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An Indirect Method for Predicting Road Surface Temperature in Coastal Areas with Snowy Winters

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EXTENDED ABSTRACT

In places that experience snow and ice, road clearing and deicing operations are a necessity to ensure that road networks remain open and safe for travel. Such operations, however, are costly to both taxpayers and the environment making it all the more important that they are used in an efficient manner. Efficient use of road treatment resources takes experience on the part of the road network manager as well as access to reliable road surface temperature (RST) data which are used to determine when roads are conducive to snow and ice accumulation. On major roads and highways, road surface temperature is primarily obtained via road weather information systems (RWIS), thermal mapping, or a combination of the two methods. RWIS data are collected remotely from roadside weather stations which transmit meteorological readings and RST to a central computer running a predictive model such as HS4Cast (Hertl and Schaffar, 1998) or METRo (Crevier and Delage, 2001). RWIS are, however, limited in their usefulness because they only provide forecasts at their specific point locations. In reality, road surface temperatures can vary as much as 10°C at any given time depending on spatial location due to a number of interacting meteorological and geographical parameters (Shao *et al*., 1996). Thermal mapping was first described in the 1980s as a method to obtain RST in areas between roadside weather stations, thereby incorporating the spatial component of RST prediction (Gustavsson and Bogren, 1988). This method uses an infrared camera attached to a vehicle which travels along a subject route collecting data serving as a thermal "fingerprint" of the road surface that displays spatial variations of RST. When combined with RWIS data for verification, thermal mapping has proven to be an effective and economical method to visualize RST for large road networks (Shao *et al*., 1996).

RWIS and thermal mapping, however, are not universally used and may be impractical for certain areas such as southeastern Massachusetts that are in close proximity to the ocean and have very limited access to in situ road temperature data. This region of New England frequently experiences dramatic horizontal gradients of air temperature within short distances especially along the coast due to the influence of relatively warm ocean winds. This, combined with the unpredictable nature of ocean storms, introduces complexity to models and creates a challenge for road network managers to identify where and when conditions are right for the accumulation of ice and snow on roadways. Roadside weather stations for RWIS exist in this area, but are usually restricted to major state roads and are too few to verify thermal maps. As a result, local jurisdictions are required to decide when to dispatch road crews primarily based on visual interpretations of road conditions, which can be inefficient for large areas. There is much research describing methods to create point specific forecasts of RST on major roads, but little addressing the needs of local road networks without RWIS. Considering this fact, this ongoing project attempts to develop an alternative to thermal mapping and RWIS by indirectly estimating road surface temperature using Geographic Information Systems (GIS) and numerical modeling with metrological and geographical parameters.

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METHODS

The study domain consists of three Massachusetts towns, Duxbury, Pembroke, and Hanson, and a twenty-four kilometer stretch of route MA-14 which intersects the towns. The road was chosen because it runs nearly perpendicular to the coastline, experiences various changes in topography, and travels through a number of different land use types. The area is one that would greatly benefit from having an alternative method for road surface temperature prediction to due to its coastal location and lack of RWIS data.

By statistical analysis techniques, it is known that patterns of road surface temperature across a network are closely tied to patterns of air temperature and solar radiation (Bogren and Gustavsson, 1991). These variables are therefore used as the basis for identifying spatial variation of road surface temperature. Due to the lack of availability of RST data in the study domain, two strategically placed roadside weather stations were deployed within 3 km of each other in two different land use types. Between March 6, 2014 and April 24, 2014 each station collected wind, air temperature, global solar irradiance, and road surface temperature data, and was defined geographically using parameters identified by Chapman *et al*. (2001) including land use and topography. The two stations were also used to verify the model developed, as well as provide insight on the differing conditions of two points within the study domain.

Efforts to identify patterns of the horizontal air temperature gradient were centered on 24 data runs along MA-14. The runs were carried out by affixing a probe to the front bumper of a car which traveled along the study route taking 10 second air temperature samples. This procedure resulted in data records which were used to identify patterns of air temperature change as the coast is approached under varying weather conditions and times of day. Run data were also used to locate points along the route which showed signs of influence from known phenomena such as the heat island effect (Johnson, 1985) and cold air pooling (Whiteman *et al.*, 2001). If consistent patterns were found at certain points along the route, the change of temperature was attributed to the land use type of the location.

A numerical model is being developed using statistical analysis of the results to predict road surface temperature using common meteorological and geographical parameters. ESRI's ArcGIS software was utilized to input spatial information, calculate, and produce output for the model. Considerations were made to ensure that input data are easily accessible to the public using only existing Automatic Weather Stations (AWS) within or nearby the study domain.

RESULTS AND DISCUSSION

Table 1. Summarization of mean station readings between March 6 and April 24, 2014

	Mean daytime irradiance reading (W/m^2)	Mean daytime RST (°C)	Mean nighttime RST (°C)	Mean air temp. (°C)	Mean daily wind speed avg. (m/s)
Station 1	469	13.9	5.1	5.1	0.4
Station 2	92	8.6	3.7	4.7	0.1
Difference 1-2	377	5.3	1.4	0.4	0.3

The greatest differential between the two stations was in irradiance readings followed by daytime RST. Forested areas are known to be places where screening of solar radiation from vegetation plays a significant role in reducing the amount of short-wave radiation which can reach the road surface. (Bogren, 1991). The lower the amount of short-wave radiation that reaches the surface, the lower the RST values will be. At night, with irradiation at zero, the RST gap between the two stations closes and follows the pattern of air temperature closer, but Station 1 still records the highest mean. This phenomenon can best be attributed to the roadway's thermal memory in which it retains its heat through the night (Thornes, 1991). This would make roadways that are not shaded by vegetation less susceptible to freezing in the evening because they have a higher initial temperature. Heavily screened areas, such as the location of Station 2, would have a higher risk of freezing even on nights when most of the road network is too warm to freeze.

The small distance between the two stations showed a minor, but notable difference of air temperature. Considering that the two stations were in areas that are not highly conducive to cold air pooling or the heat island effect, it is assumed that the slightly lower air temperature reading at Station 2 was caused by its closer proximity to the relatively cold ocean. There may be some instrument error introduced here, but considering that the pattern between the two stations matches that of other local stations, proximity to the ocean was determined to be the primary variable of air temperature change over the spatial domain.

Figure 1. A comparison of two distinct patterns of coastal air temperature change.
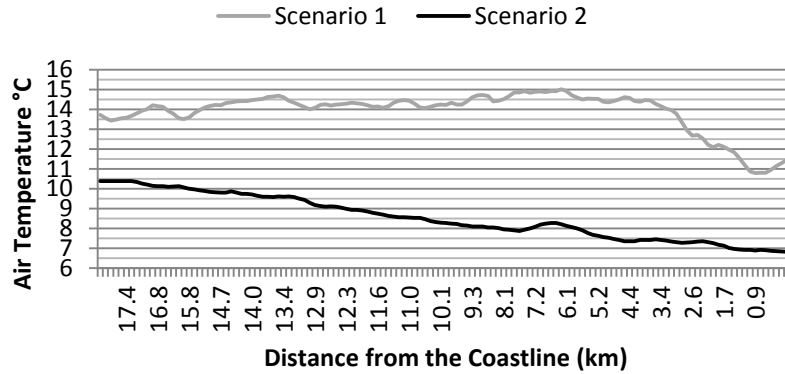
Among the 24 data runs along the study route, a linear rate of air temperature change, as shown in Scenario 2, Figure 1, was seen in 80% of the cases. The remaining 20% displayed a pattern similar to Scenario 1 in which air temperature increased or decreased suddenly at a point approaching the ocean. This feature would be characteristic of a coastal front which frequents the region. There was minimal change in air temperature as the car drove through different land use types except through notable heat islands around 6.5 and 14 km. Air temperatures had a tendency to spike in these areas with the largest deviation from the linear pattern of approximately 1°C. There was no evidence of significant cold air pooling in the runs due to the lack of nights with favorable conditions. The identification of areas along the study route, that are susceptible to cold air pooling, will likely be a topic of future research.

Each run was associated with meteorological data reported from the nearest ocean buoy as well as field measurements to identify patterns in the run. In general, with an ocean wind, greater differences between inland air temperature and ocean air temperature caused a steeper horizontal air temperature gradient. The higher the wind speeds over the ocean, the closer the coastal air temperature was to the temperatures reported from the buoy. Runs that were made with west winds showed the lowest ocean influence overall.

THE MODEL (CRSTM)

The preliminary version of the Coastal Road Surface Temperature Model (CRSTm) follows:

$$T_s = \left(\frac{Q_i S}{50} + 2.979 + 0.686 T_a\right) + \left(\frac{Q_{max}}{40} - l\right) \qquad (1)$$

Air temperature (T_a) is provided by a trusted weather station in, or near, the study domain and may be modified using formula 3 below depending on the influence of the ocean winds. In the absence of location specific irradiance data, calculated clear sky irradiance (Q_i) combined with cloud cover attenuation (S) can substitute. S can be determined using an adaption of the cloud cover attenuation formula described by the Tennessee Valley Authority (1972):

$$S = 1 - 0.65 N^2 \qquad (2)$$

where *S* describes the relationship of clear sky irradiance to clouded sky irradiance and *N* represents the total opaque cloud cover. Total opaque cloud cover is attainable from most airports with AWS and can be considered constant over the entire study domain. The variable (Q_{max}) stands for the theoretical daily maximum of hourly irradiance which can be derived from using either the Ryan–Stolzenbach (1972) or Bras (1990) algorithm. The value corrects for the changing angle of the sun throughout the year and was obtained simply by using a Microsoft Excel program developed by Greg Pelletier of the Washington State Department of Ecology. The land use code (*l*) is a categorical variable which acts as a correction for the different environmental conditions for roads that travel through multiple land use types. Station 1 is categorized as low-density residential and is assigned an *l* code of 19. Station 2 is categorized as forest and has an *l* code of 20.5. The numbers were obtained on a trial and error basis which can be repeated for any land use type.

The following formulas can be used to roughly estimate air temperature at a given distance from the ocean within the study domain using data supplied by local trusted weather stations. It is important to note that this method is a simplification of a complex system and only works when there is a linear air temperature change as the coast is approached.

$$T_a = T_i + e(D_s - D_p)r \tag{3}$$

Inland air temperature (T_i) is obtained from the nearest trusted weather station that is ideally west of the road in question. The shorter the distance from the road to the trusted station, the higher the chances are for an accurate estimate of air temperature. The variable denoted (*e*) is a numerical value between 0 and 1 and was created to specify whether winds are prevailing from the ocean. In the case of the study area, the value would be 1 if winds were blowing from the SE, E, or NE. Other wind directions would be denoted as 0. D_s is the distance of the trusted weather station in kilometers from the coast in the direction of the prevailing winds. D_p represents the distance of the road in km to the coast. The rate of temperature change (*r*) from the coast can be found using:

$$r = \frac{T_c - T_i}{D_s} \tag{4}$$

where T_c is the approximated air temperature at the coast. T_c can be found according to:

$$T_c = T_o - \frac{T_o - T_i}{w} \tag{5}$$

The calculation of T_c requires the collection of data from a nearby ocean buoy. The buoy used to verify the model is approximately 30 km from the coast of the study area. Wind speed is denoted as *w* and is reported from the nearest ocean buoy in m/s. T_o represents the air temperature over the ocean.

APPLICATION OF GIS

The CRSTm requires no spatial information, other than *l,* to produce RST estimates so long as it has access to location specific irradiance and air temperature readings. In practice, these types of data are rarely available at a high enough resolution for road network modeling of RST. GIS is a vital component of the model as it serves as a way to input spatial information and produce a visual output for all areas without in situ data. Applying spatial information to the model comes in the form of modifying clear sky irradiance and air temperature inputs as well as incorporating geographic parameters such as land use (*l*).

Solar Radiation tools in ArcGIS use hemispherical view shed algorithms defined by Rich *et al.*, (1994) to produce high resolution solar radiation maps from digital elevation models. Typically used for determining potential locations for solar panels, the tools provide an output of global solar irradiation in W/m^2 which can be directly applied to the model. To compensate for screening caused by forests or buildings, it is possible to modify the digital elevation model using land use

and building footprint data, which is made available by Massachusetts GIS (Massachusetts Geographic Information Systems). Although it is possible to adjust the solar radiation tools to compensate for cloud cover, the most accurate results seem to come when they are set to produce clear sky values, followed by formula 2. Ocean proximity can be found using the proximity tool, which outputs a distance which can be used in the estimation of air temperature for any given point in the study area using formulas 3, 4, and 5. Calculation of the model can be completed using the built in raster calculator and outputted on a map with overlaid modeled RST.

MODEL VERIFICATION

Figure 2. Model performance under clear and calm conditions for March 8-9, 2014 at Station 2.
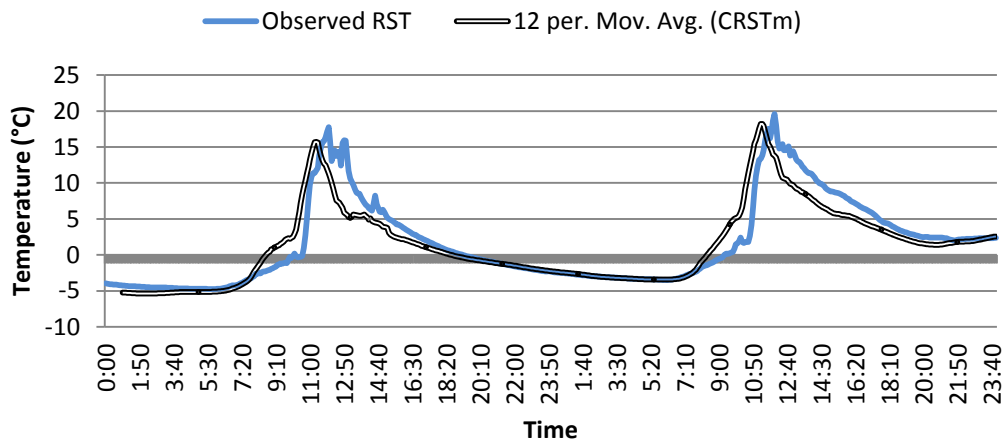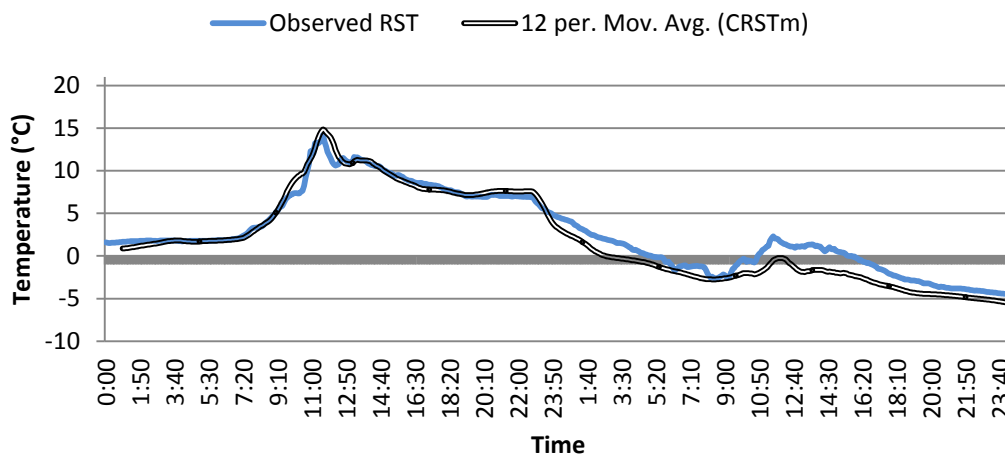

Figure 3. Model performance under overcast and stormy conditions for March 12-13, 2014 at Station 2.

The patterns on the verification graphs were consistent between the two stations. Station 2 verifies the model most accurately with a mean error of 0.63 with a standard deviation of 2.93. The mean error was less for Station 1 at 0.24, but the standard deviation of 4 shows greater variability. The effort is ongoing to resolve the inaccuracies which are greatest in the morning and late afternoon hours on clear and calm days as shown in Figure 2. Errors at these times are likely the result of the differing rate at which roadways and air change temperature. When the sun rises on clear days, air temperature increases rapidly until midday, when it reaches its peak and begins to drop. RST has a very similar pattern, but is delayed temporally. The model output reflects this delay. Overall, the model performs best on overcast and stormy days, such as those seen on March 12 and 13 in Figure 3.

CONCLUSIONS AND FUTURE WORK

At the time of this publication, the CRSTm has the capability of providing reasonably accurate estimates of road surface temperature. There are inherent difficulties of trying to obtain road surface temperature without in situ data because no two locations on the earth's surface are exactly alike. Despite this, the results have shown that it is possible to model RST using meteorlogical data coupled with geographical parameters at a decent level of accuracy. Although the CRSTm is not yet ready for real-world use, there is much confidence that accuracy will improve with further research. Literature review suggests the significance of geographical parameters such as sky-view, screening under differing cloudcover conditions, and road construction, which have an effect on RST (Chapman *et al.*, 2001). These parameters also play a role in the rate at which the road surface increases or decreases in temperature which was determined to be a primary cause of error. There will also be further study to identify factors of the *l* code which is likely a function of meteorological and geographical variables influenced by the land use surrounding the road. It would also be beneficial to identify more *l* codes for different landuse types along the route. This will be accomplished by either relocating the current roadside weather stations or the deployment of small, portable stations througout the study area. A full winter's RST dataset is expected to be completed in April of 2015 and will be used to verify the model throughout the winter under a greater variety of conditions.

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REFERENCES

Massachusetts Department of Transportation. n.d. A 2014 synthesis; the status of intelligent transportation systems deployment. *Massdot*. Retrieved July 31, 2014, <http://www.massdot.state.ma.us/Portals/8/>.

ESRI. 2008. An overview of the Solar Radiation tools. *Esri.com*. Retrieved July 30, 2014, <http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=An_overview_of_the_ solar_Radiation_tools>

Bogren J. 1991. Screening effects on road surface temperature and road slipperiness. *J. Theoretical Appl. Climatol* **43:** 91–99.

Bogren J, and Gustavsson T. 1991. Nocturnal air and road surface temperature variations in complex terrain. *International Journal of Climatology* **11**: 443-455.

Bras RL. 1990. Solar radiation and the earth's energy balance. *Hydrology: an introduction to hydrologic science*: 19-49.

Chapman L, Thornes JE, and Bradley AV. 2001. Modelling of road surface temperature from a geographical parameter database: part 1. *Meteorological Applications* **8**: 409-419.

Crevier L, and Delage Y. 2001. METRo: A new model for road-condition forecasting in Canada. *Journal of Applied Meteorology* **40**: 2026-2037.

Feng T, and Feng S. 2012. A numerical model for predicting road surface temperature in the highway. *Procedia Engineering* **37**: 137-142.

Gustavsson T, and Bogren J. 1988. Thermal mapping by use of infrared technique. *Proceedings of the 4th International Conference on Weather and Road Safety*, Florence, Italy. (as cited in Shao *et al.*, 1996).

Tennessee Valley Authority. 1972. Heat and mass transfer between a water surface and the atmosphere. *Laboratory report no.14; water resources research report no.0-6803*. (as cited in Bras, 1990).

Hertl S, and Schaffar G. 1998. An autonomous approach to road temperature prediction. *Meteorological Applications*, **5**: 227-238.

Johnson DB. 1985. Urban modification of diurnal temperature cycles in Birmingham, UK. *J. Climatol* **5:** 221–225.

Massachusetts Geographic Information Systems. MassGIS Data - Land Use (2005). *Mass.gov*. Retrieved July 30, 2014, <http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/lus2005.html>

Pelletier G. 2013. Models for total maximum daily load studies. *Ecy.wa.gov*. Retrieved July 29, 2014, <http://www.ecy.wa.gov/programs/eap/models.html>

Rich PM, Dubayah R, Hetrick WA, and Saving SC. 1994. Using viewshed models to calculate intercepted solar radiation: applications in ecology. *American Society for Photogrammetry and Remote Sensing Technical Papers*: 524–529.

Ryan PJ, and Stolzenbach KD. 1972. *Environmental Heat Transfer, in Engineering Aspects of Heat Disposal from Power Generation*.

Shao J, Lister PJ, Hart GD, and Pearson HB. 1996. Thermal mapping – reliability and repeatability. *Proceedings of the 6th International Road Weather Conference, Birmingham, April 1996. SIRWEC*: 235–242.

Thornes JE. 1991. Thermal mapping and road-weather information systems for highway engineers. *Highway Meteorology*: 39–67. (as cited in Shao *et al.,* 1997)

Whiteman CD, Zhong S, Shaw WJ, Hubbe JM, Bian X, and Mittelstadt J. 2001. Cold pools in the columbia basin. *Weather and Forecasting* **16**: 432–447.