ROAD ICE PREDICTION USING GEOMATICS

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ABSTRACT

A GIS based model for the prediction of road surface temperature is presented which has the ability to explain up to 74% of the spatial variation in road surface temperature in the West Midlands, UK. The approach combines basic spatial datasets with GPS based surveying techniques to produce a geographical parameter database which drives the spatial component of a road weather prediction model.

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1. INTRODUCTION

Over the last couple of decades, thermal interpolations between road weather outstations have been made using thermal mapping surveys. By using a vehicle mounted infrared thermometer, nocturnal road surface temperatures (RST) are measured at a set spatial resolution across the road network. The magnitude (amplitude) of temperature variations across an area is dependent on atmospheric stability, but the actual pattern of RST variation (thermal fingerprint) generally remains similar on a nightly basis (Figure 1). Such variations are controlled by the surrounding geography of the site under study. For example, sections of road through urban or forested areas are always the warmest sections of the network, regardless of weather conditions. The impact of various geographical parameters and how they are measured is summarised in Table 1.

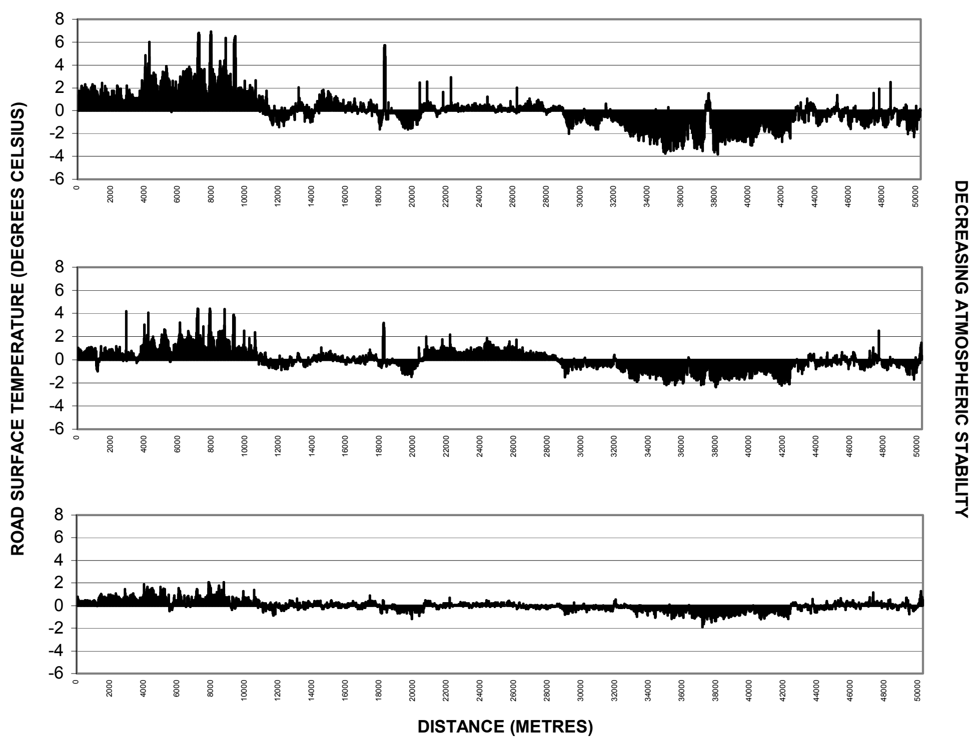

Figure 1: Thermal fingerprints showing the variation in residual road surface temperature for various levels of atmospheric stability.

Table 1 Geographical parameters affecting road surface temperature

Parameter	**Impact upon road surface temperature**	**Measurement technique**
Latitude[1]	Major control upon theoretical maximum incoming short-wave radiation and thus daytime RST.	GPS.
Altitude	Non-linear control on RST (Shao *et al*, 1997). RST decreases with altitude in line with lapse rates and is a dominant parameter during times of low atmospheric stability (Chapman *et al*, 2001)	GPS or Digital Elevation Models.
Topography	During stable conditions, katabatic flow can generate pools of cold air in hollows and valley bottoms. Any decrease in air temperature is linearly related to RST (Gustavsson, 1990)	Commonly estimated empirically (e.g. Bogren & Gustavsson, 1991; Laughlin & Kalma, 1990).
Slope & Aspect[1]	Unfavourable slope and aspect reduce the theoretical maximum of incoming short-wave radiation and thus daytime RST.	Easily derived from digital elevation models.
Sky-View Factor	A dimensionless parameterisation of the amount of visible sky at a location (Chapman *et al*, 2001b). Surface geometry is the dominant parameter controlling surface radiation loss and the sky-view factor enables this geometry to be quantified.	Calculated from fish-eye photographs or proxy techniques (e.g. Chapman *et al*, 2001b, Grimmond *et al* 2001, Chapman & Thornes, 2004)
Screening[1]	Closely related to the sky-view factor, this is a measurement of how canyon geometry prevents short-wave radiation from reaching a surface.	Can be estimated by plotting sun-tracks on fish eye photographs (Chapman *et al*, 2001b).
Landuse	The thermal properties of surfaces will vary with landuse. For example, a city centre will have increased canyon geometry, surface roughness, traffic and anthropogenic heat. The impact of landuse can be quantified by measuring the urban heat island.	Impacts can be estimated empirically. An alternative is to use classified satellite imagery. (e.g. Bradley *et al*, 2001)
Road Construction	Variations exist in the construction materials used and depth of construction across the road network. The 'thermal memory' of a surface is related to such properties (Thornes, 1991).	Site specific quantifications can be obtained by coring. Alternatively, estimates can be provided remotely by the use of ground penetrating radar.
Traffic	Traffic increases RST by additional heat sources, blocking radiative loss and promoting mixing of layers (Thornes, 1991).	Traffic counters can be used and empirical formulae derived on multi-laned roads (Parmenter & Thornes, 1986).

[1.] These parameters influence daytime RST and impact upon night-time temperatures by providing an increased lag effect.

To achieve an adequate sample of different weather types, a series of thermal surveys are conducted for three pre-defined levels of atmospheric stability; *extreme*, *intermediate* and *damped*. These can be roughly classified into the Pasquill Gifford stability classes G, F/E and D respectively (Pasquill & Smith, 1983). To provide a forecast for a particular night, the thermal fingerprint (map) most closely representing the current atmospheric stability is made 'live' by adjusting the values in line with RST forecasted at the outstation.

Thermal surveying techniques have remained largely unchanged over the past 20 years, but they are now starting to date:

- Several surveys are required to adequately cover the different weather types, making thermal maps expensive and time consuming to create.
- It is assumed that the use of three thermal maps adequately covers the range of atmospheric stability and weather conditions experienced over the course of a winter.
- Thermal maps contain no information regarding the temporal thermal behaviour of the road. Such information is advantageous as it enables the time of the onset of freezing conditions to be predicted allowing for optimisation strategies.

These problems can be overcome by modelling rather than just measuring RST spatially.

The recent proliferation of 'commercial off-the-shelf' geomatics technology, in particular Geographical Information Systems (GIS) and Global Positioning Systems (GPS) has enabled massive innovation in winter road maintenance. GIS provides a means of visualising RST variation across the road network as temperature data can now be plotted accurately to within ±5m when using GPS. However, GIS applications are not limited to visualisation. Li & Eglese (1996) used GIS to devise a heuristic algorithm to optimise treatment routes, while Gustavsson *et al* (1998) present a technique to predict likely winter maintenance costs for planned new road stretches. Such studies provide good examples of how the use of new geomatics technologies can greatly facilitate improvements in winter maintenance. This paper outlines how geomatics can be used to unite pre-existing components of road weather prediction systems to provide a high-resolution GIS-based road ice prediction system.

2 GEOGRAPHICAL DATA

Road-weather outstations are strategically located to measure climatic variability in a particular 'climate zone'. Climate zones are simply a classification of a geographical area into a series of regions which experience a similar climate e.g. coastal plains, urban areas, etc. At least one outstation is located per climate zone and the weather recorded is considered representative of the zone as a whole. It can be hypothesised that as the regional climate is constant, any variation in climate and RST across the zone is controlled by the variation in geographical parameters. Therefore, by measuring local variations in geography and modelling the impact on RST, it should be possible to provide an accurate 'virtual' forecast away from the outstation. However, in order to achieve this, it is necessary to have efficient techniques to measure or estimate the geographical variations across the climate zone.

Chapman *et al* (2001a) use a mobile platform to measure the spatial variation in geographical parameters. 3D positional data are obtained from a GPS, ψ_s is calculated from fisheye imagery (Chapman *et al*, 2001b), where as ordinal landuse and road classifications were manually recorded by the driver whilst surveying. Disadvantages of this approach include:

- No scope for identifying the advectional impact of geographical features
- Subjective interpretations of landuse and road classifications.
- Calculation of ψ_s by fish-eye imaging is restricted to homogenous overcast conditions (Chapman *et al*, 2001b). The limited surveying window available compromises the potential of using the surveying technique operationally.
- Unreliability of GPS to provide accurate altitude data. In order to achieve a good 3D positional fix, the trilateration of four or more satellites is required; the visibility of four satellites cannot be guaranteed in heavily urbanised or forested areas.

Overall, the survey method employed provided fast results but was unreliable and subjective. By translating many of the survey tasks into a GIS environment, more objective surveying and hence, modelling can be achieved.

2.1 Spatial Data Sets

The simplest variable to be obtained using a GIS is altitude data. High resolution Digital Elevation Models (DEM) accurate to within ±5m are now freely available to the academic community. In this study *Panorama* data are used, which is a 50m resolution gridded altitude dataset developed by the UK Ordnance Survey. This provides an excellent base layer for the GIS from which other useful spatial datasets can be derived. For example, slope gradient and aspect are important parameters when calculating incoming radiation and these can be easily calculated using standard surface analysis functions. There is also the potential for algorithms to be developed to model the temporal and spatial development of katabatic drainage and cold-air pools (e.g. Laughlan & Kalma, 1991).

Vector road data is also freely available to the academic community at a variety of scales from the UK Ordnance Survey. The spatial data product used in this study was the *Meridian 2* dataset, which contains attribute data on all the public roads in the UK. An algorithm is also run on this product to provide a simple, but effective proxy classification of landuse density. This is achieved by clipping the road network with a delineated urban area polygon (part of the *Meridian 2* product) and running a density analysis to locate dense areas of the road network. As urban areas have a much denser road network then rural areas, this algorithm approximates population density by proxy. A kernel with search radius of 1000m is used and the results classified into five classes with respect to standard deviation.

2.2 Survey Data

In addition to the GIS data described, RST and ψ_s data still need to be collected in the field. Nocturnal RST data is collected using an infrared camera (emissivity set to a constant 0.95) and is used to identify systematic thermal anomalies or singularities which cannot be explained by simple modelling. A typical example would be a bridge, whose shallower construction would reduce the 'thermal memory' of the road (Thornes, 1991). Modelling just using just geographical parameters would not be able to pick up such a feature and hence an undetected cold spot, or thermal singularity, would occur on the network.

The second parameter measured via surveying is ψ_s. Both empirical and numerical modelling of RST has shown this to be the dominant parameter for controlling variations in RST (Chapman *et al*, 2001a). Traditionally, measurements of ψ_s are calculated from fisheye imagery taken during homogenous overcast conditions (Figure 2a: e.g. Grimmond *et al* 2001). The delineation of buildings and trees from sky pixels on fisheye imagery requires the use of a threshold algorithm. If light levels are either too low or too bright, then a single threshold cannot be set for the entire image and ψ_s cannot be calculated. In the past, this has severely restricted ψ_s research, but recently a new all weather proxy technique has been developed which enables large ψ_s datasets to be rapidly assembled. Chapman & Thornes (2004) use a artificial neural network to calculate ψ_s by proxy using raw GPS data (Figure 2b). By measuring the number and quality of incoming signal to noise ratios from satellites in the global GPS network, a real-time approximation of ψ_s can be obtained (typical $R^2 = 0.69$).

a) b)

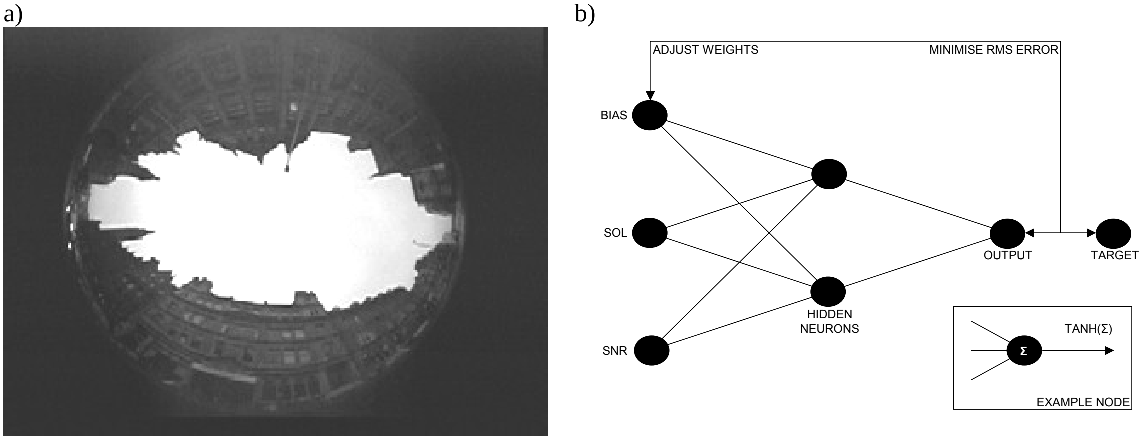

Figure 2 a) Sample fisheye imagery and b) Artificial Neural Network used to calculate the sky-view factor by GPS proxy. SOL is the number of visible satellites used in the position solution where as SNR is the sum of signal to noise ratios of available satellites.

There are two main advantages of using the ψ_s by GPS proxy technique. Firstly, as there are no environmental constraints, real-time ψ_s data can be collected simultaneously with RST data during a thermal mapping survey, thus reducing the total number of surveys required. Secondly, unlike traditional techniques no additional, specialist fisheye imagery apparatus is required. In this study, RST and ψ_s by GPS proxy data is collected and processed in real-time at a one second temporal resolution. Each survey point is stored in a database format file and contains RST data from the infrared thermometer along with 2D positional and ψ_s data from the GPS. Surveys are undertaken prior to sunrise on *extreme* (Class G) nights of high atmospheric stability. This is to ensure that all possible thermal singularities (e.g. katabatic drainage) are identified.

2.3 Spatial processing

The GIS used is ESRI's ArcGIS 8. Macros can be freely written in Microsoft Visual Basic for Applications™ (VBA) to customise the GIS and to perform bespoke tasks. The GPS survey database is converted into a shapefile and loaded into the GIS with the other spatial datasets. The GIS now contains examples of the three common GIS data models ranging from the point data contained in the GPS survey datafile, to vector road data, to the raster DEM. It is now necessary to compress the datasets into one useful geodatabase file which can be read on a site by site loop. This is a achieved by using a series of spatial joins which relate the vector data and identifies the raster data for appending to the point survey file. A schematic diagram of the GIS is shown in Figure 3.

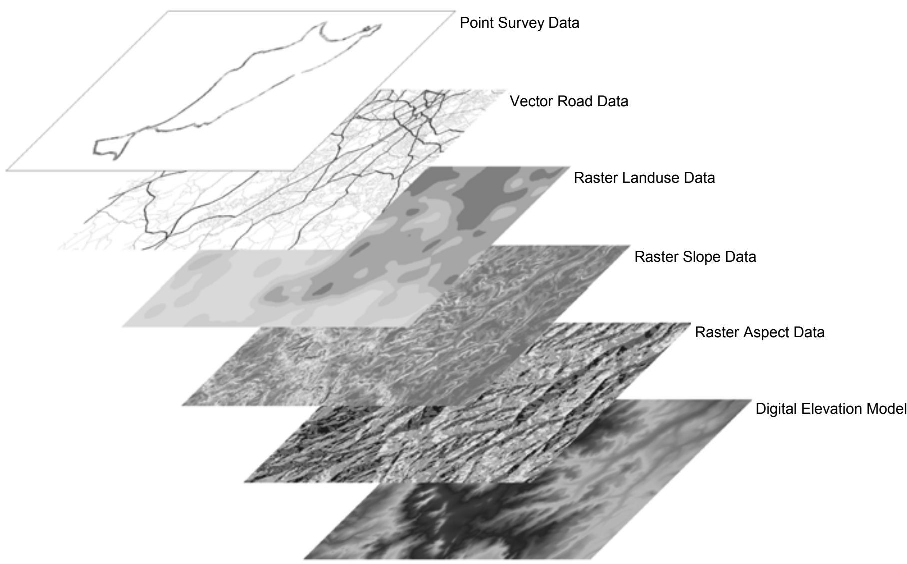

Figure 3 Schematic diagram of layers of geographical data used by the GIS based model.

3 THE GIS MODEL

After the spatial processing is completed, the geodatabase is ready to be used for the forecasting of RST. The model can generally be broken into two distinct parts. Firstly, there is the temporal component which consists of a standard road weather prediction model. This uses forecast meteorological data to produce an RST forecast curve. Secondly, there is a spatial component which uses geographical attribute data to modify the forecast curve on a site-specific basis. In effect, the road weather prediction model is run on a loop to provide a forecast curve for each site in the GIS.

3.1 Temporal Component

The temporal component of the model is based around the Thornes (1984) model and uses a zero-dimensional energy balance approach. RST is forecasted by finding the equilibrium temperature which balances energy flow across a surface. The model uses 3-hourly forecast meteorological data to produce the 24-hour site specific RST forecast curve. A sensitivity test of the model is described in Thornes & Shao (1991) and the temporal forecasting ability of the model is covered in Parmenter & Thornes (1986). Both studies indicated that the model has significant forecasting ability and compares favourably with other road weather models.

3.2 Spatial Component

Chapman *et al* (2001a) added a spatial component to the Thornes (1984) model by replacing the geographical constants with variables. In the original model, latitude, roughness length (landuse), road construction and the ψ_s were all constant. In the revised model, these variables along with altitude and traffic are parameterised. A full explanation and sensitivity analysis of the parameterisations is given in Chapman *et al* (2001a) and will not be discussed here. In this study the model was incorporated directly into the GIS environment by rewriting the original FORTRAN commands as a VBA macro. When the macro is run, it reads in both the meteorological and spatial attribute data and produces a forecast curve for each survey point in the GIS. For example, a point located in the central business district of a major city with low ψ_s will have a substantially warmer forecast curve than that of a high altitude rural site. A major advantage of running the model directly in a GIS environment is that the output data can be displayed as a new 'results' layer. Any point can then be selected in the view and a 24 hour forecast graph displayed (Figure 4).

3.3 Thermal Singularities

One key improvement from the Chapman *et al* (2001a) model is the inclusion of RST training data in the modelling process. The current model, using just geographical parameters, is unable to explain all the variation in RST due to thermal singularities. Bridges provide one example, but areas prone to katabatic drainage and cold air pooling are also problematic. Previously, Chapman *et al* (2001a) differentiated GPS altitude data to locate and classify valley bottoms in a crude attempt to model such features. However, for this model it was decided that the impact of topography and other thermal singularities would be easily considered using actual RST values.

The technique used to incorporate thermal data relies on the assumption that although the amplitude of a thermal fingerprint varies with atmospheric stability, the actual pattern of RST actually varies vary little (Figure 1). A useful classification technique is to calculate the standard deviation of the fingerprint for use as a proxy to atmospheric stability (Shao, 2000). If the standard deviation for a particular night can be determined, then the amplitude of the fingerprint can be adjusted accordingly to provide a reasonable *expected* thermal fingerprint. As the standard deviation (atmospheric stability) for a particular night can be determined from model predictions, by adjusting the amplitude of the training fingerprint to match the standard deviation of the model predictions, a useful comparison can be made between expected and modelled RST. Any sites where modelled RST is ±1ºC different from expected is considered a thermal singularity and the modelled value is substituted by the expected value. Although this step ensures greater forecasting ability, is does compromise the dynamic nature of the approach. Expected temperatures are only estimates of the minimum temperature and therefore cannot be used to provide time-slice information on cooling rates. However, due to the low frequency of thermal singularities, this is not considered to be a major problem.

3.4 Data Dissemination

Although a COTS GIS is a self contained means of displaying model results, it does require the end-user to have the software installed locally. A simpler way of disseminating the data rapidly to the engineer is via the internet. This requires the engineer to have no specialist software (other than a web browser) or indeed, GIS skills. An internet version of the model was realised by recoding the macro in PHP4. The results are displayed using an interactive Java GIS applet (Figure 4a) which displays a map of RST across hourly time-slices throughout the night. Each time slice consists of a series of points which when clicked display the forecast curve for the particular site under investigation (Figure 4b).

a) b)

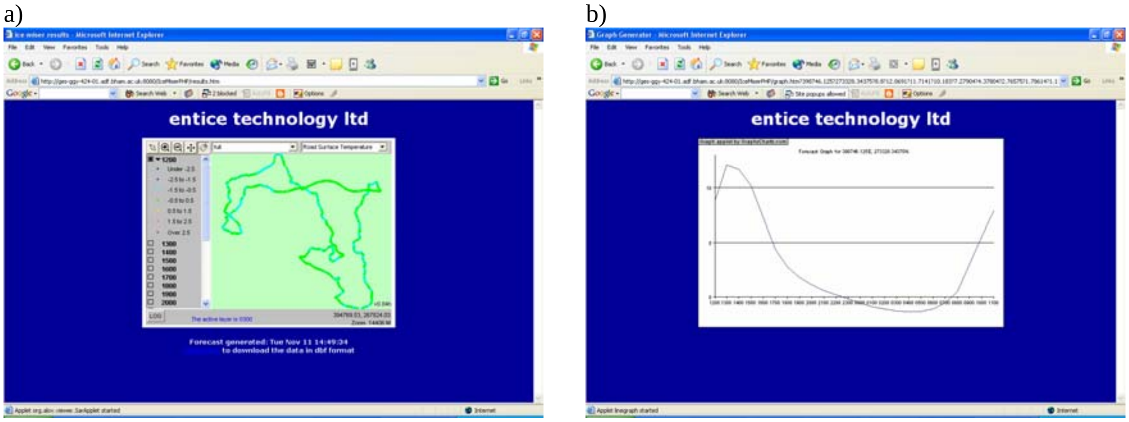

Figure 4 Internet disseminated model output showing a) GIS applet and b) forecast graph.

4 MODEL PERFORMANCE

The model was tested on two survey routes in the West Midlands, UK. One route is predominantly urban and traverses across the Birmingham conurbation where as the second route is more rural and consists of a transect of small towns and villages in Worcestershire. Both routes however, have a large variety of altitude differences, landuse, roadtypes and ψ_s. Firstly, the routes were surveyed to provide the ψ_s and thermal training data to produce the geodatabase. Secondly, a number of additional thermal surveys of the two routes were conducted to validate the model. The urban route was thermally surveyed 24 times and the rural route 14 times over 2 winter seasons (1999-2000 & 2002-2003). Thermal surveys were then spatially joined to the geodatabase for analysis.

The model was run for each of the validation thermal mapping surveys using retrospective meteorological data from the nearby Coleshill weather station. Modelled temperatures were then compared with the actual temperatures measured from thermal surveys to assess the forecasting ability of the model. The overall performance of the model in explaining the variation of RST around the study routes is variable. Up to 73% (average = 62%) of the variation in RST can be explained from model predictions in urban areas compared to up to 58% (average = 46%) in rural areas. The model was on average residually correct to within 1ºC for up to 95.1% (average = 86.5%) of the urban route and up to 94.7% (average = 84.3%) of the rural route. These figures indicate significant forecasting ability and are backed up by average RMS errors of 1.07 and 1.06 for urban and rural areas respectively. The decreased model performance in rural areas can be partially attributed to the limitations of mapping ψ_s by GPS proxy in rural areas. Variations in the transmissivity and crown closure of trees ensure that ψ_s is highly spatially variable, thus reducing the performance of the ψ_s by GPS proxy neural network algorithm (Chapman & Thornes, 2004). Thermal variations on the rural route are also more subtle than in urban areas.

The spatial performance of the model (correlation coefficients) generally improves as atmospheric stability increases, although forecasting accuracy (RMS error) is reduced. Increased spatial performance is to be expected as the model is trained using thermal data collected under stable conditions. However, RMS errors are greater due to the increased amplitude of thermal fingerprints in stable conditions. The percentage of residual RSTs correct to within ±1ºC increases with atmospheric stability as expected in rural areas. However, the opposite is true for urban areas and is hypothesised to be a consequence of the accuracy of the spatial joining technique used. As it is virtually impossible for the same site to be surveyed twice on subsequent surveys, a point may be modelled to be under a bridge when in actuality it is several metres away. The result is a thermal singularity which will become increasingly apparent in stable conditions.

5 CONCLUSIONS

Geomatic techniques have been presented to dynamically forecast RST across an entire climate zone. The use of a GIS enables pre existing spatial datasets to be algorithmically joined to a single GPS based night-time survey of RST and ψ_s. A new GPS proxy technique to calculate ψ_s has been presented which when coupled with the thermal singularity substitution approach, greatly improves both the speed of which models can be assembled and the accuracy of the forecasts obtained. These innovations now facilitate the rapid and low cost assembly of ice prediction models for large geographical areas. The utility of which will be operationally tested in South Gloucestershire, UK over the winter 2003/2004.

Further work is required to add an advective component to the model. Although mesoscale climate models provide a solution to this, they do add significant complexity to what is essentially a simple working environment. Model performance could also be improved at lower atmospheric stability by incorporating other thermal maps into the training process. However, any future improvements to the model need to be undertaken on the understanding that the overall accuracy of the model (as with other road weather models) is still hugely dependent on the accuracy of the meteorological forecast data.

Overall, the use of a 'commercial off the shelf' GIS enables these new technologies to be easily disseminated to the end user. Other winter maintenance tasks could then be translated into the same GIS environment such as GPS fleet monitoring and salting route optimisation. Indeed the proliferation of internet GIS products will make this task even simpler. Easy access to such detailed information will enable the engineer to reduce the high costs of winter road maintenance both financially and environmentally.

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