Towards Topoclimate Maps of Frost and Frost Risk for Southland, New Zealand.

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Presented at SIRC 2003 – The 15th Annual Colloquium of the Spatial Information Research Centre
University of Otago, Dunedin, New Zealand
December 1st-3rd 2003

ABSTRACT

The spatial distribution of radiation frosts is closely associated with topographic patterns, and this link makes frost an obvious candidate for topoclimate mapping. There are several potential approaches involving field studies, numerical modelling and/or satellite imagery. For southern New Zealand, the Topoclimate South data set of 223 million temperature values provides an opportunity to map frost and frost risk information. To date, only a few exploratory studies have been undertaken. These typically involve only a few of the 2550 available sites and/or only a single night. Nevertheless, initial investigations indicate that frost mapping in Southland is likely to be a fruitful and interesting topic of study. Funding has recently been obtained to set up a coherent database to contain the data set, and this will greatly help future research in this area.

***Keywords and phrases*:** frost, mapping, topoclimate, Topoclimate South, Southland

1.0 INTRODUCTION

Climate can be defined as the long-term environmental conditions associated with factors such as energy, temperature, wind and moisture conditions. Climate varies at horizontal spatial scales ranging from an individual leaf (1 mm to 1 m) to the entire Earth. Topoclimates are specifically local-scale climate features which are due to the presence of topography. That is, they occur at horizontal scales of about 100 m to 50 km (Oke, 1987) and are associated with raised terrain. Topoclimates are governed by combinations of well-known physical factors. These include aspect, slope angle, height above sea level, relative elevation above the local valley floor, the propensity for ponding of cold air at night and topographic wind patterns. The latter includes mechanical effects such as topographic shelter (e.g. in the lee of hill) and funnelling (e.g. through a mountain saddle or canyon), and density-driven air flows, such as anabatic and katabatic winds. Topoclimates are often associated with strong spatial contrasts in air and soil temperatures, rainfall, snow deposition and melting, evaporation rates, rock weathering, and plant and animal habitats and behaviour. Consequently, they have can have important implications for land use management decisions in rural areas, e.g. relating to crop selection, land use profitability and sustainability.

Frost damage is a serious concern for many types of temperate climate crops. Frost may damage leaves and fruit, impact on plant health and cause death, depending on the severity of a frost and the susceptibility of a particular plant. Frost is generally divided into *radiation frost*, i.e. created in cloudless, calm conditions by the longwave radiative cooling of near-surface air, and *advective frost*, which is caused by large-scale cold air masses moving into an area in windier conditions. To illustrate the difference, frosts are common in New Zealand in all but the mildest locations for many/several nights every winter. These are radiation frosts, and they typically vary in intensity from place to place, at scales ranging from a lawn to a topographic basin. In contrast, an advection frost may envelope an entire region in freezing temperatures, e.g. on 22 September, 1995, a very cold air mass pushed into Illinois, USA, from Canada, and the associated advection frost affected the entire state (Angel, 2001).

Patterns of radiation frost (the topic of this paper) are known to be closely associated with topography. Radiation frost tends to form earlier in a night, be more frequent and more severe at sites located on a valley floor. In contrast, frost may be delayed, reduced in severity, or absent on any particular night at sites which are located on an open hill slope or hill top. This is because, at night in weather conditions when frost tends to form, cold and therefore relatively dense air tends to pond in lower lying positions in the landscape (Oke, 1987). This link between frost and topography makes frost occurrence and frost risk obvious candidates for topoclimate mapping.

Much of New Zealand's land area is characterised by raised terrain and New Zealand possesses a wide range of topoclimate conditions, often occurring within small distances. This paper presents on-going investigations concerning topoclimate mapping in the Southland region, New Zealand. The work is built upon on the Topoclimate South temperature data set, a world-leading spatio-temporal data set containing about 223 million temperature values. Preliminary work by the author has focussed primarily on problems relating to data management and to questions concerning frost occurrence and frost risk.

2.0 LITERATURE REVIEW

A review of the climatological literature indicates that there are several potential approaches to the mapping of minimum temperatures, frosts events and/or frost risk. Historically, researchers have had to rely on thermometers which were read manually, e.g. once a day at 0900 h. Logistics normally severely limited the size of study area and number of sites that could be monitored by an individual researcher. Computer software for pinpointing locations and elevations (i.e. Global Positions Systems or GPS) and for map-making and spatial analysis (i.e. Geographical Information Systems or GIS) were also absent until fairly recently. For example, Turner and Fitzharris (1986) measured daily minimum and maximum temperatures at 45 sites in the 21 km^2 Bannockburn district, Central Otago, New Zealand. Data were measured for one warm season (i.e. November 1980-March 1981). Subsequent regression correlations with a local long-term climate station (Cromwell) allowed 30-year long-term values to be computed for each site. Long-term mean data were mapped "taking into account the groupings [of sites] provided by covariance analysis, the role of topography, and any trends suggested by the data" (Turner and Fitzharris, 1986: 62). In practice, this meant that the resulting maps were contoured 'by hand' using expert knowledge.

More recently, several papers dealing with minimum temperature mapping in Sweden have originated from the University of Göteborg, Sweden (e.g. Söderström and Magnusson, 1995; Blennow, 1998; Blennow and Persson, 1998; Lindkvist et al., 2000). Söderström and Magnusson (1995) studied an area of 80 km^2 and used kriging to spatially interpolate air temperature values which had been measured using thermometers mounted on mobile vehicles. As expected, areas of cold air correlated with valley floors and followed the contour lines fairly well, while warmer areas were seen on hills. A cold air drainage model was run using a GIS network analysis function. Terrain data were initially available at a 50 m resolution, however, these were converted to a Triangular Irregular Network (TIN) of 1600 polygons to conserve computing power. The drainage model simulated channel and overland flow in the direction of the steepest slope and was relatively sophisticated. For example, break lines were installed around forests to inhibit throughflow of air across these rough features, and source areas for cold air were identified using terrain-based criteria.

Blennow and Persson (1998) measured air temperatures in a 7.5 km^2 area of forest, also using mobile surveys undertaken on five clear, calm nights. Several factors derived from a GIS and Digital Elevation Model (DEM) with 10 m pixels (i.e. sky view factor or site openness, altitude, relative relief and the presence of peat soils) were used to model the observed spatial variations in temperature. The model showed good success and was able to explained 88% of the observed variation, and 87% of the variation for an independent set of validation data. Cold air drainage was investigated using a re-sampled (i.e. simplified) DEM, however, this factor did not improve the model for this forested area. It was surmised that if it was run for the same terrain but with the forest cover removed, cold air drainage would likely to be important. Under forest canopy the processes of cold air production, drainage and ponding appeared to be inhibited.

Blennow (1998) presented data on minimum temperatures for the same forest but for the growing seasons of 1992 and 1993 and for 104 and 119 fixed sites, respectively. The spatial variation of minimum temperature was modelled for clear, calm nights using DEM-derived indices which described the drainage, ponding and stagnation of cold air. The stepwise linear regression model developed was able to explained 87% to 89% of the spatial variation in minimum temperature.

Lindkvist et al. (2000) measured and modelling frost patterns in more mountainous areas than those described above. Temperature data were collected at 38 sites in a 625 km^2 area during the growing season of 1996, at sites ranged in elevation from 500 m to 1200 m. Measurements showed that frosts were strongly correlated with valley sites and that few frosts occurred on elevated areas with a convex shape. On this basis, digital elevation data on a 100 m grid were used to assign a terrain type to each sampling site. A grid with pixels 2.5 km × 2.5 km in width was then applied and used to extend the terrain classification across the entire study area. Pixels were classed as predominantly convex, linear slope, linear flat, wide concave or narrow concave in form. A frost risk was estimated for each pixel based on the measured temperatures at the field sites, and a cluster analysis was used to group pixels into six classes of frost risk, i.e. from very low to extremely high risk.

European research dealing with frost mapping is not restricted to Scandinavia. Jarvis and Stuart (2001) investigated strategies for interpolating maximum and minimum daily temperatures over England and Wales. Their aim was to predict temperatures for an annual cycle at a resolution of 1 km. A DEM with 50 m resolution was used to derive an approximate drainage network and grids at a resolution of 500 m × 500 m or 1 km. A total of 35 candidate variables were investigated for a case study year (1976), including surface type (e.g. suburban or urban), drainage basin size (a surrogate for the propensity for cold air drainage), elevation, distance to each coast, and the potential effects of föhn winds behind dominant mountain barriers. Latitude (expressed as 'northing'), elevation, and coastal and urban effects were found to be particularly significant variables for predicting spatial variations in daily minimum temperatures. Investigations using *ANUSPLIN* and partial thin plate splines suggested that local-scale predictions may improve if information on coastal shape and situation, land cover, and soils were added. However, the results achieved (RMS errors of 0.8°C for maxima and 1.14°C for minima aggregated over a year) may be close to the limits of accuracy given that the network used consisted of only 174 selected climate stations.

Zinoni et al. (2002) investigated frost risk in the 22 000 km^2 Emilia-Romagna region of Italy. Frost events were identified for 161 climate stations for the period March-April 1987-2000. A DEM with a resolution of 250 m × 250 m provided terrain variables such as slope, aspect, absolute elevation, relative elevation above valley bottom, valley width, closeness to the sea, and surface roughness (a surrogate for topography in the plain areas). For hill areas, significant correlation was found between the mean minimum temperature during frost events, relative elevation above valley bottom, and closeness to the sea. Correlations for the plains were less certain and had to be estimated using arbitrary coefficients based on previous experience (Zinoni et al., 2002). Frost patterns were mapped and a frost risk determined based on the combination of temperature and plant phenology. The latter was incorporated because frost damage is not solely a function of temperature, but varies with the crop of interest (e.g. kiwi *vs* apricot).

An alternative approach is to use remotely-sensed data, i.e. satellite imagery, to collect spatial temperature data. Several researchers in South America have used this approach. Kerdiles et al. (1996) mapped frost in the 500 000 km^2 Pampean region, Argentina, using satellite data. In November 1992 this region experienced three out-of-season frost events which caused serious damage to crops. NOAA AVHRR satellite data with a resolution of 1 km were examined for the 0300 h pass for each event. Qualitatively, the surface temperature distribution agreed with the reports of frost affected areas. Regressions of satellite-derived surface temperature against the minimum air temperature values measured at up to 41 climate stations gave a pooled correlation of 0.85 and a standard error of 1.8°C. This was a satisfactory outcome given the contrasts between the two temperature sets and the size of the study area. Including geographical variables (latitude, longitude and altitude) in the regressions did not significantly improve the outcome.

Francois et al. (1999) mapped frost risk for the 100 000 km^2 Bolivian Altiplano, based on NOAA satellite-derived surface temperatures and measurements of air temperature at 17 climate stations with suitable long-term data. Linear regressions of minimum air temperature against satellite-derived surface temperatures were computed for each station and for up to 25 satellite images. The region was then classified based on the surface temperatures into 17 zones, each representative of a particular climate station. The historical climate records were then used to construct maps of 30-year mean minimum temperatures, extreme minimum temperatures, and frost risk (expressed as a percentage) for different months and frost thresholds (e.g. -1°C to -5°C). The mapped distributions seemed to be in accord with known topographical details, e.g. frosts were less on areas of raised ground.

Satellite imagery has the potential to rapidly provide relatively high resolution spatial data in areas where surface sites (i.e. field sites or climate stations) are sparse. Satellite data may not always be available or optimally timed, but the need for cloudless conditions makes it inherently useful for mapping radiation frosts (Kerdiles et al., 1996). The combined use of satellite-derived surface temperatures and measurements of air temperature from climate stations allows point data with important historical records to be extrapolated over large horizontal areas, i.e. utilising satellite data which is spatially extensive but has poor temporal coverage (Francois et al., 1999).

Given an appropriate numerical model, forecasting of frost risk is also possible, i.e. the prediction of future frost conditions. Santibáñez et al. (1997) reported a methodology for forecasting minimum temperatures in the Central Valley, Chile. The method was based on an empirical frost prediction model run for a few reference climate stations. The model predicted frost occurrence as a function of the air temperature and humidity (wet bulb temperature) at 2000 h on the previous day, and the forecasted cloudiness for the next day at the time of the minimum temperature. NOAA satellite infrared imagery, a digital terrain model (DTM), and terrain variables derived from the DTM (i.e. elevation, aspect and distance from the coast) were used to extend the prediction over a greater area. The satellite imagery had a spatial resolution of 1 km, but re-sampling allowed the spatial resolution of the original images to be improved to 250 m × 250 m. The approach proved useful for short range (12 h) predictions of minimum temperature and, thus, frost risk.

3.0 THE TOPOCLIMATE SOUTH DATA SET

The Topoclimate South project was undertaken in Southland, New Zealand, during the period 1998 to 2001 (Topoclimate South, 2000). The study area included 805 000 ha of rural plains and hills. Mountainous areas were excluded because the focus was agriculture, and such areas were perceived to have little agricultural relevance. Air temperatures and, to a lesser extent, soil temperatures were sampled over three, one-year field seasons at about 2550 sites. Air temperatures were recorded at 1.2 m height at 6-minute intervals for one year at each site. Soil temperatures were recorded at selected sites at 20-minute intervals. The result was an unprecedented, world-leading data set consisting of about 223 million temperature values. Detailed soil descriptions were also recorded for the entire study area. The project was community-driven and mandated to produce two map series at a scale of 1: 50 000. One showed long-term mean annual growing degree-days (heat units) for a threshold of 4°C (Hutchinson et al., 2000, 2001). The other showed soil types. Each series involved 36 map sheets roughly A2-A1 in size. For logistical reasons, map contours for both series were drawn 'by hand' using expert knowledge and extensive field reconnaissance, then transferred into *MapInfo* for digitising and printing.

Growing degree-days (GDD) are calculated as the sum of mean daily temperatures above a threshold temperature for a stated period, usually one year or one growing season. It is common to compute annual sums starting in winter, e.g. June, July, or August in New Zealand. Thus, annual growing degree-days are found:

$$\begin{cases} \overline{T} > B, \ GDD = \sum_{i}^{n} \left(\overline{T} - B \right) \\ \overline{T} \le B, \ GDD = 0 \end{cases} \tag{1}$$

where $\overline{T} = \left(\dfrac{T_{Max} + T_{Min}}{2} \right)$, (2)

$\overline{T}$ is daily mean temperature, T_{Max} and T_{Min} are the instantaneous maximum and minimum daily temperature, B is the threshold temperature for a particular crop (all with units °C), and values are summed for days i to n, e.g. 1 July to 30 June.

In the Topoclimate South project, values for daily T_{Min} for the year of measurement were extracted from the 6-minute temperature record. Regression relationships and long-term records at selected climate stations were then used to produce a 30-year record for each of the 2550 sites. Although the original project did not examine the long-term daily T_{Min} data directly, it is now available for detailed analysis. That is, maps of frost occurrence and frost in Southland can potentially be constructed for both a one-year and 30-year period. Work to date, however, is limited to a few exploratory studies using very limited subsets of the data.

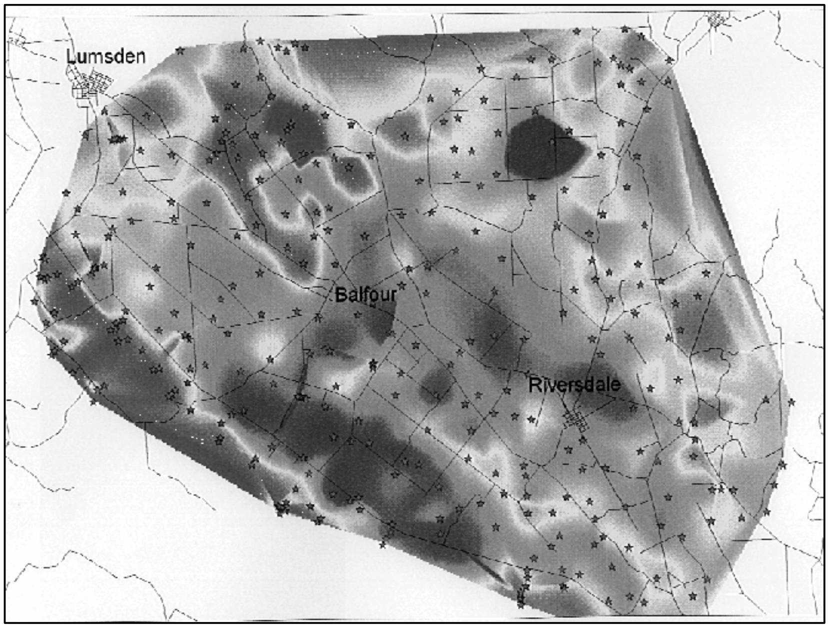

Figure 1: 'Sketch' map for the Lumsden-Riversdale region showing air temperatures measured at 0600 h on 27 November 1998. Values range from -5°C (darkest grey) to 5°C (mid grey ares bounded by narrow, pale bands). Note: original map is in colour. Source: Topoclimate South (1998).

4.0 EXPLORATORY STUDIES

Anatomy of an out-of-season frost: In November 1998 Southland experienced a severe, out-of-season frost which damaged crops, especially wheat. To quickly capture spatial data on this event, Topoclimate South produced a one-off map of the air temperature values measured at 0600 h (Figure 1)(Topoclimate South, 1998). A TIN was used as a crude interpolation device and the resulting 'sketch' map was used to inform stakeholders about the spatial extent of frost damaged areas (Hutchinson, *pers. comm.*, 1998). When the local topography was considered, temperatures were seen to range from about -5°C on the valley floor to about 5°C on hill slopes above the zone inferred to be affected by cold air ponding.

Heriot frosts 1998-1999: The author (Richards, 2001) compiled two simple frost maps for the Heriot region using point data measured by Topoclimate South during the period mid-1998 to mid-1999. The study area (Figure 2) is about 10 km wide and was divided into several terrain units. These were: (1) an enclosed basin to the west (below the dashed 160 m contour), (2) a central series of hills lying north-to-south (up to a spot height of 320 m), (3) a relatively narrow valley immediately to the east of this (flanked by 200 m contours), and (4) a broad 'terrace' sloping up towards the mountains to the east. Given these general zones, spatial correlation appeared to be present between topographic location, number of frosts, and the severity of the extreme frost (Figure 3). That is, sites in the western, enclosed basin tended to have more frosts (up to 100) and a colder extreme frost (to -8ºC). A 'frost hollow' seemed to be also present on the valley floor immediately to the east of the central series of hills. These areas were inferred to be subject to cold air ponding on nights when frost formed. In contrast, some 'mild' sites on the higher portions of the eastern slope had only 20 frosts, and an extreme frost of -2ºC in the year of measurement. The latter feature is termed a 'thermal belt'.

Frosty night near Lumsden: Jones and Richards (2001) report a study to map minimum temperatures for 21 July 1999, for the Lumsden-Riversdale area of the Topoclimate South survey (Figure 4). *Idrisi* and ordinary kriging were used to interpolate data from 212 sites. An isotropy of 135º was defined to account for the association seen between elevation and temperature on the flanks of the Hokonui Hills. Temperatures ranged from -8.3^{o}C on the valley floor to about 0^{o}C on elevated areas. Cross validation indicated that, although variance was low close to the measurement sites, variance around the boundary of the study area was relatively high (up to 2.07).

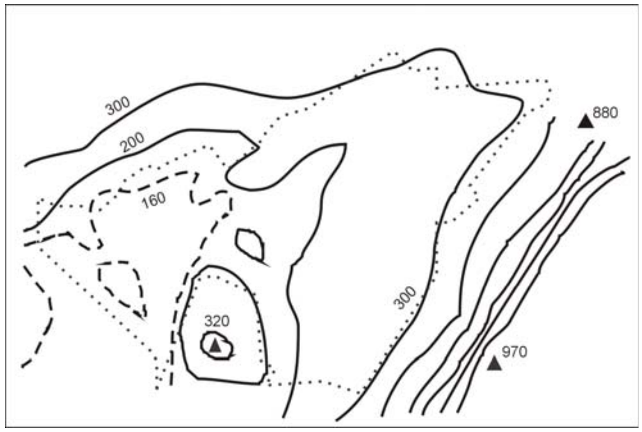

Figure 2: Map of Heriot area showing approximate boundary of study area (dotted line),generalised topographic contours (lines), and peak heights (triangles) in units m above sea level.

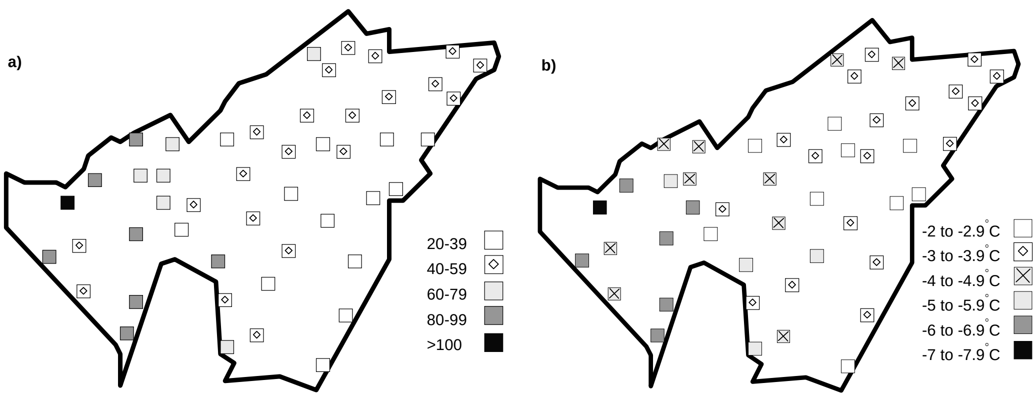

Figure 3: Frost maps for the Heriot region showing a) number of observed frosts and b) most extreme frost (ºC) measured from mid-1998 to mid-1999. Source: Richards (2001).

Heriot Animation: Baumgarten (2003) also selected a frosty night in 1999 for which to map temperatures. In this case, 30-minute temperature data were extracted from the 6-minute data set for the Heriot area (Figure 5). This step reduced the time needed for processing and the size of the data set. Measurements were not necessarily synchronised between sites, so the value closest to the half hour was chosen in each case. *ArcGIS* and kriging was used to create 24 maps of temperature, one for each time step from 1600 h to 0900 h. Colour classes were set manually to maintain a consistent colour ramp between images. A bipolar colour range was chosen, from blue (cold) for negative temperatures, to yellow for 0°C and red (warm) for positive temperatures. The terrain for the area was visualised using a TIN, which was loaded into *ArcScene* to create a 3-dimensional view with hill shading. To visualise the temperature data without masking the underlying terrain, the temperature layer was made transparent. Finally, the resulting images were exported as tifs and animated using a simple *Microsoft PowerPoint* slide show.

5.0 CONCLUSION

The spatial distribution of radiation frosts is closely associated with topographic patterns, and this link makes frost an obvious candidate for topoclimate mapping. There are several potential approaches. Historically, researchers have had to rely on thermometers which were read manually, but electronically-read temperature sensors, GPS and GIS technology is now widely used. Several researchers have modelled cold air drainage and related frost patterns using a DEM, TIN or pixels classed according to terrain shape (e.g. concave or convex). The effects of factors such as surface type, aspect, elevation, latitude and distance to the coast have been

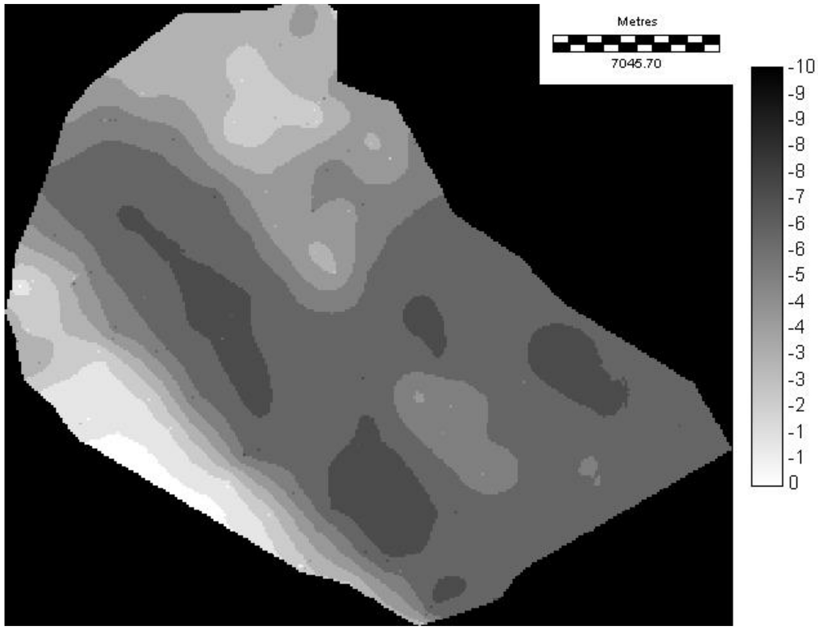

Figure 4: Minimum air temperatures for 21 July 1999, for the Lumsden-Riversdale area. Values range from 0℃ (white) to -8℃ (dark grey). Black denotes margins were excluded from the interpolation. Source: Jones and Richards (2001).

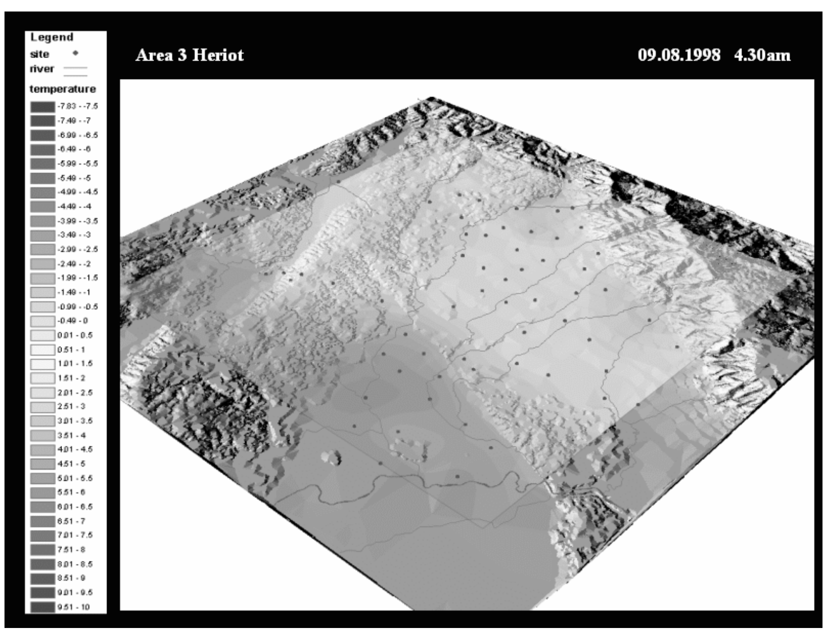

Figure 5. Air temperatures for the Heriot area at 0430 h on 9 August 1998. Measurement sites are shown as black dots. Temperature values range from about 0^oC (pale grey) to -8^oC (dark grey). Note: The original image is in colour. Source: Baumgarten (2003).

investigated. Surface temperature data derived from satellite imagery have also been used to extend frost maps across regions where point data from climate stations are widely-spaced.

For southern New Zealand, the Topoclimate South temperature data set provides an opportunity to map new frost and frost risk information. To date, only a few exploratory studies have been undertaken. These typically involve only a few of the 2550 available sites and/or only a single night. Nevertheless, initial investigations indicate that frost mapping in Southland is likely to be a fruitful and interesting topic of study. Funding has recently been obtained to set up a coherent database to contain the data set (Fitzharris, *pers. comm*., 2002), and this will greatly help future research in this area.

ACKNOWLEDGEMENTS

The authors and editor wish to thank Topoclimate South Trust, the New Zealand Geographical Society and the Spatial Information Research Centre, University of Otago, for the use of the material reproduced in Figures 1, 2 and 3, respectively.

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