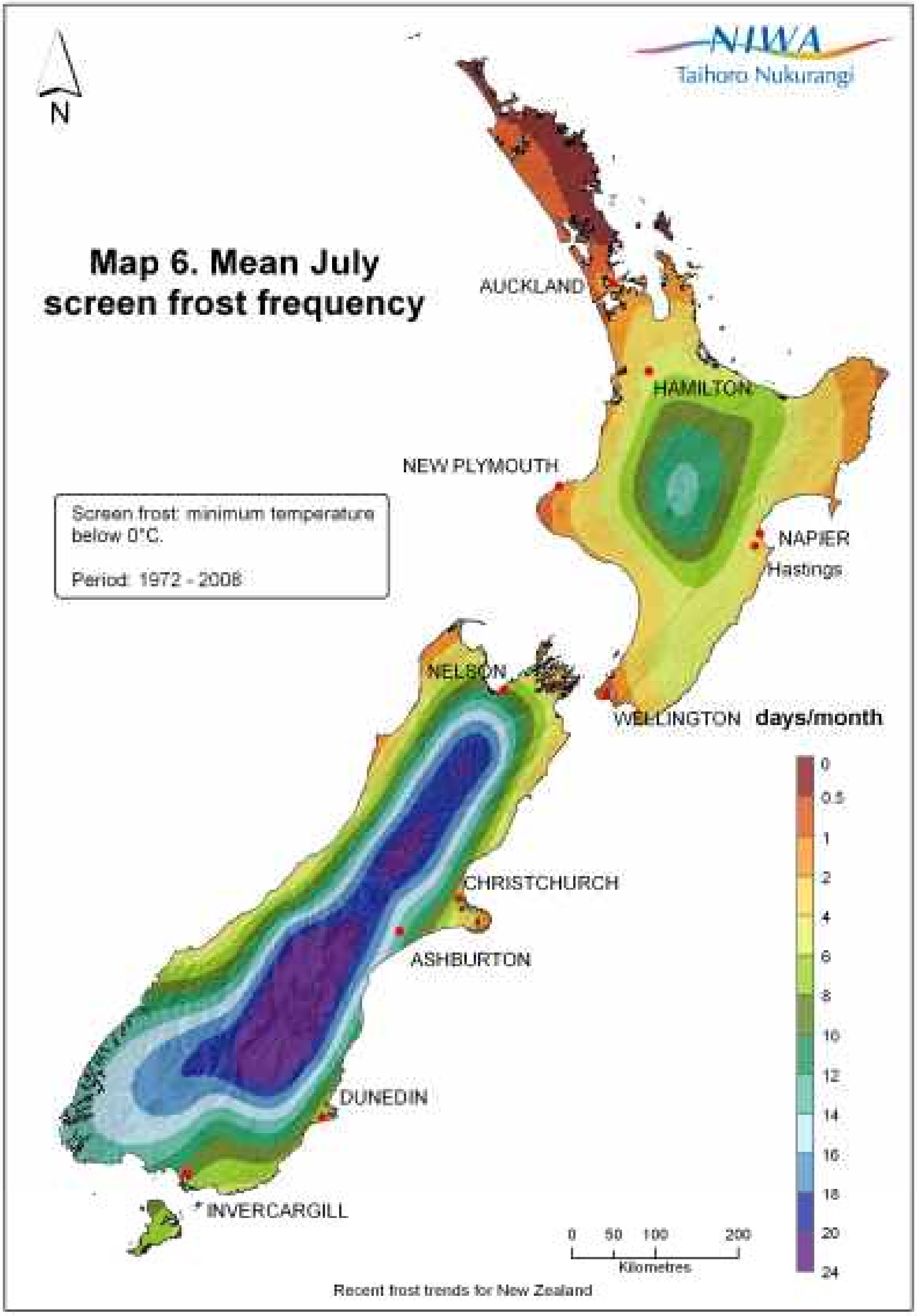
* Growing season, September-April.

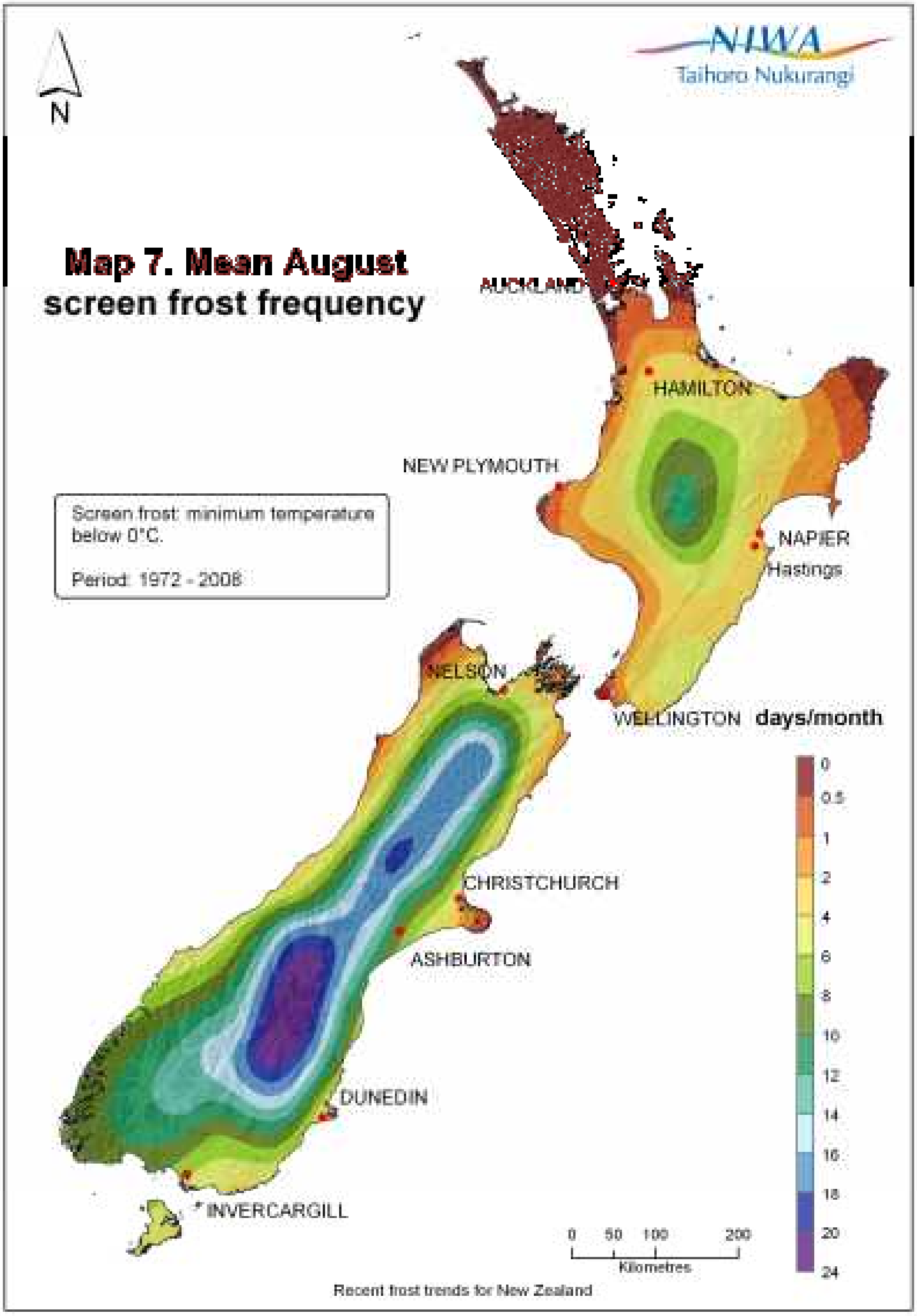


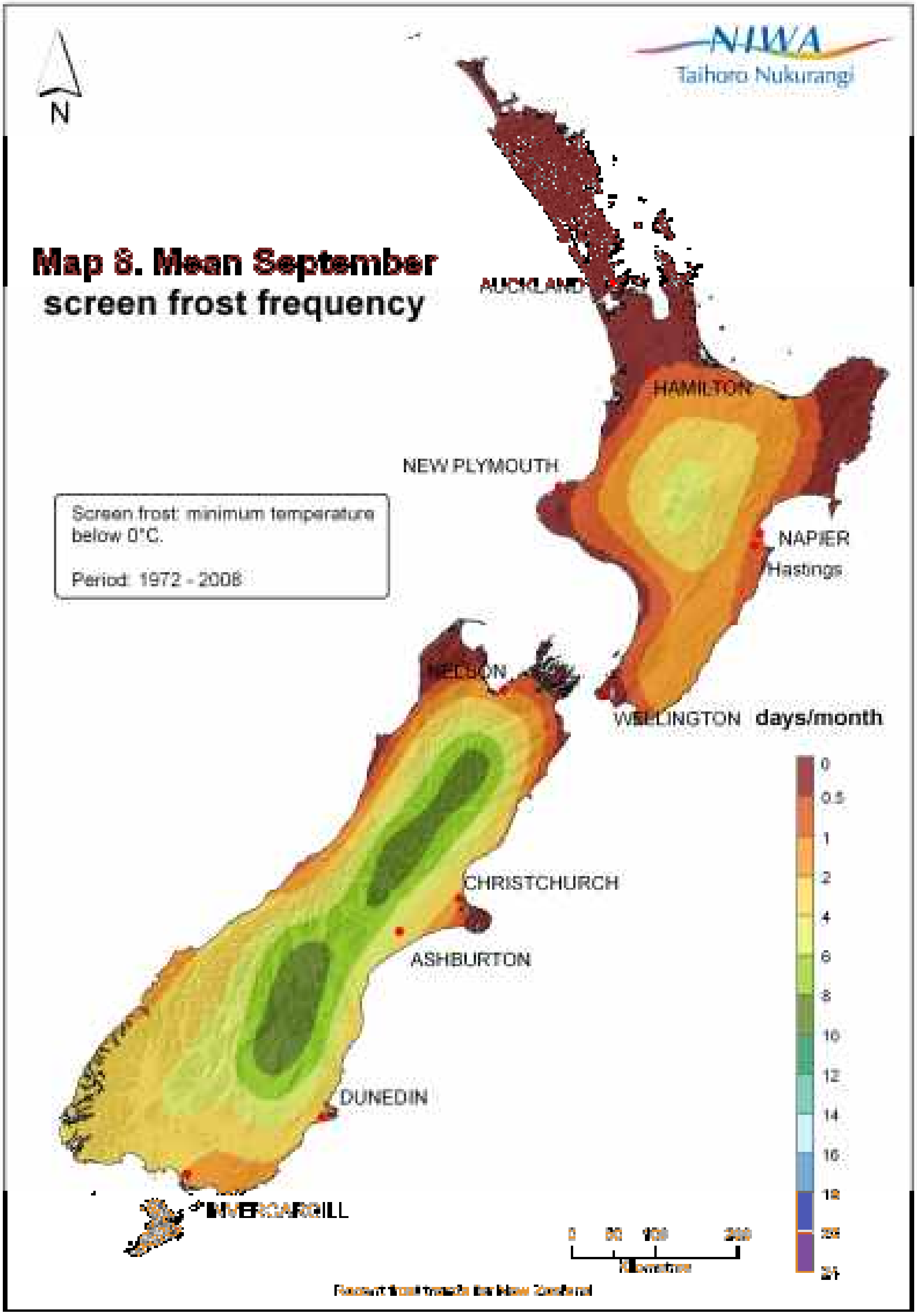
N
NIWA
Taihoro Nukurangi
Map 3. Mean April
screen frost frequency
AUCKLAND
HAMILTON
NEW PLYMOUTH
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NAPIER
Hastings
WELLINGTON
days/month
0
0.5
1
2
4
6
8
10
12
14
16
CHRISTCHURCH
ASHBURTON
DUNEDIN
Kilometres

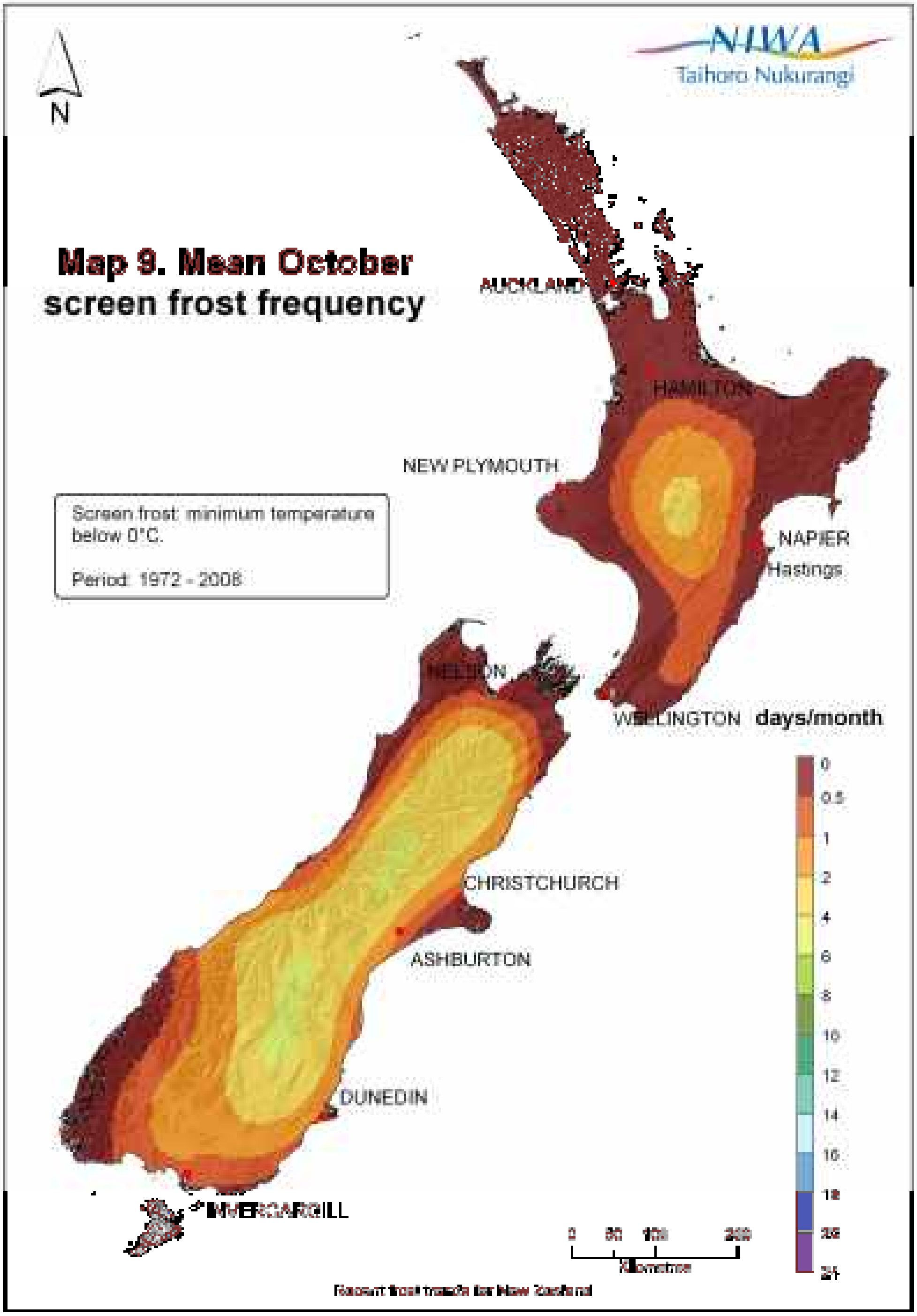

N
NIWA
Taihoro Nukurangi
Map 4. Mean May
screen frost frequency
AUCKLAND
HAMILTON
NEW PLYMOUTH
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NAPIER
Hastings
NELSON
WELLINGTON
days/month
0
0.5
1
2
4
6
8
10
12
14
16
18
20
24
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
0 50 100 200
Kilometres
Recent frost trends for New Zealand

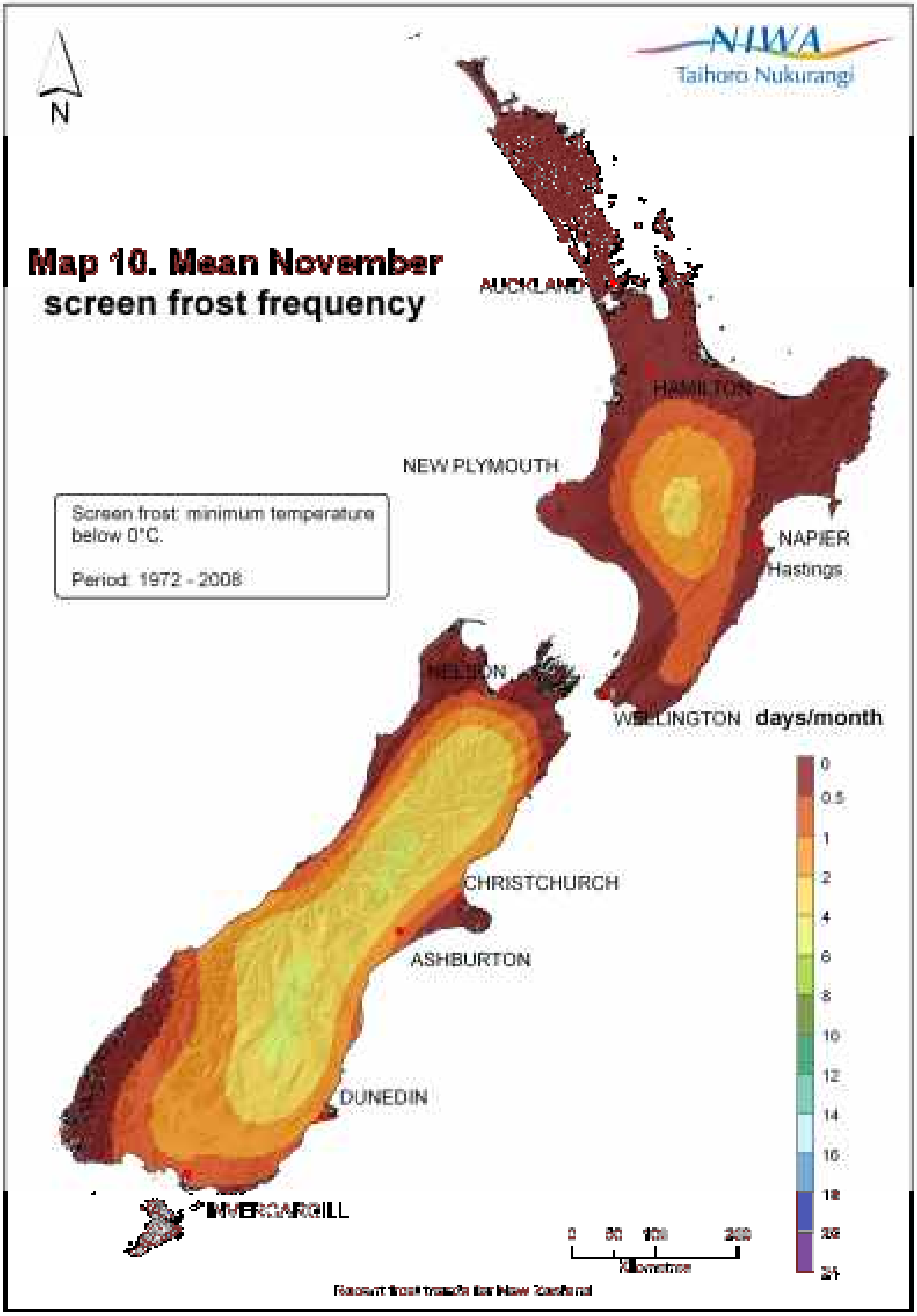

NIWA
Taihoro Nukurangi
N
Map 5. Mean June screen frost frequency
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
days/month
0
0.5
1
2
4
6
8
10
12
14
16
18
20
24
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
0 50 100 200
Kilometres
Recent frost trends for New Zealand

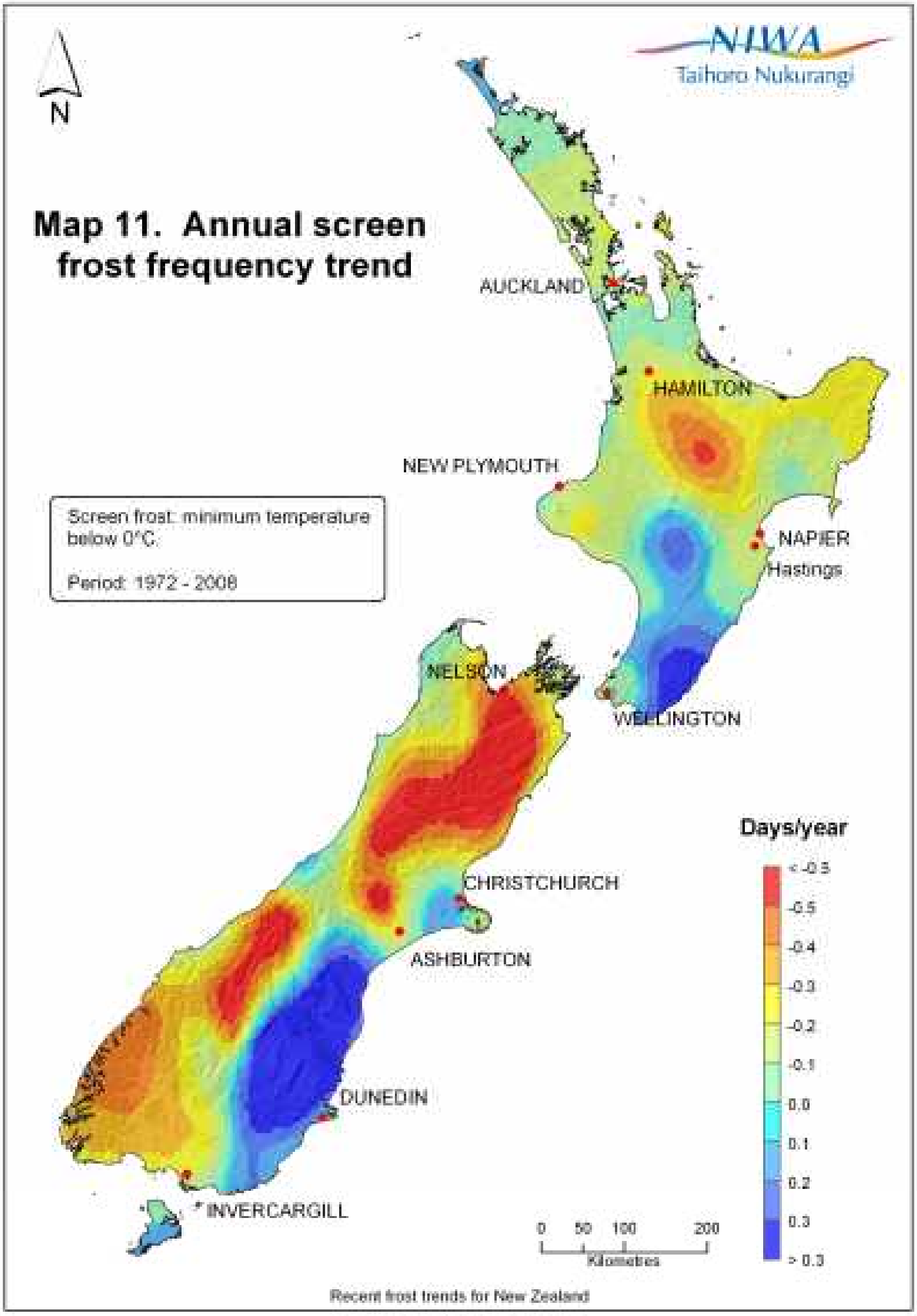

Map 6. Mean July screen frost frequency
NIWA
Taihoro Nukurangi
N
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NELSON
WELLINGTON
days/month
0
0.5
1
2
4
6
8
10
12
14
16
18
20
24
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
0 50 100 200
Kilometres
Recent frost trends for New Zealand

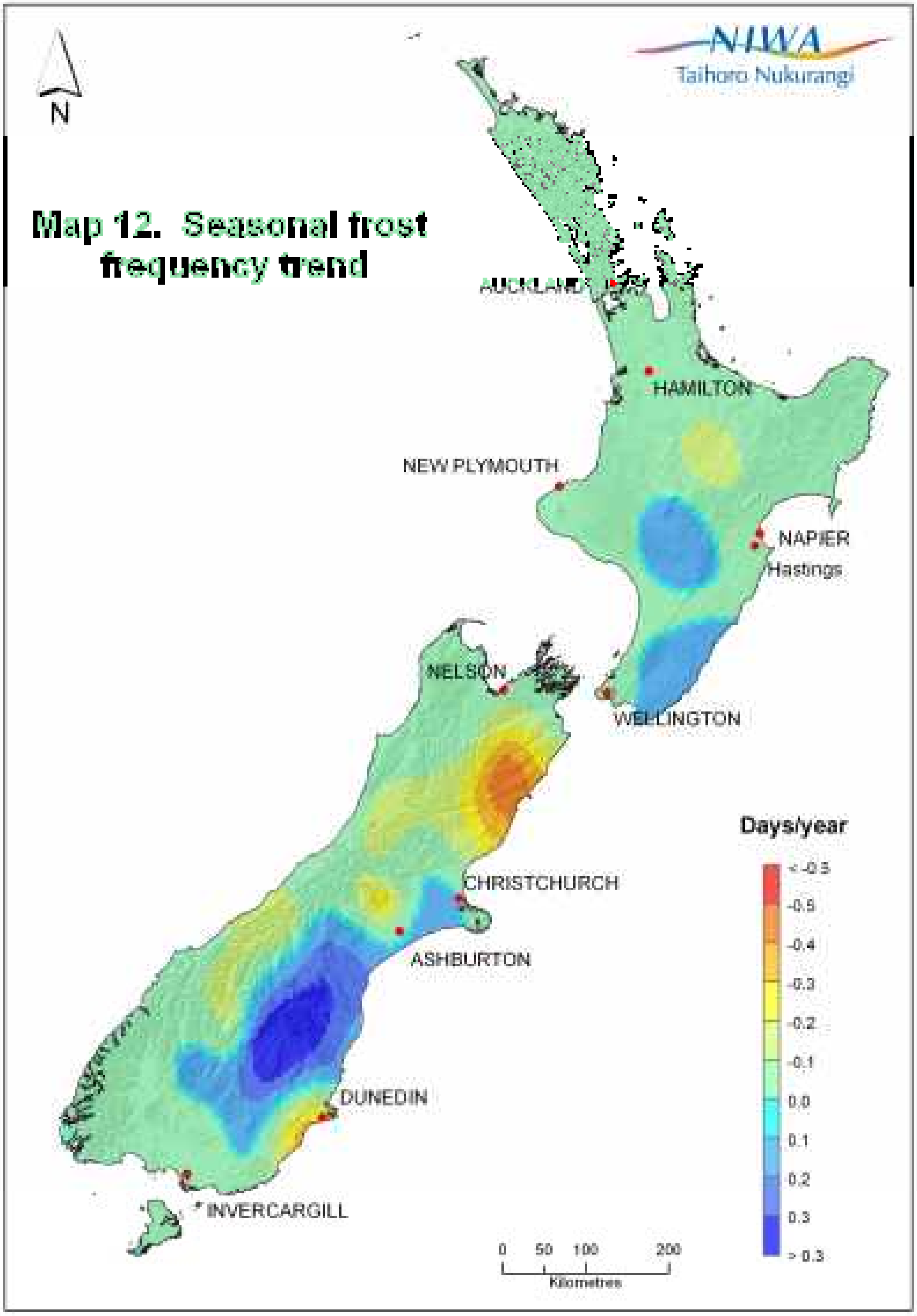

N
NIWA
Taihoro Nukurangi
Map 7. Mean August
screen frost frequency
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
days/month
0
0.5
1
2
4
6
8
10
12
14
16
18
20
24
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
0 50 100 200
Kilometres
Recent frost trends for New Zealand


NIWA
Taihoro Nukurangi
N
Map 8. Mean September
screen frost frequency
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
days/month
0
0.5
1
2
4
6
8
10
12
14
16
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL

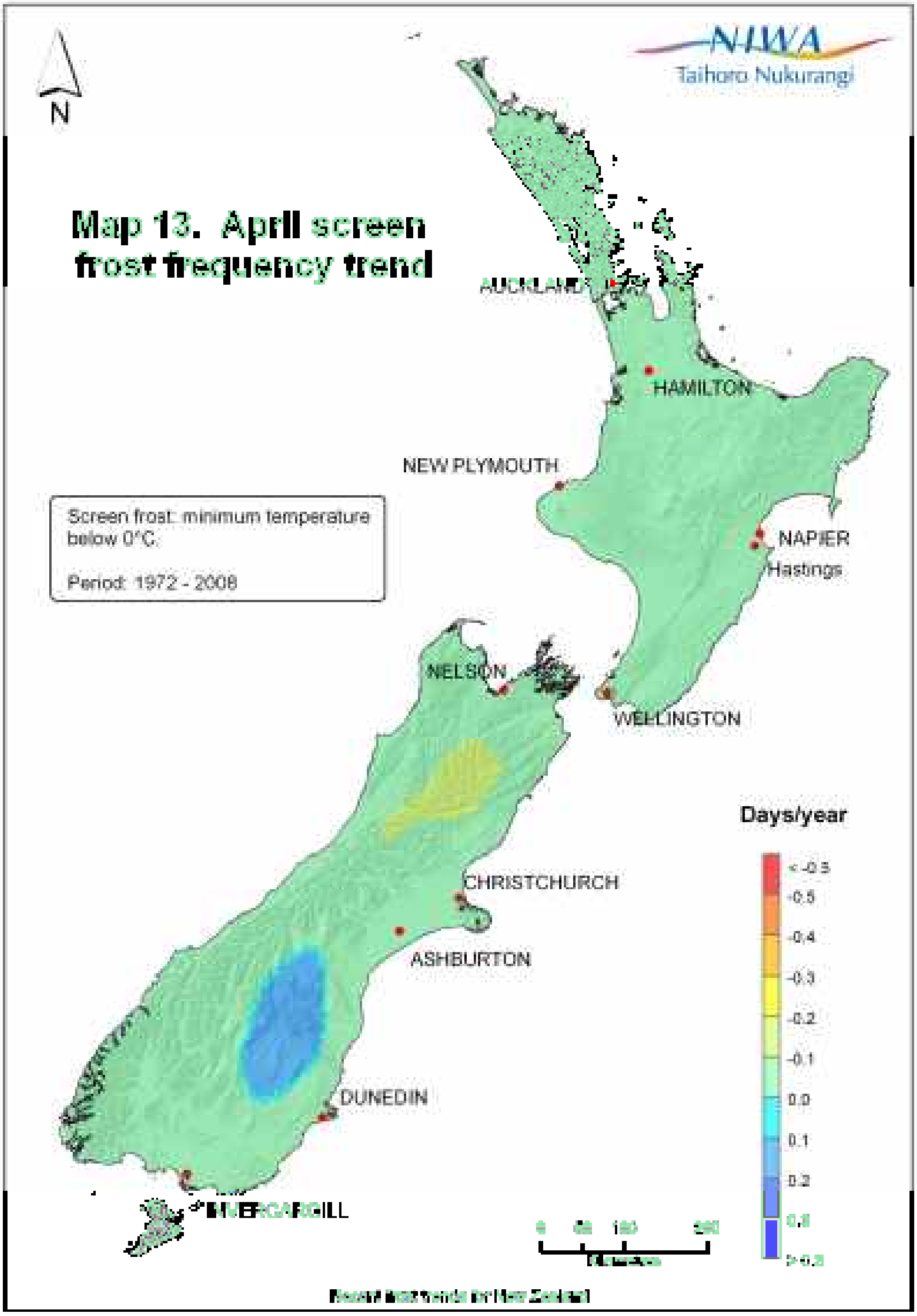

Map 9. Mean October
screen frost frequency
N
NIWA
Taihoro Nukurangi
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
days/month
0
0.5
1
2
4
6
8
10
12
14
16
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL

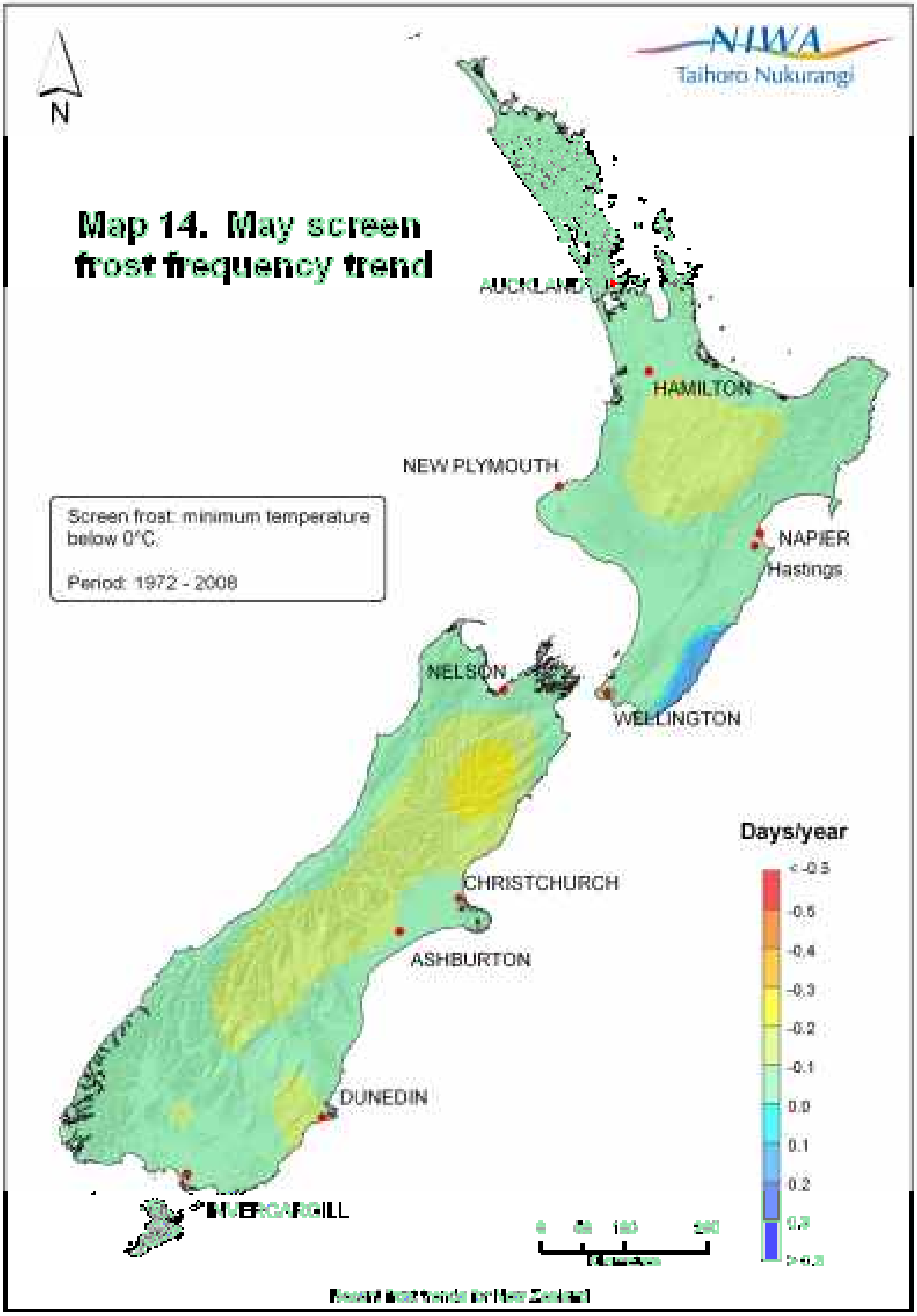

NIWA
Taihoro Nukurangi
N
Map 10. Mean November screen frost frequency
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
days/month
0
0.5
1
2
4
6
8
10
12
14
16
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL

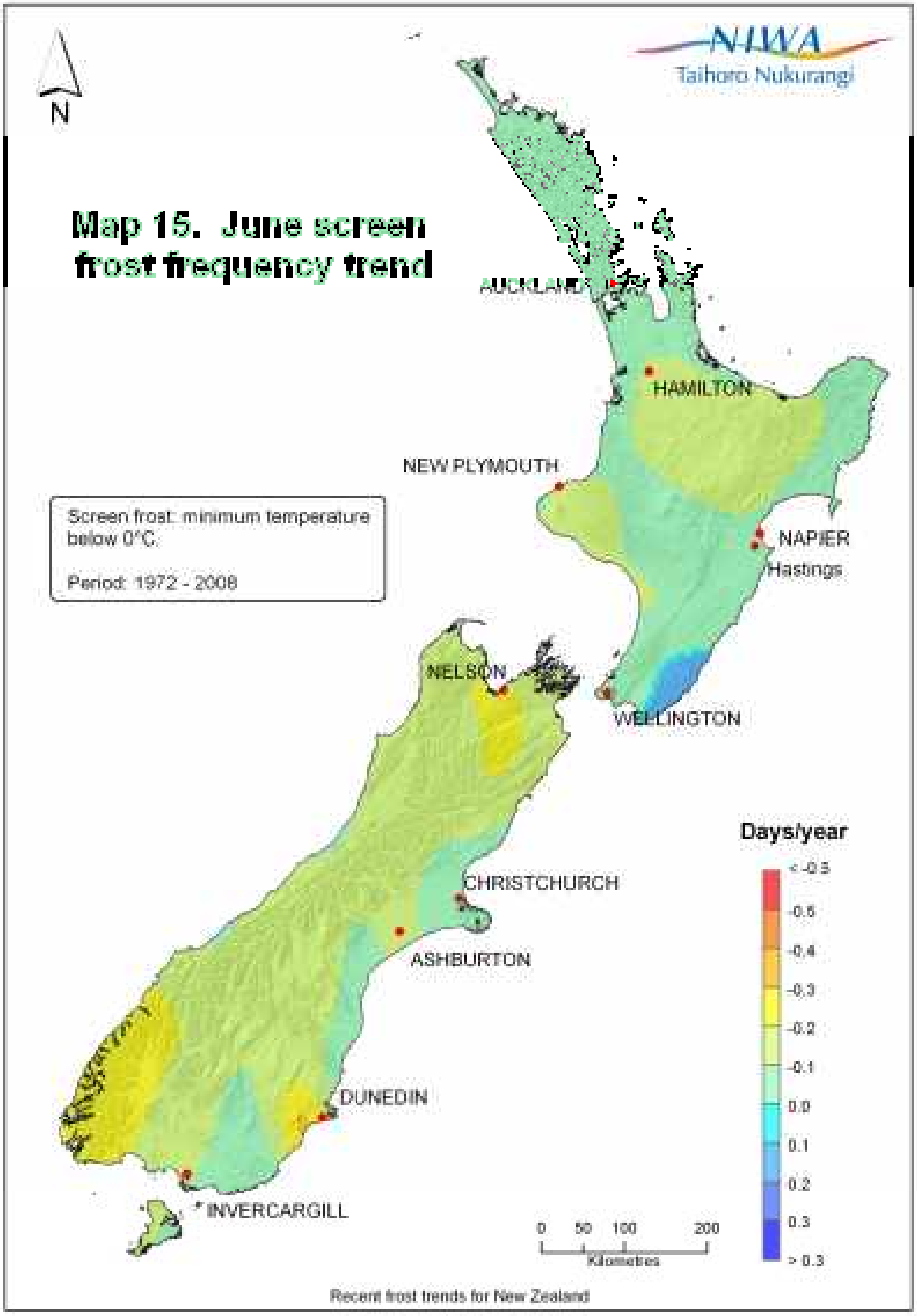

NIWA
Taihoro Nukurangi
N
Map 11. Annual screen frost frequency trend
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NELSON
WELLINGTON
Days/year
< -0.5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
> 0.3
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
0 50 100 200
Kilometres
Recent frost trends for New Zealand

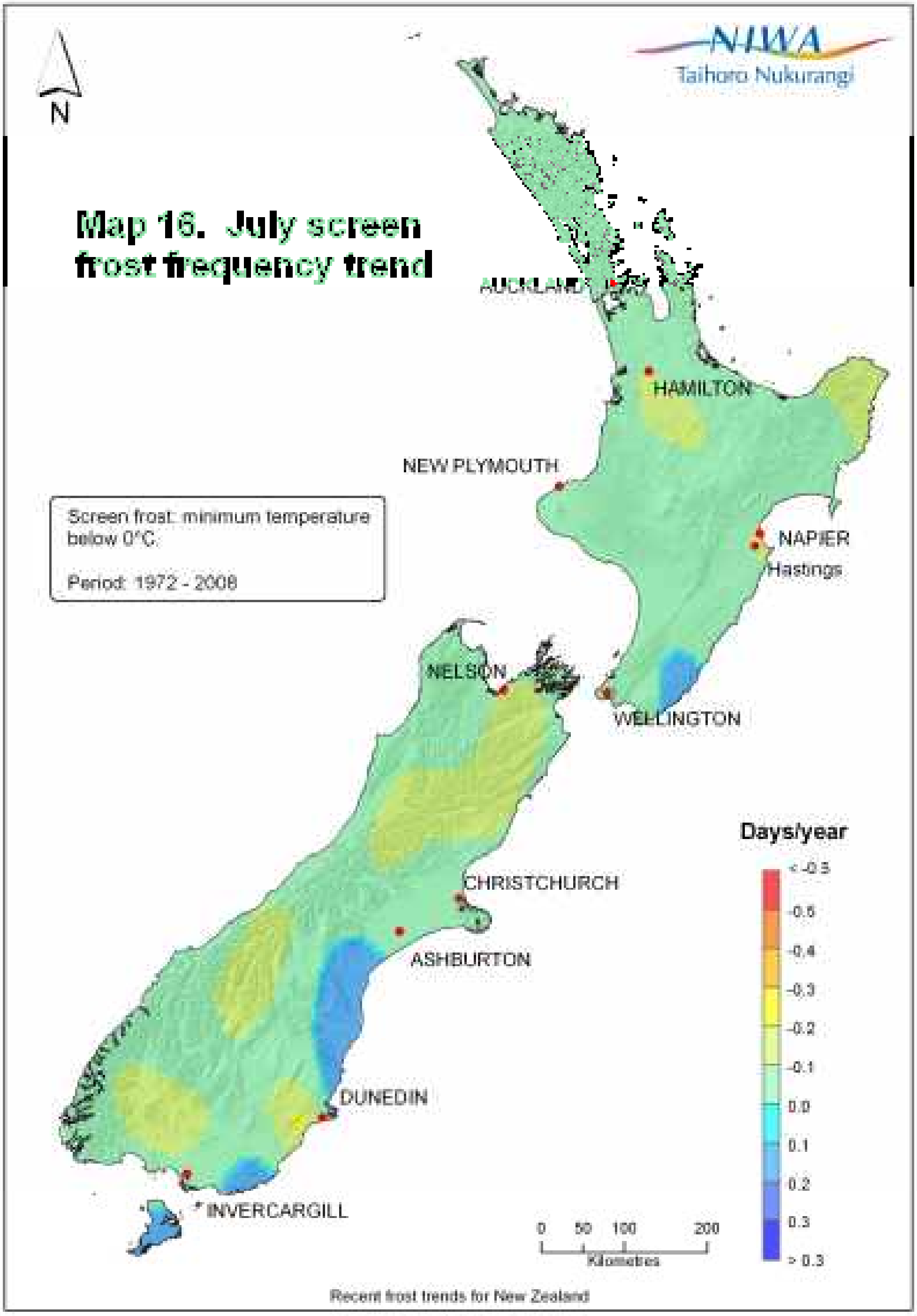


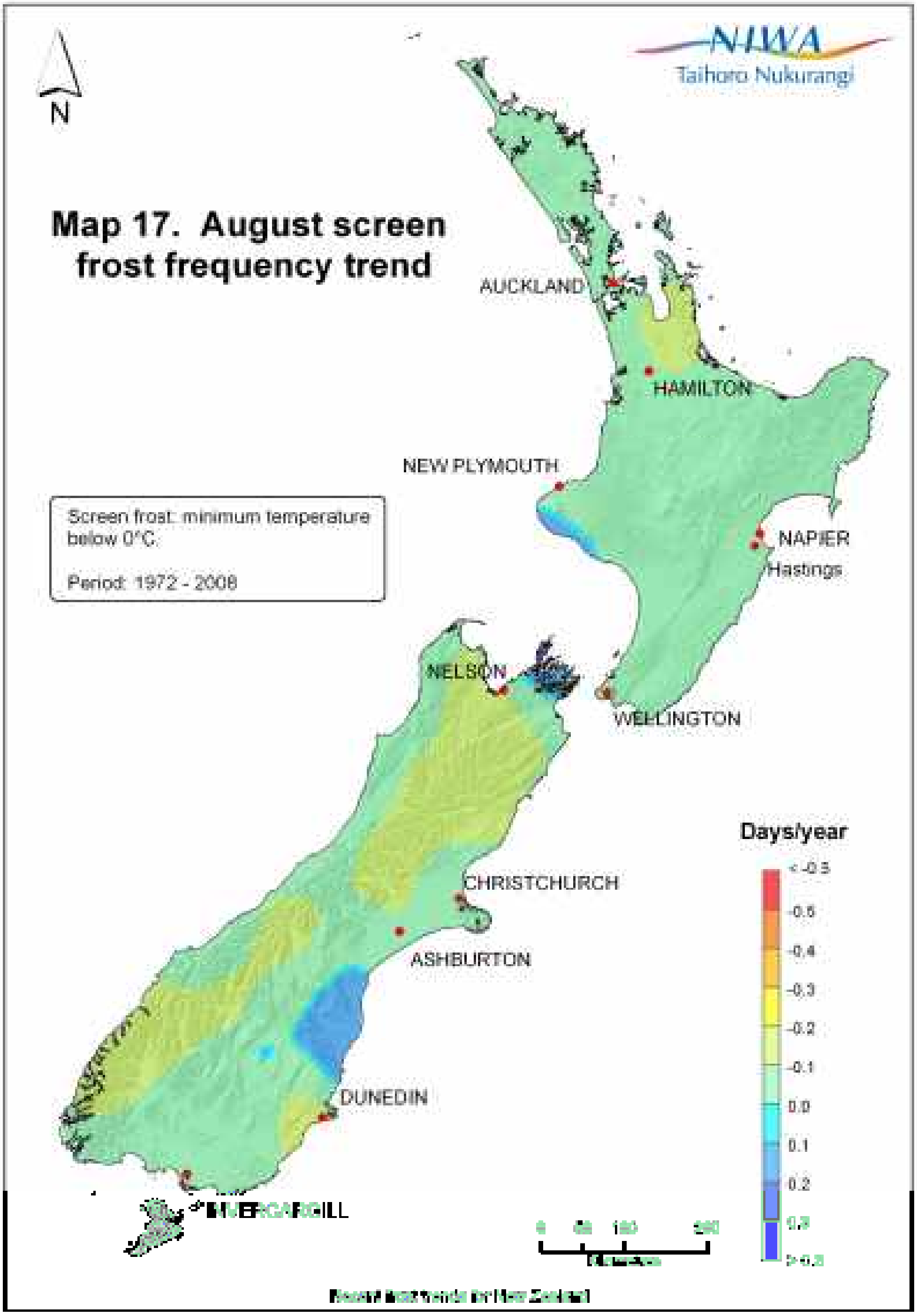
* Growing season, September-April.

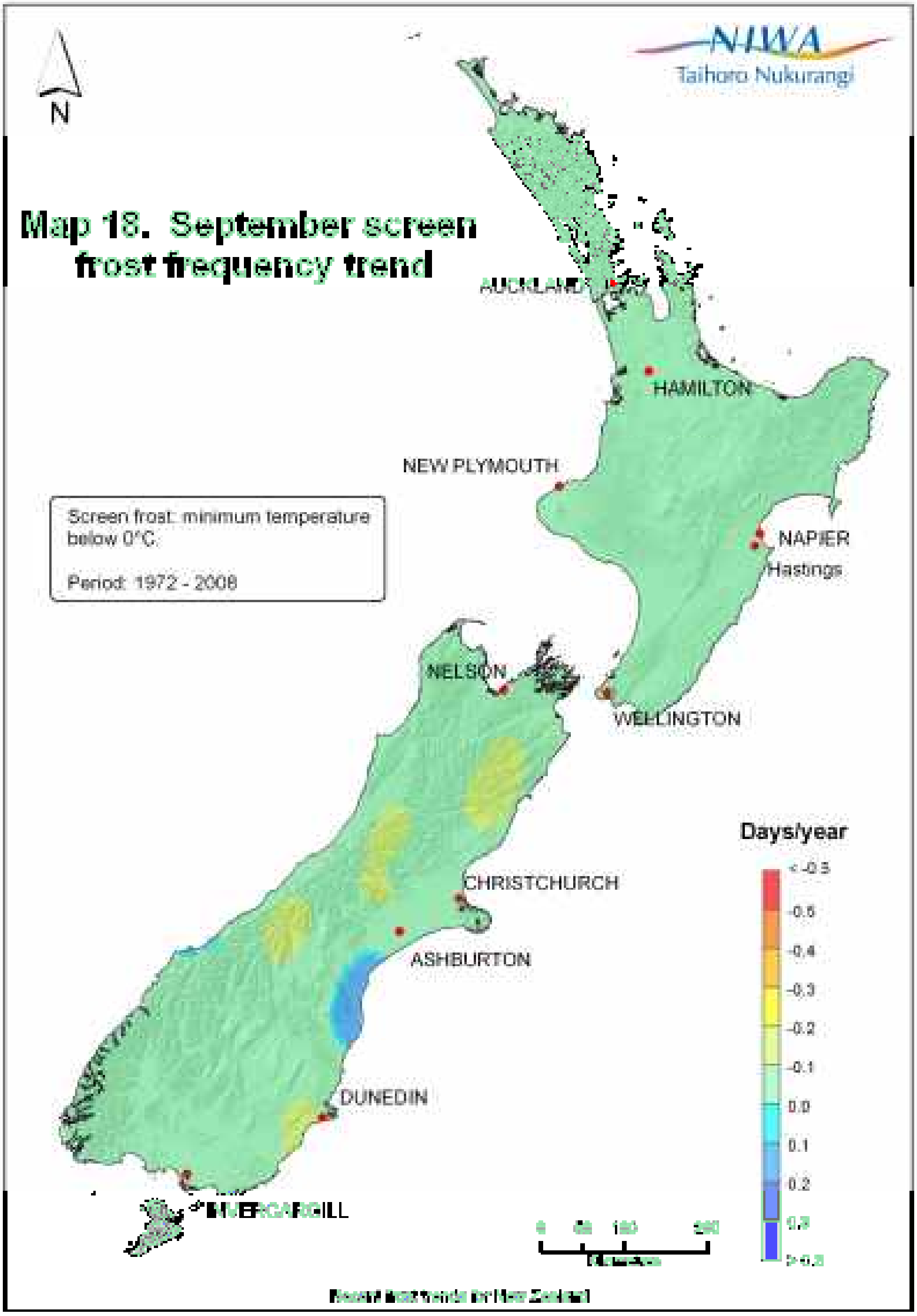

NIWA
Taihoro Nukurangi
N
Map 13. April screen frost frequency trend
AUCKLAND
HAMILTON
NEW PLYMOUTH
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NAPIER
Hastings
NELSON
WELLINGTON
Days/year
< -0.5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL

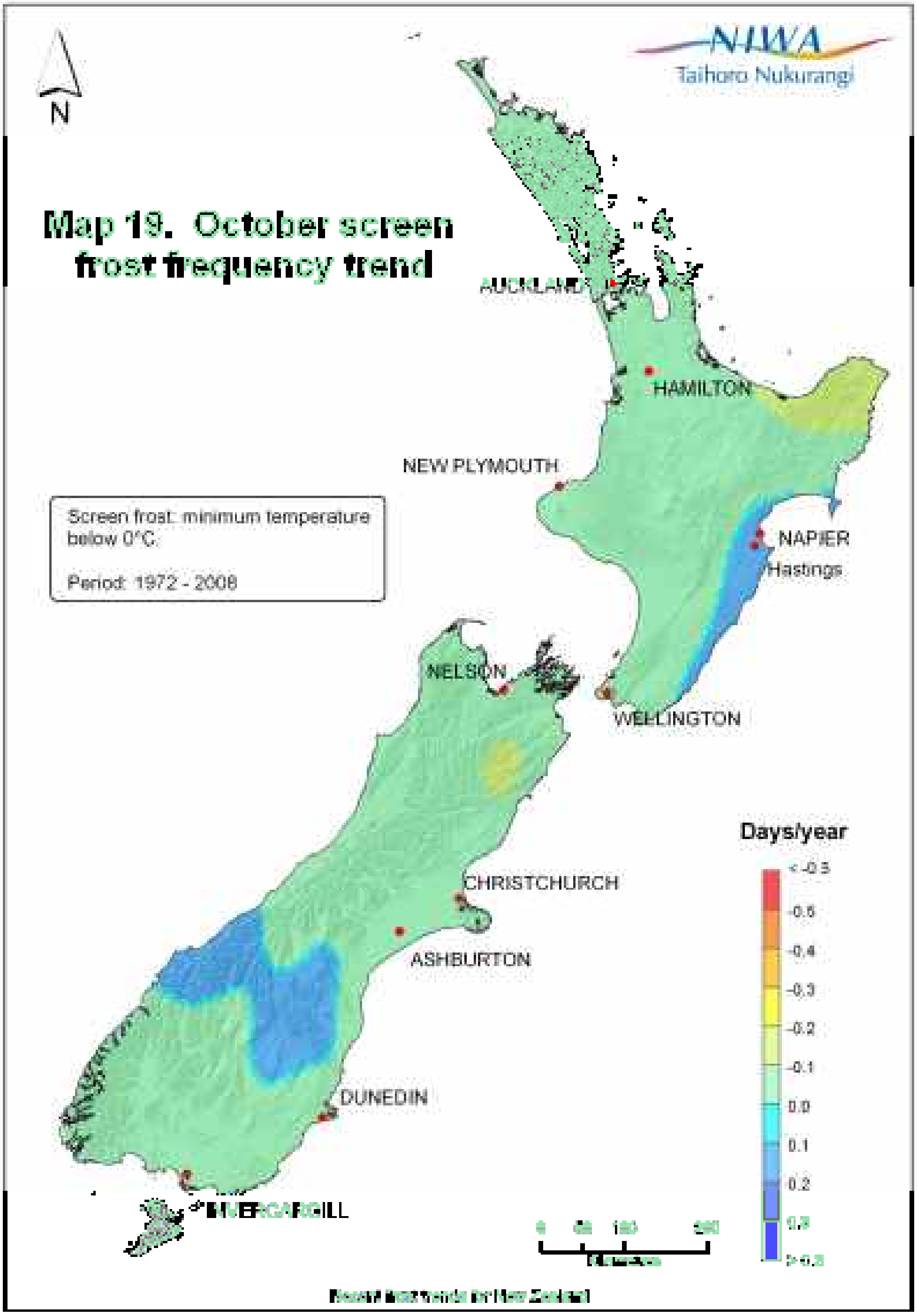

NIWA
Taihoro Nukurangi
N
Map 14. May screen frost frequency trend
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Days/year
< -0.5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2


NIWA
Taihoro Nukurangi
N
Map 15. June screen frost frequency trend
AUCKLAND
HAMILTON
NEW PLYMOUTH
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NAPIER
Hastings
NELSON
WELLINGTON
Days/year
< -0.5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
> 0.3
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
0 50 100 200
Kilometres
Recent frost trends for New Zealand

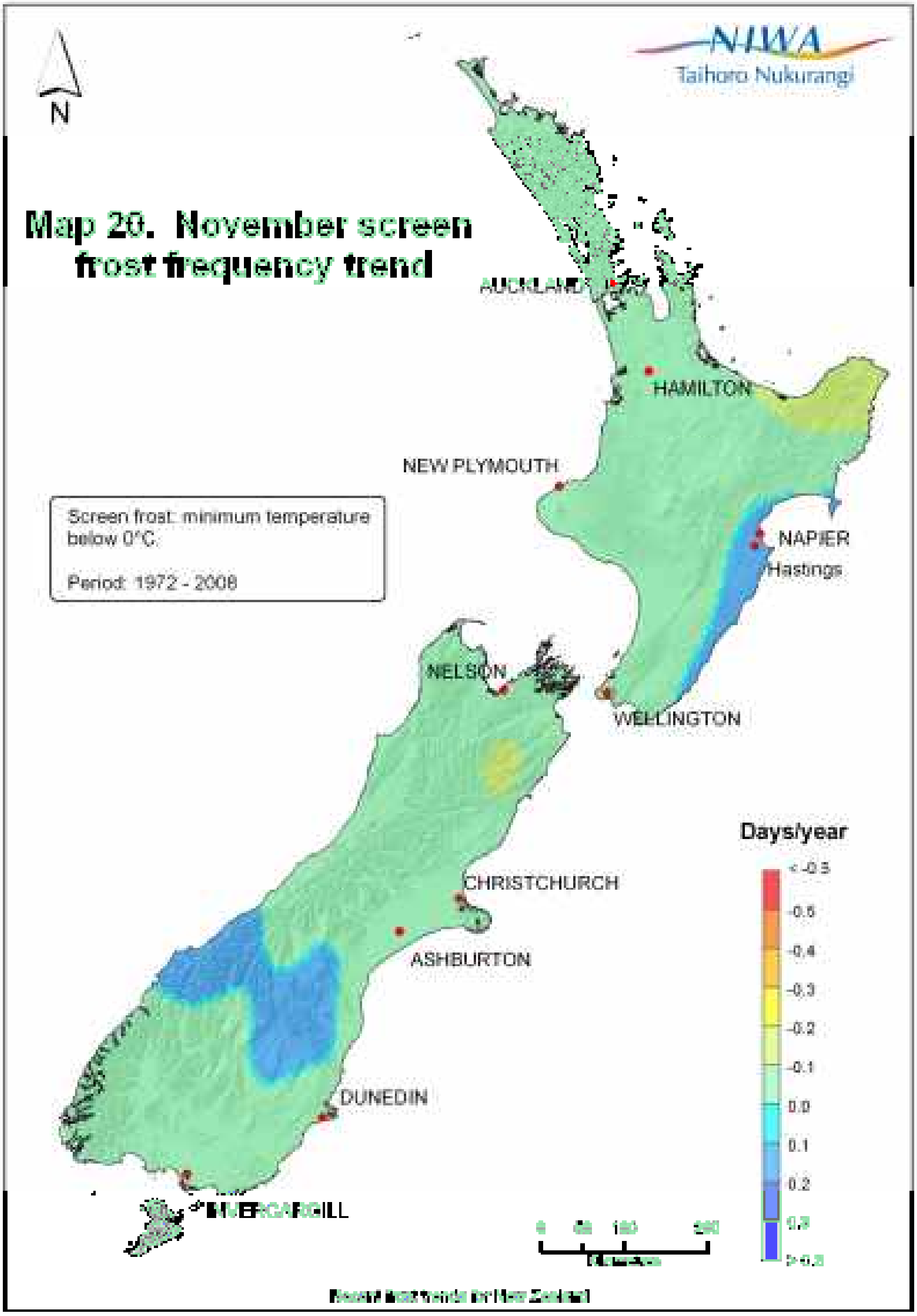

NIWA
Taihoro Nukurangi
N
Map 16. July screen frost frequency trend
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Days/year
< -0.5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
> 0.3
0 50 100 200
Kilometres
Recent frost trends for New Zealand

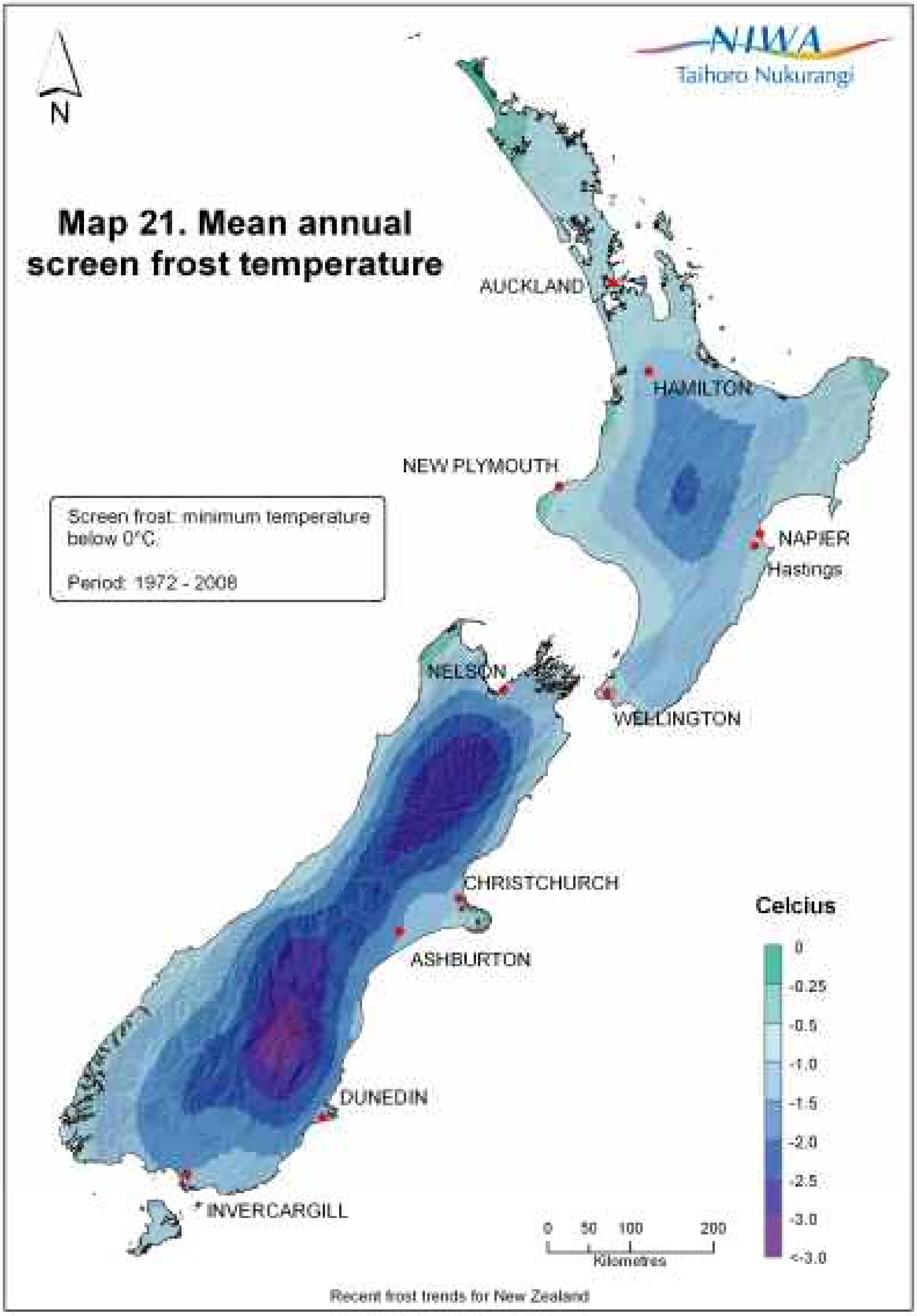

NIWA
Taihoro Nukurangi
N
Map 17. August screen frost frequency trend
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Days/year
< -0.5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2

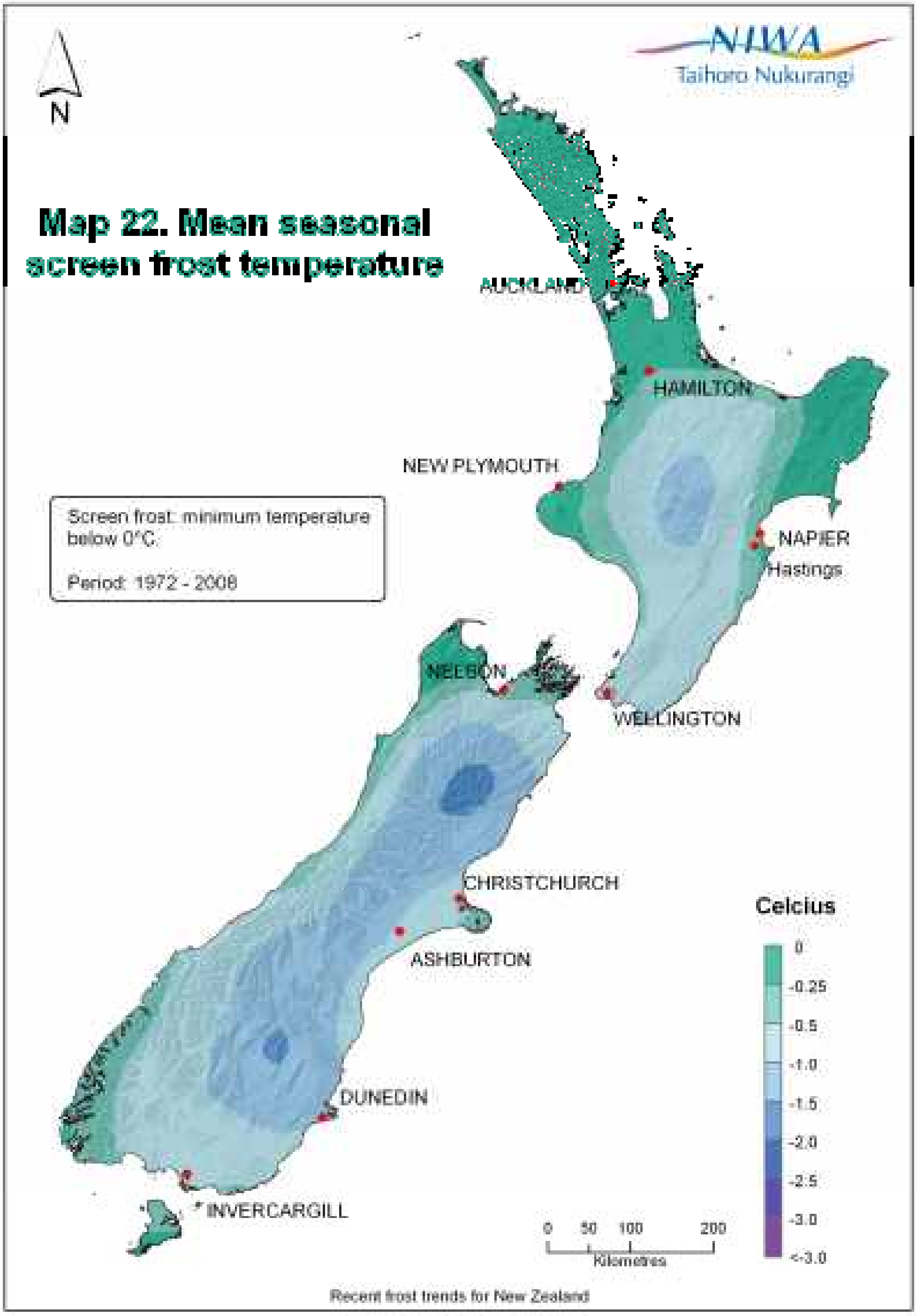

NIWA
Taihoro Nukurangi
N
Map 18. September screen frost frequency trend
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Days/year
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2



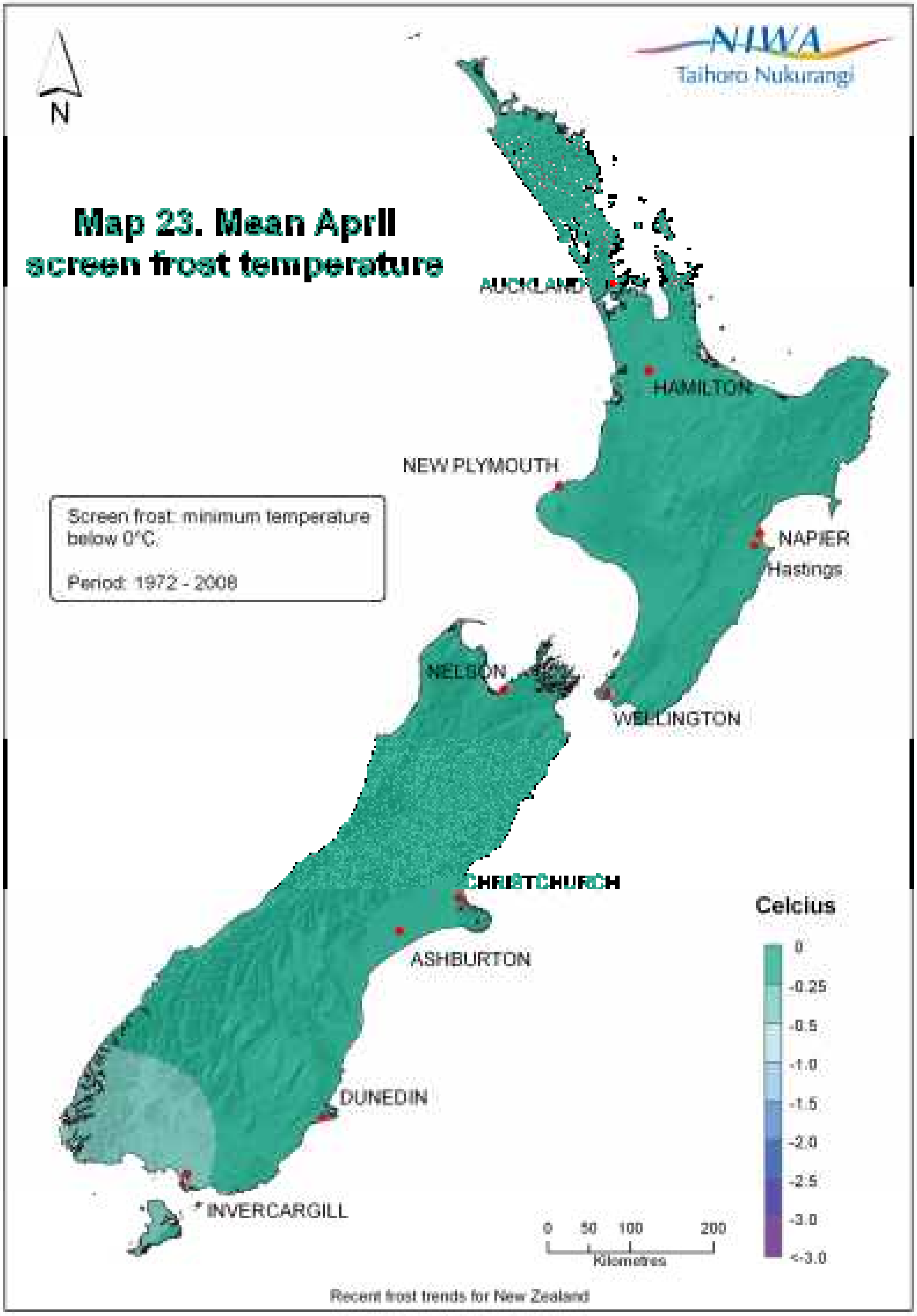
N
Taihoro Nukurangi
Map 19. October screen frost frequency trend
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Days/year
< -0.5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2

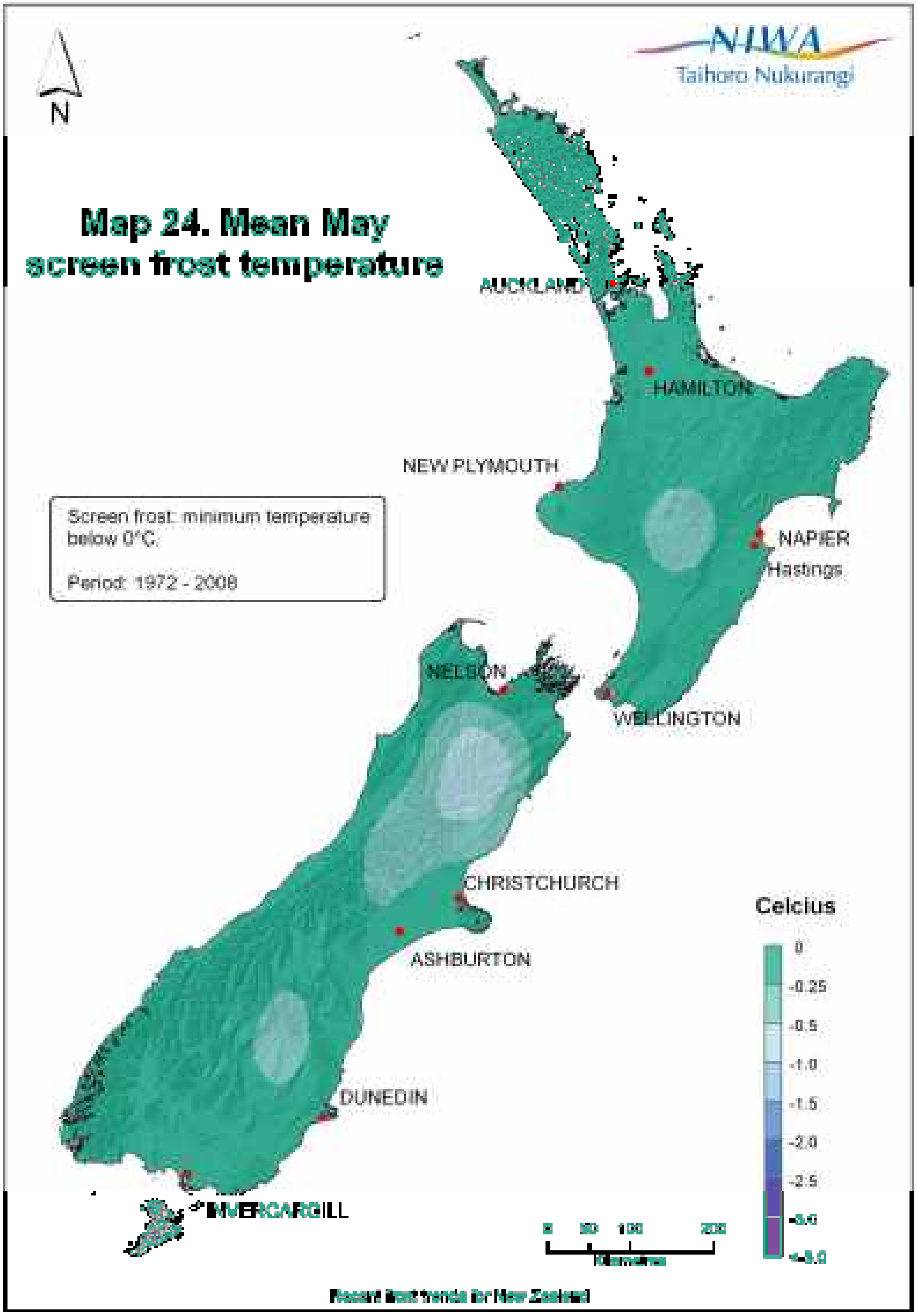

N
NIWA
Taihoro Nukurangi
Map 20. November screen frost frequency trend
AUCKLAND
HAMILTON
NEW PLYMOUTH
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NAPIER
Hastings
NELSON
WELLINGTON
Days/year
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL

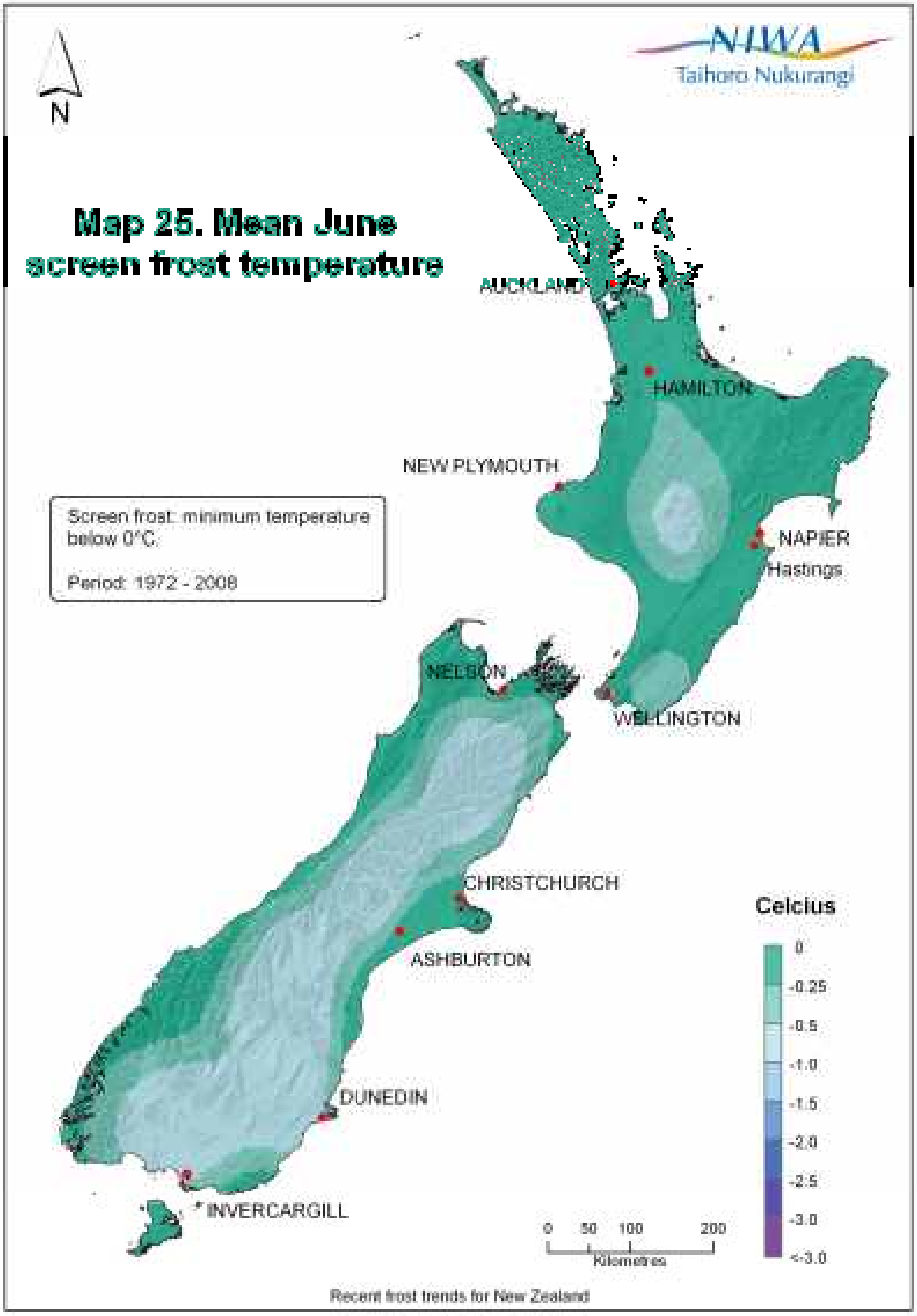

NIWA
Taihoro Nukurangi
N
Map 21. Mean annual screen frost temperature
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
0 50 100 200
Kilometres
Recent frost trends for New Zealand

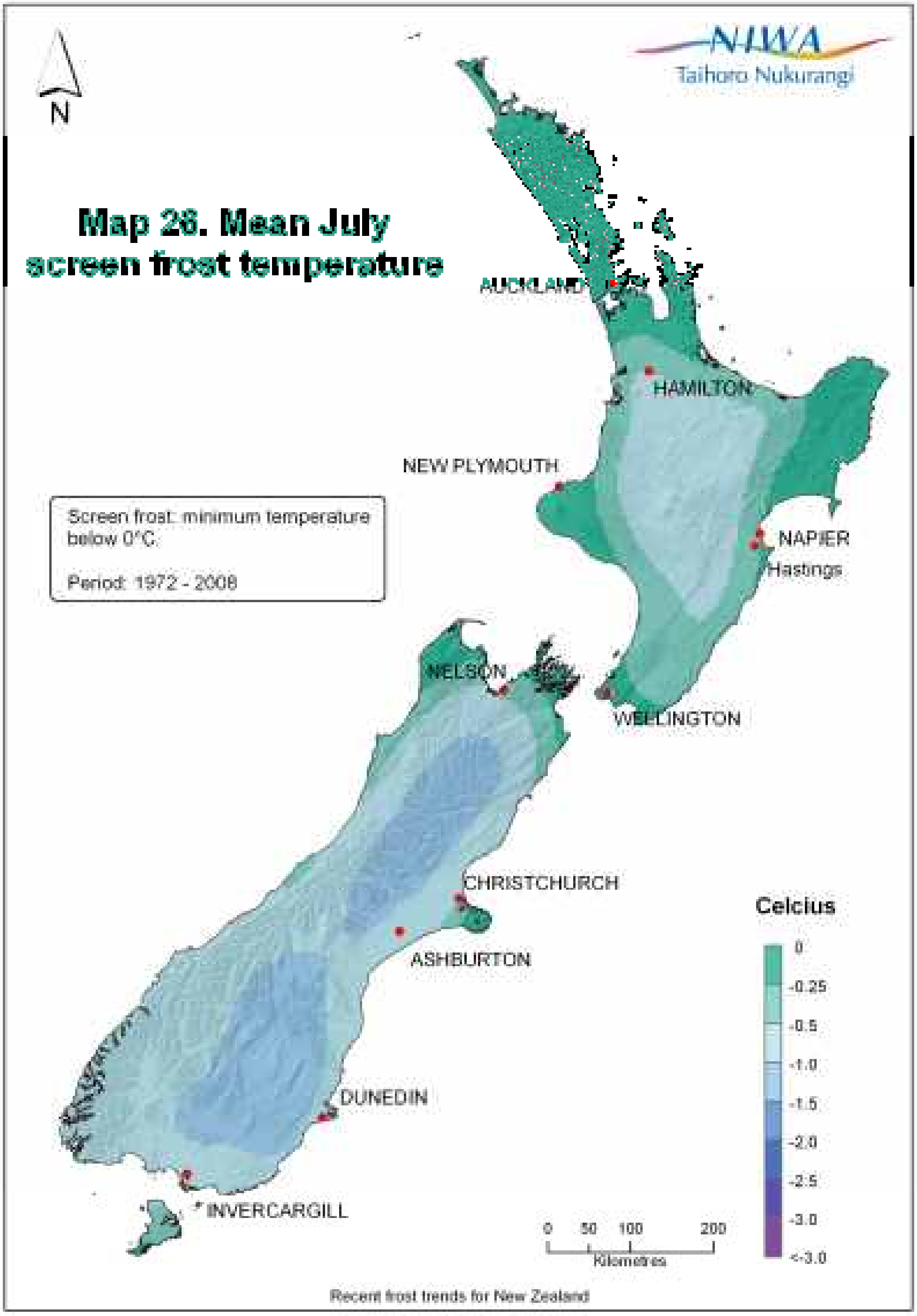


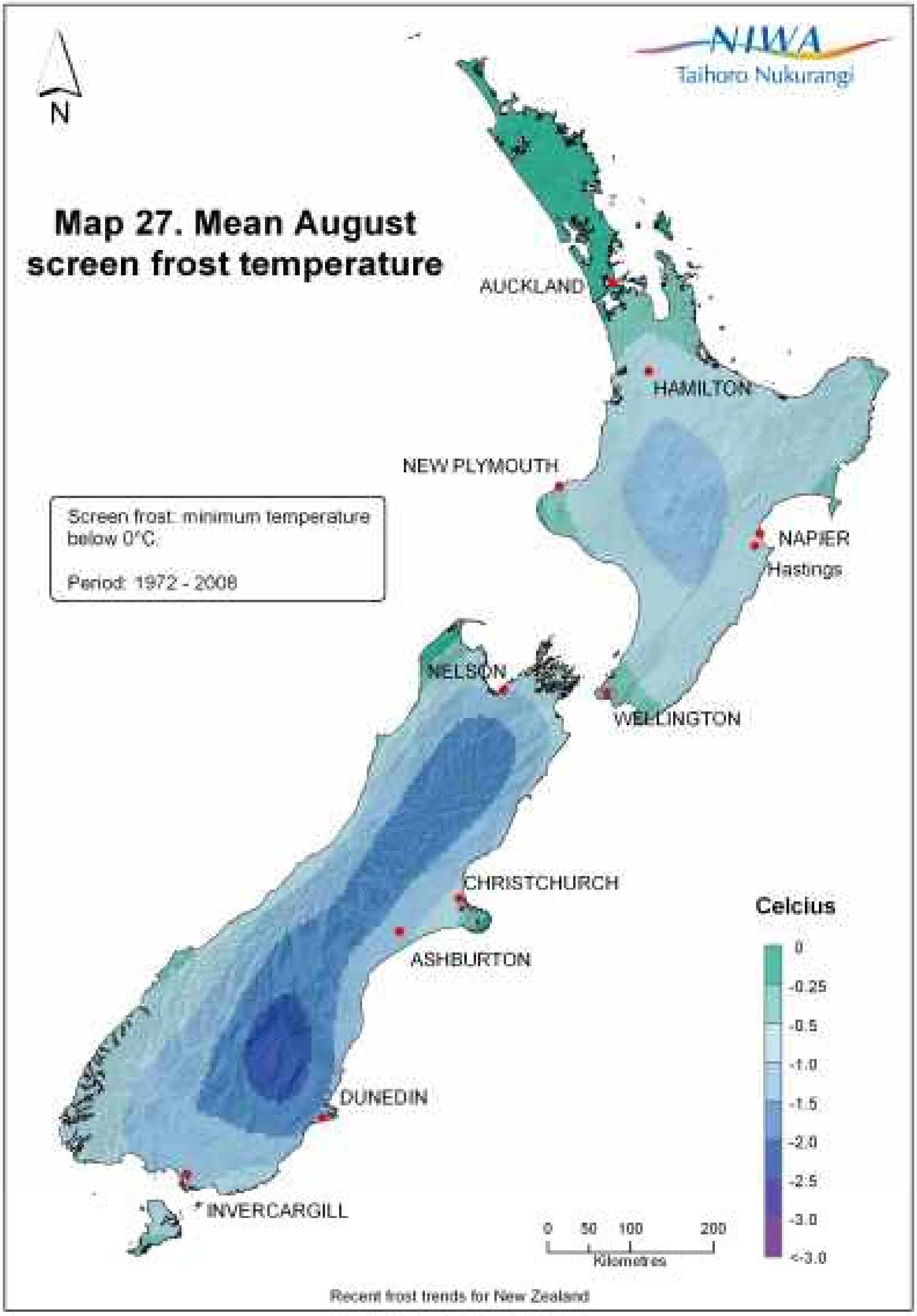
* Growing season, September-April.

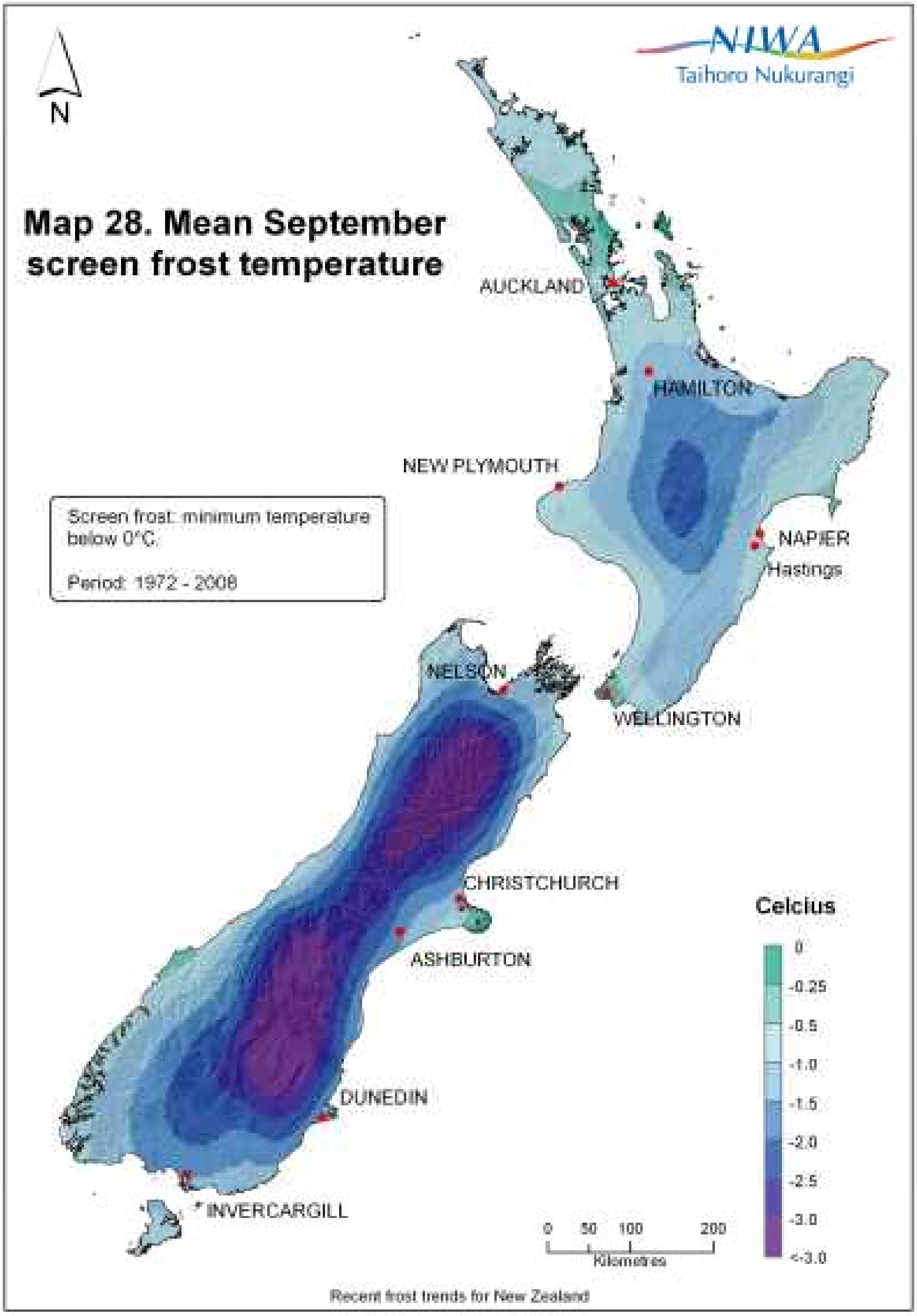

Map 23. Mean April screen frost temperature
NIWA
Taihoro Nukurangi
N
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
0 50 100 200
Kilometres
Recent frost trends for New Zealand

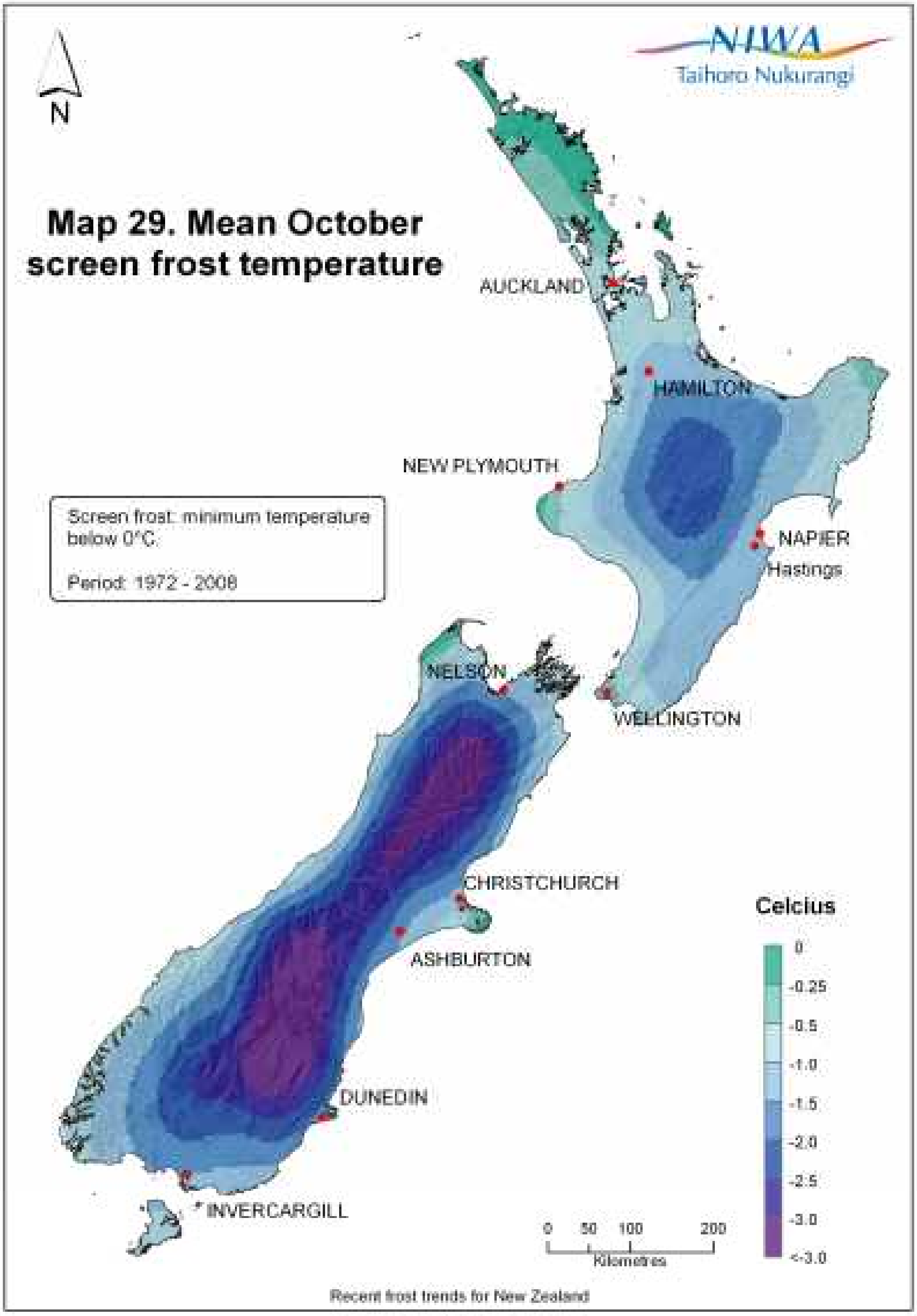

NIWA
Taihoro Nukurangi
N
Map 24. Mean May
screen frost temperature
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
Recent frost trends for New Zealand

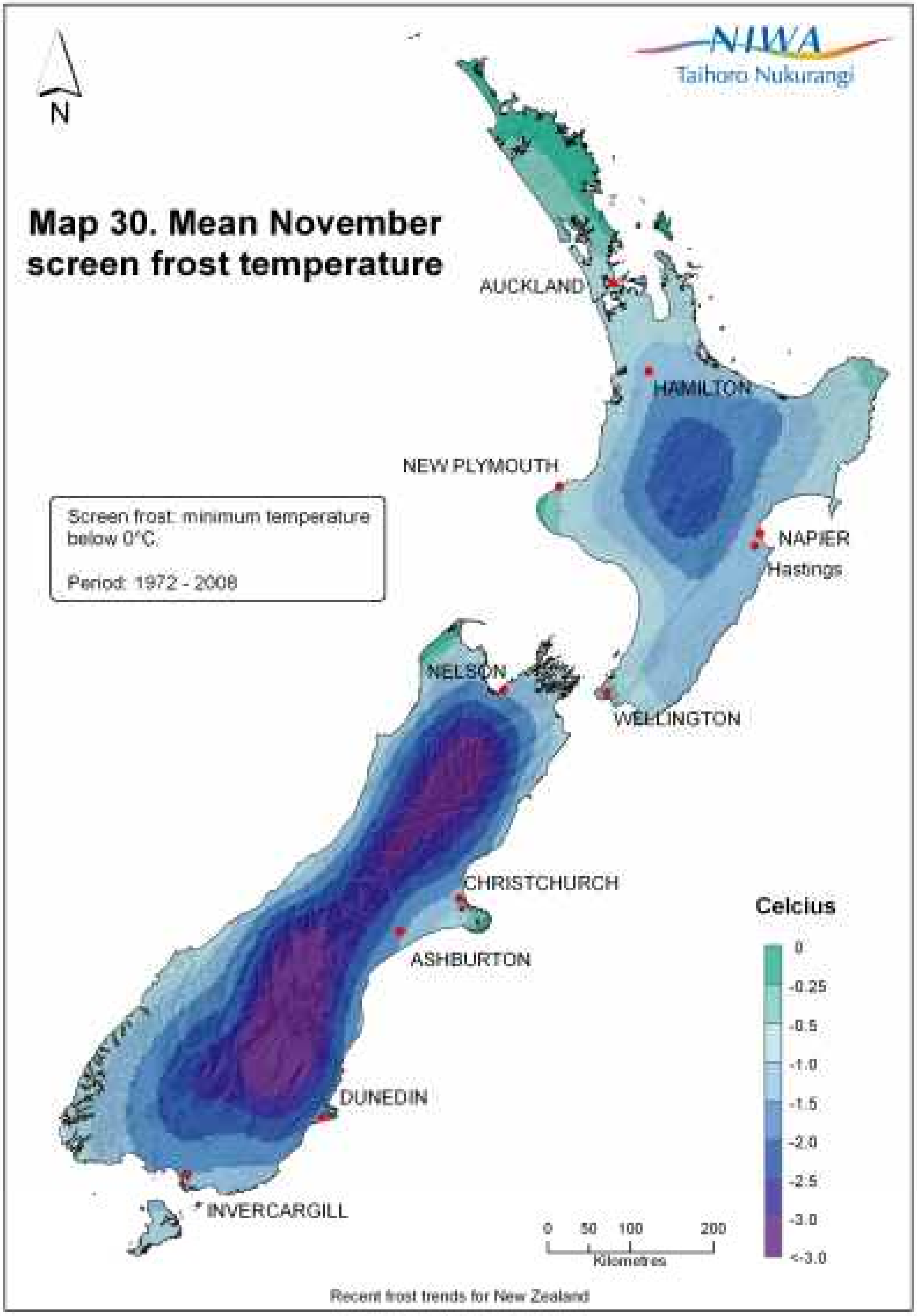

NIWA
Taihoro Nukurangi
N
Map 25. Mean June screen frost temperature
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
0 50 100 200
Kilometres
Recent frost trends for New Zealand

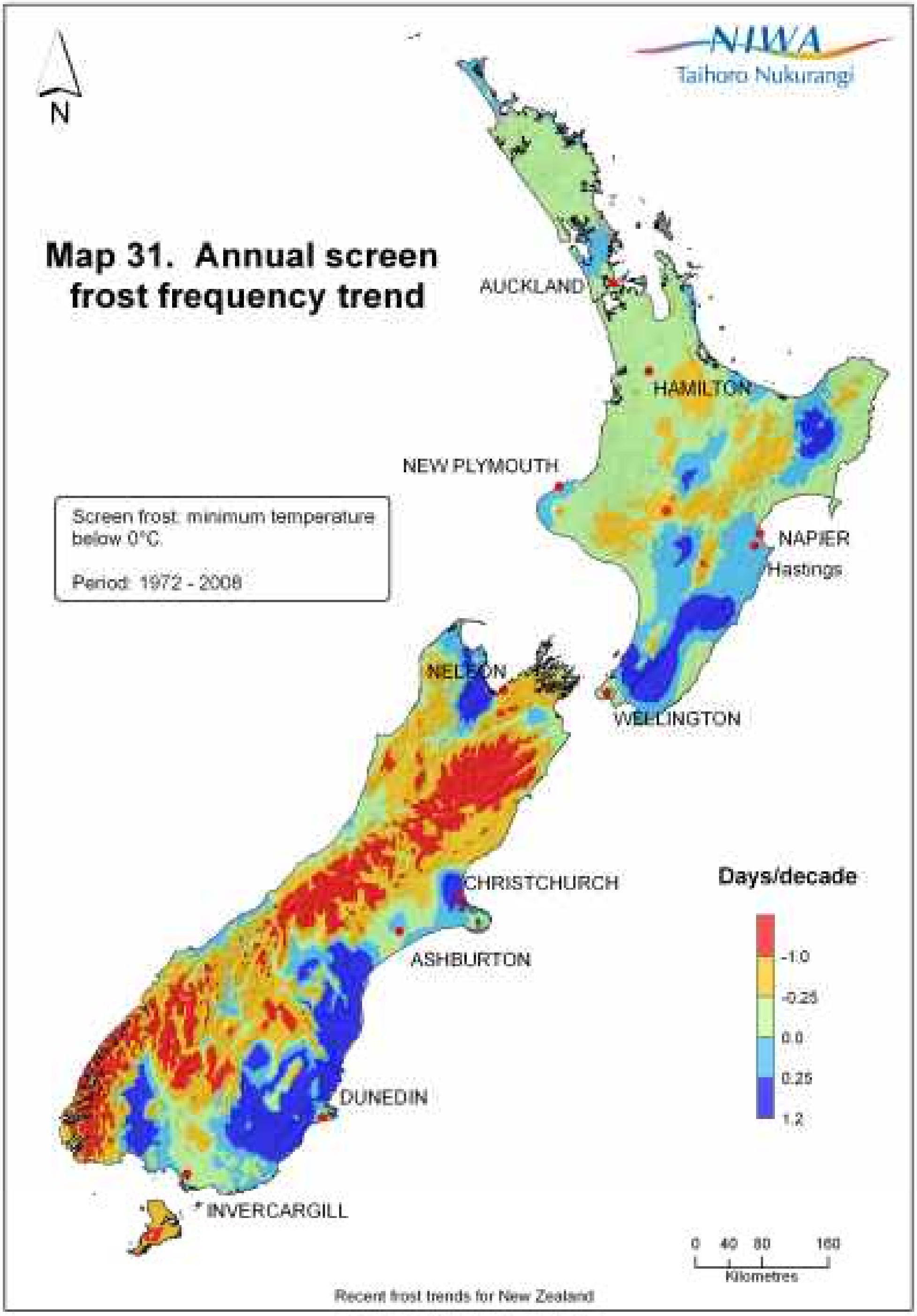

N
NIWA
Taihoro Nukurangi
Map 26. Mean July
screen frost temperature
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
0 50 100 200
Kilometres
Recent frost trends for New Zealand

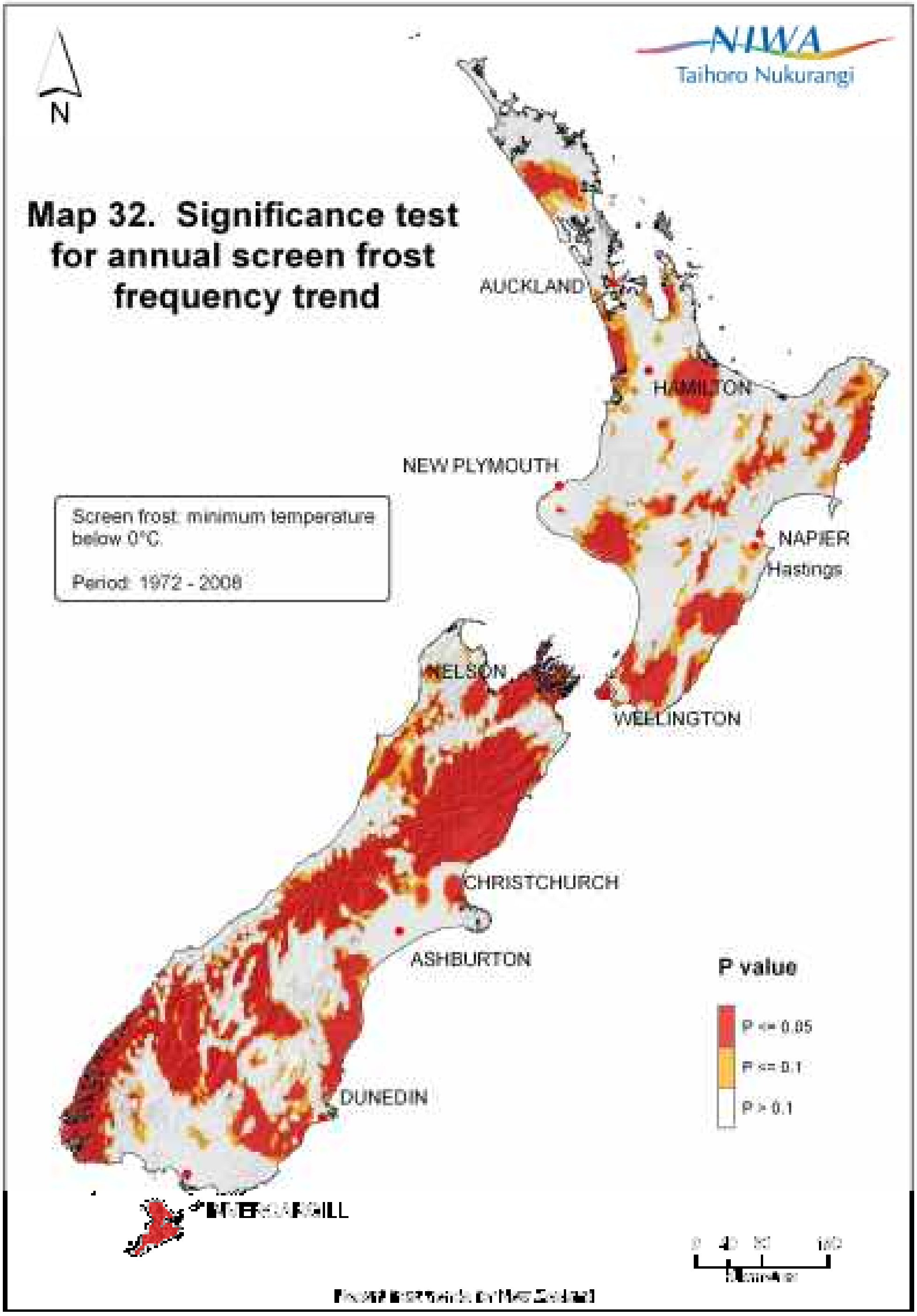

N
NIWA
Taihoro Nukurangi
Map 27. Mean August screen frost temperature
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
0 50 100 200
Kilometres
Recent frost trends for New Zealand


NIWA
Taihoro Nukurangi
N
Map 28. Mean September screen frost temperature
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
0 50 100 200
Kilometres
Recent frost trends for New Zealand


N
NIWA
Taihoro Nukurangi
Map 29. Mean October screen frost temperature
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
0 50 100 200
Kilometres
Recent frost trends for New Zealand


N
NIWA
Taihoro Nukurangi
Map 30. Mean November screen frost temperature
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Celcius
0
-0.25
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
<-3.0
0 50 100 200
Kilometres
Recent frost trends for New Zealand


NIWA
Taihoro Nukurangi
N
Map 31. Annual screen frost frequency trend
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
DUNEDIN
INVERCARGILL
Days/decade
-1.0
-0.25
0.0
0.25
1.2
0 40 80 160
Kilometres
Recent frost trends for New Zealand


N
Map 32. Significance test for annual screen frost frequency trend
AUCKLAND
HAMILTON
NEW PLYMOUTH
NAPIER
Hastings
Screen frost: minimum temperature below 0°C.
Period: 1972 - 2008
NELSON
WELLINGTON
CHRISTCHURCH
ASHBURTON
P value
P <= 0.05
P <= 0.1
P > 0.1
DUNEDIN
INVERCARGILL