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USING MODIS LST TO ESTIMATE MINIMUM AIR TEMPERATURES AT NIGHT

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1. INTRODUCTION

Forecasting minimum air temperatures accurately on clear, calm nights is an important service to businesses, agriculture, utility companies and the average citizen. It is most important when frost and freeze warnings are a concern and when power consumption is a crucial matter. Meteorologists must consider all factors that influence minimum air temperature when preparing their forecast.

A meteorologist prepares a minimum temperature forecast based on knowledge of local terrain, climatology, and information from local surface observations. However, heterogeneity of the land surface makes single point surface measurements less representative of the surrounding area. In addition, surface observation stations are irregularly spaced meaning a sparse network of surface stations is less insightful than one that is dense. An estimation of temperature at the resolution of satellite imagery will provide detail to regions void of temperature observations between stations.

High resolution air temperature data may help NWS forecasters better populate their IFPS product. The Interactive Forecast Preparation System (IFPS) is an experimental NWS product that provides an interface for the public to access graphical depictions of current and predicted weather on a gridded environment at 2.5 to 5 km resolution. An IFPS minimum temperature forecast is shown figure 1 with the Huntsville County Warning Area (CWA) counties outlined, displays little variation and detail in temperature. The grid is populated with model data or other information and a Graphical Forecast Editor (GFE) allows the forecaster to edit the grids to reflect local experience and knowledge, providing valuable insight to the forecast. Air temperatures can be modified according to inversion and lapse rate information but currently, there is no tool to adjust temperatures inside the IFPS product based on land use and terrain-types such as valleys and plateaus.

The Huntsville National Weather Service (NWS) forecast office utilizes products from NASA's Global Hydrology and Climate Center (GHCC) to help with weather analyses and to aid in short-term forecasting. This partnership falls under the NASA funded Short-term Prediction Research and Transition (SPoRT) program, the objective of which is to identify and transition unique NASA data and technologies to the NWS in order to improve their short-term weather forecast (Goodman et al., 2004). The development of a minimum temperature estimation technique is just one research application which is being considered for transition.

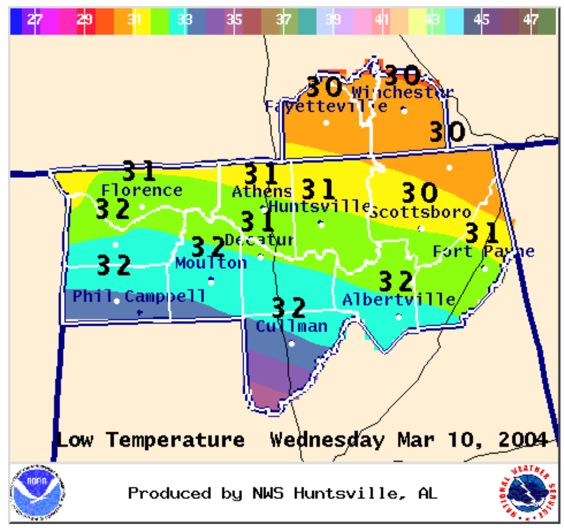

Figure 1. Huntsville NWS IFPS grid of forecasted minimum temperatures in degrees Fahrenheit for March 10, 2004.

2. BACKGROUND

2.1 Nocturnal Radiational Cooling

Long wave (LW) emission on clear nights cools the surface to a temperature below that of the air above it creating a stable temperature inversion up to hundreds of feet deep. Differences in terrain height allow cold, dense surface air to settle under the influence of gravity into the lowest levels in valleys and basins. This flow, referred to as cold air drainage, enhances the inversion in valleys where it is colder relative to the surrounding warm slopes and ridges. The strength of the valley inversion depends on the topography of the valley and the area of cold sources that feed the cold pool (Oke, 1992). The wind maximum is typically near the top of the stable temperature inversion which intersects the hillsides and warms the air from turbulent mixing. Winds at the surface can cause turbulence and mixing with the warmer air above which can weaken the inversion.

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Cloud cover can also weaken the inversion by diminishing the LW radiational cooling.

The most favorable conditions for nocturnal cooling at the surface require clear sky, light to calm winds, low water vapor pressure, and low thermal conductivity and specific heat of the radiating surface. Factors that govern radiational cooling at night can change. A longer night allows for more radiational cooling to take place before sunrise. Time of year can also determine the amplitude of temperature on a diurnal cycle which describes the amount of heat absorbed by the surface during the preceding day. Changes in vegetation cover and growth influence the thermal properties of the surface by the amount of water vapor released into the air through evapotranspiration and by increasing carbon dioxide release (respiration) rates during the growing season. Surface cooling is also dependent on the amount of cloud cover, winds, air moisture and soil moisture.

When LW emission exceeds solar absorption (after sunset) the local Land Surface Temperature (LST) is less than the local air temperature as seen in figure 2. This figure displays a 36 hour cycle of GHCC GOES LST and surface air temperature recorded at the Huntsville automated surface observing system (ASOS) on a calm, clear night. LST and air temperature closely follow each other as they approach minimum temperature. The minimum for both air and surface temperature occurs near sunrise until solar radiation absorption begins to exceed the long-wave radiation loss, and then the temperature rises.

2.2 Satellite-Derived LST

Satellite-derived LST is defined as the radiating temperature of the land surface observed by the satellite sensors. The land surface is vegetation canopy, soil, or any other surface objects. LST can only be retrieved for clear sky conditions from infrared (IR) channels since most clouds are opaque to IR energy emitted from the surface.

The algorithm used for the retrieval of GOES LST is the Split Window Technique (PSW) which has been successfully applied to the GOES-8 imager and GOES-12 sounder (Haines et al., 2001, Suggs et al., 2003). The sounder data provides LST values with a 10km spatial resolution. This technique is an approach based on the perturbation formulation of the radiative transfer equation and it requires first guess profiles of temperature and moisture, which are obtained from model output. Transmittance was calculated from the first guess field. However, the emissivities for GHCC GOES LST were fixed-values (0.98), which is common practice when a priori information is not available.

The Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua platforms is an instrument with 36 channels between 0.62 and 14.385 µm. These 36 channels are divided into 11 channels in the visible range (VIS), 9 in the near-IR range (NIR), 6 in the thermal-IR range (IR), 4 in the shortwave-IR (SWIR) range, and 6 in the longwave-IR range (LWIR). MODIS is a scanning imaging radiometer with a viewing swath width of 2330 km (the field of view sweeps ± 55° across-track).

Earth Observing System (EOS) MODIS LST (MOD11 Level 2 Version 4) was obtained from the NASA Land Processes Distributed Active Archive Center (LP DAAC) and was retrieved with a generalized split window algorithm using bands 31 and 32. This method uses band emissivities estimated from land cover types through look-up tables (Wan and Li, 1997). The EOS values were available for clear-sky conditions at a 99% confidence level defined in the MODIS cloud mask product (MOD35). EOS MODIS LST products have been validated and have an absolute bias of less than one degree Kelvin (Wan et al., 1997).

MODIS high spatial resolution imager (1 km at nadir) allows improved spatial resolution over that of GOES LST (figure 3). Cold valleys and rural areas and warm ridges and water bodies stand out in the MODIS image but are indiscernible in the GOES image. MODIS LST enhances the small scale temperature variations, and thus, it gives clues to the small scale surface features that influence LST and air temperature.

2.3 Previous Estimation of Air Temperature

Both LST and air temperatures vary moderately when the surface layer is stable on a clear night and a regression equation can adequately describe a LST/surface-air temperature relationship (Jin et al., 2000). Jin derived such a relationship for a method to calculate sensible and latent heat fluxes and found that the relationship can estimate air temperature to a first order approximation, and that this depends on surface vegetation cover, topographical properties, soil moisture and atmospheric conditions. Currently, no method or boundary layer theory can adequately describe this relationship although some well accepted relationships, such as surface-air temperature is warmer than skin temperature at night, may be used as constraining guidelines (Jin et al., 2000).

3. THEORY AND DATA

LST is highly correlated with air temperature although this can differ with atmospheric, seasonal and geographical changes. This study uses EOS MODIS and GHCC GOES-derived LST to understand regional temperature dependency and variability on calm, clear nights. The high temporal resolution (hourly) GOES LST product, produced at the GHCC (Haines et al., 2001, Suggs et al, 2000), was used to determine the relationship between the diurnal cycles of LST and surface air temperature. The MODIS LST (Wan and Li, 1997) provided improved spatial resolution (1 km) over the GOES-12 product (10 km). Linear regression equations for specific terrain types were used to estimate the corresponding minimum air temperature from the high resolution MODIS LST (1km) in order to depict the local structure of minimum air temperature on calm, clear nights and possibly apply this knowledge to guide forecasts.

Data from five nights from the spring and fall of

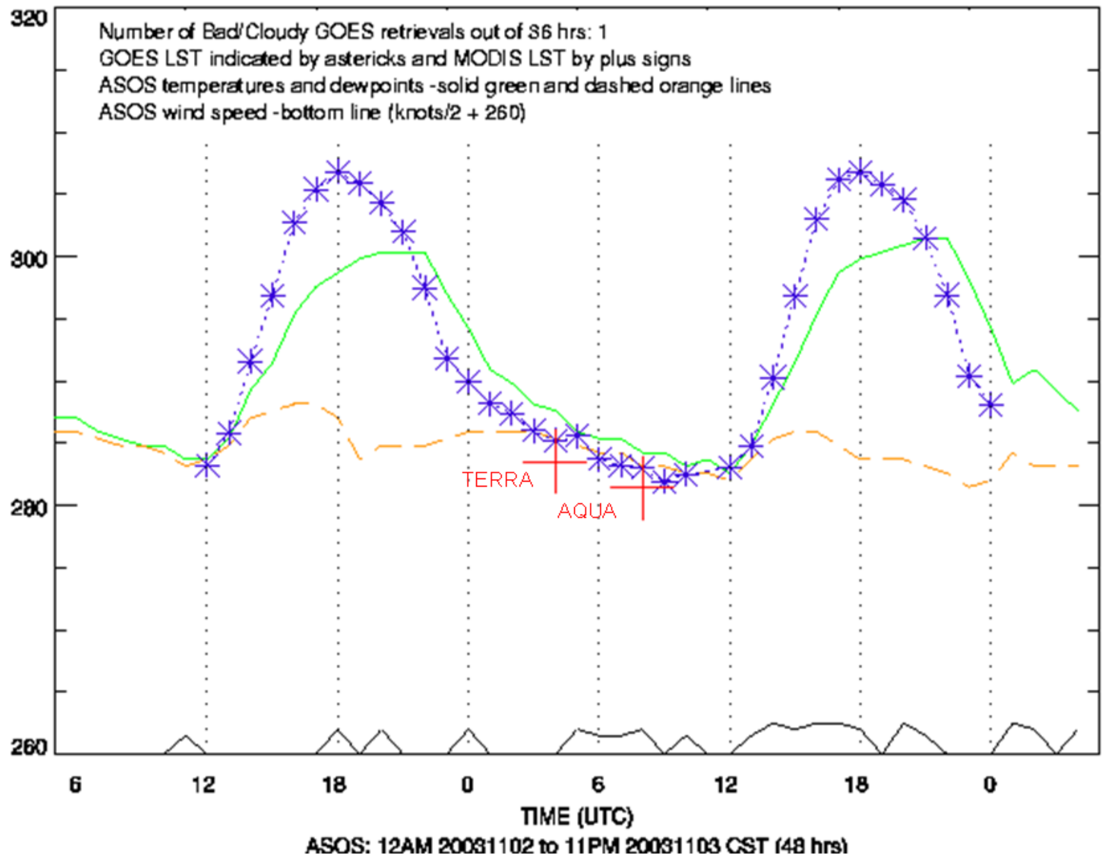

Figure 2. Time Series plot (36 hour period) of ASOS recorded air temperature and dew point temperature (in degrees Kelvin) at Huntsville and corresponding GHCC GOES-derived LST on a clear, calm night, November 03, 2003. MODIS LST values from Terra and Aqua are also shown.

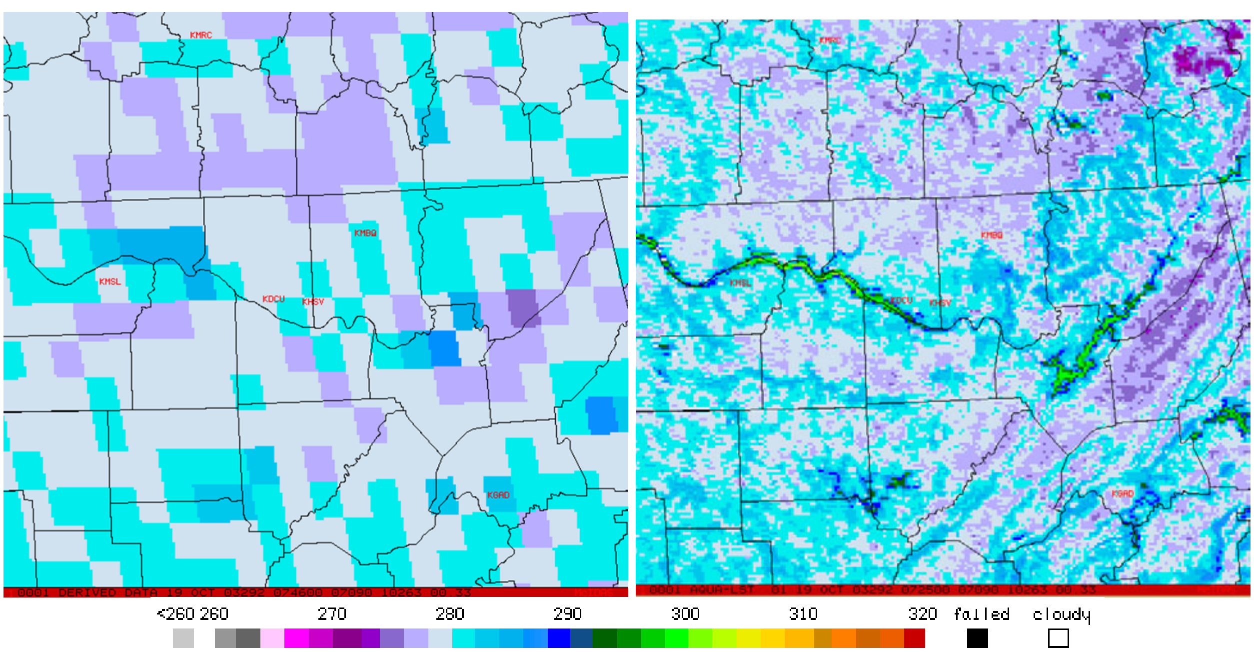

Figure 3. Nighttime LST, in degrees Kelvin, centered on Huntsville, AL on October 19, 2003 from GOES-12 Sounder at 07:46 UTC (left) and Aqua MODIS at 07:25 UTC (right). The high resolution (1 km) MODIS product shows more temperature detail related to the variability in land surface cover and topography.

2003 were used to study the variability of nighttime LST and minimum air temperature in northern Alabama. The nights had similar surface weather conditions of light to calm winds and the sky was clear throughout the night. These conditions reduced the effects of winds and turbulence on surface air temperature, and the absence of cloud cover allowed for abundant LW cooling. Nights were limited to MODIS passes with an appropriate low scan angle over the area of interest to maintain LST accuracy. Only nighttime MODIS LST on the Aqua satellite were used since this overpass time (1:30 am local time) is the closest representation of minimum surface temperatures overnight. The time of the Terra overpass (10:30 pm local time) was too early in the night because the stable, nocturnal temperature inversion may not yet be present and high heat capacity surfaces may still be too warm. Thus, at the time of the Aqua satellite pass the surface layer was in a radiative equilibrium state much like the surface layer at the time of minimum temperature. The assumption was made that the atmospheric state was constant from the time of the Aqua overpass until the time of observed minimum temperature near morning. It was also assumed that the soil moisture was fairly consistent over the region for each night.

4. METHODOLOGY AND RESULTS

4.1 Spatial Variation of MODIS LST

The CWA for Huntsville NWS, seen outlined in figure 1, is situated south of Nashville, Tennessee and north of Birmingham, Alabama in the Tennessee River Valley. The southernmost extremities of the Cumberland Plateau nose into Northeast Alabama and numerous ridges and valleys lie southwest to northeast in the eastern portion of the CWA. Ridges are typically forested while plateaus and valleys are pasture or developed land. The southern part of the CWA is similar, except plateaus and hills are at a lower elevation. The topography to the west and north of Huntsville is flat with rolling hillsides comprised of row crop and pasture land with scattered forested areas. The inhomogeneous surface topography and land cover influences the response of the surface to the energy and mass exchanges. Therefore, the LST variability in the CWA is considerable.

To understand how and why LST varies with land cover and terrain type, LST was compared to elevation for four terrain types and three land cover types. National Land Cover Dataset (NLCD) land type classes were grouped into open fields, forests, and residential land. NLCD was compiled from LANDSAT TM imagery and supplemented by various ancillary data with a spatial resolution of thirty meters. The National Elevation Dataset (NED), assembled by the U.S. Geological Survey (USGS), also has a resolution of approximately thirty meters.

Figure 4 shows a comparison of (NED) to MODIS LST which illustrates the spatial temperature change with terrain. The peaks and slope of the ridges and bluff are above the cold nocturnal inversion. Cold air tends to drain into the surrounding valleys, creating a temperature contrast. In general, LST was colder in valleys, elevated plateaus and rural fields, and warmer on forested slopes and ridges.

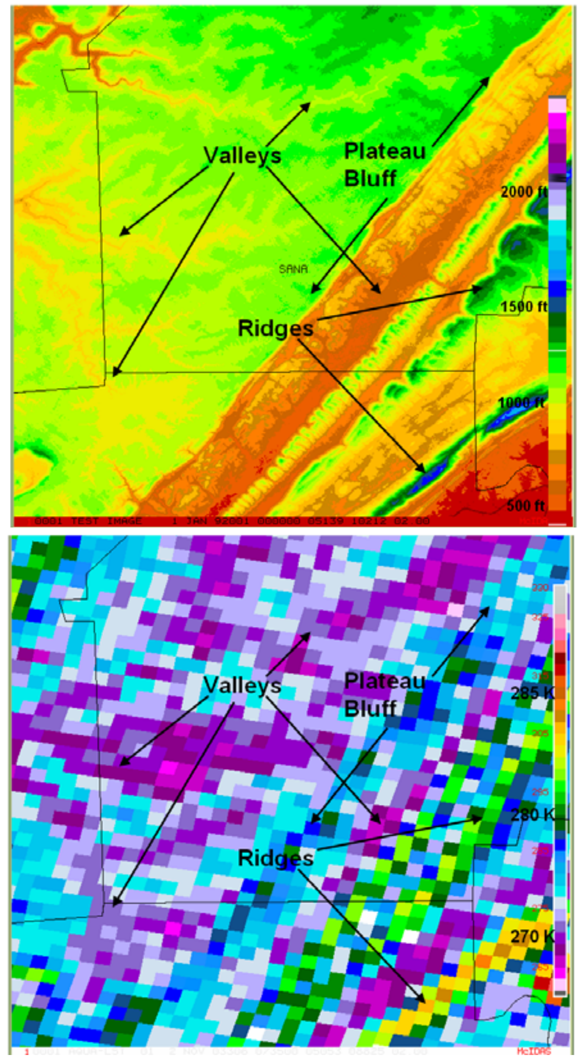

Figure 4. Elevation (top) and MODIS Aqua LST on November 02, 2003 (bottom). Cold LST values correspond to the valleys and warm LSTs are seen on the bluff and ridges. Scale of view of area (30 x 30) km.

An algorithm using the elevation dataset (NED) determined the four terrain types as plateaus, valleys, low-elevation flat terrain, and hillsides and ridges based on elevation change with distance. For each night, LST was compared to elevation for each land cover and terrain type. LST was observed to be more a function of elevation and terrain-type than land cover type on clear, calm nights. LST had a high positive correlation on sloped terrain, with all three land covers, because of the increase in temperature with height in the inversion layer. Also, higher elevated slopes and ridges were above the stable inversion and possibly experienced mixing winds. This range of LST on sloped terrain was greatest on colder nights because of a larger temperature difference between valleys below and the surrounding higher elevations. Flat terrain had little or no correlation for all three land covers. Differences between open field and forest land cover for the same terrain type were generally small (less than 1 degree K) with the largest difference less than 2 degrees K. Valley temperatures were coldest where the slopes were steep and the land was open field. Plateau regions were mostly open fields with small intermittent patches of trees, thus they radiate more effectively, and were cooler.

4.2 Air Temperature Estimation from MODIS LST

The Aqua MODIS LST product was compared to the corresponding minimum surface air temperature which is usually at a later time than the local Aqua satellite overpass. Surface observations of air temperature were from ASOS, cooperative (COOP) observers, and mesonet stations including AWIS, SCAN-USDA, APRSWXNET, and others. A linear regression equation was derived using the two temperatures. Since these relationships vary with different land types and topography, separate linear regression equations were determined for three terrain types on each case study day. Varying land use covers were not considered since most stations are in open field areas. The linear regression equations for each terrain type were then applied to the corresponding LST pixels, yielding an estimation of air temperature at 1 km resolution for that night. Estimated air temperature was then compared to actual surface observations of minimum air temperature that were excluded from the derivation of the linear relationships.

A comparison of the estimated minimum air temperature from MODIS LST to the actual observed minimum temperature was performed at six cooperative observer stations and at twelve evenly spaced, 0.5 degree, latitude and longitude points (eighteen total points) over the Huntsville NWS CWA. Minimum temperatures at the grid points were interpolated from the above six COOP station observations and an additional thirty minimum temperature station reports. The performance of a 40 km ETA 24-hour forecast from 12 UTC the previous day was also compared at these eighteen points. The ETA model was used for comparison as an example of what a forecaster may use to guide his/her forecast. For now, this temperature-estimation method is not a forecast but only an estimate based on observations.

Table 1 lists the results from comparing the air temperature estimation method and the ETA model forecast to the station observed and grid analysis of minimums temperatures. Table 2 lists the mean and standard deviation (SD) of each set of temperatures. The linear temperature estimation method performed well with the largest root mean square error (RMSE) and bias of 0.74 K and 0.17 K, respectively. The estimated air temperature had an overall average correlation (COR) of 0.71, indicating that the spatial variation in estimated temperature agreed well with the spatial variation in observed minimum temperature. The ETA model's largest RMSE and bias was 1.20 K and 0.28 K, respectively. The ETA model however, had a low correlation to the observed minimum air temperature with its highest correlation as -0.31. Low correlations indicate that the spatial variations of air temperature in the ETA model do not agree well with the actual spatial air temperature pattern. The ETA model under determined the variation of air temperature mostly in the smaller scale terrain features.

		Estimated Temperature			**ETA 24-hr forecast**		
Date	**OVERPASS TIME (UTC)**	**COR**	**BIAS (K)**	**RMSE (K)**	**COR**	**BIAS (K)**	**RMSE (K)**
20030312	7:55	0.57	0.17	0.74	-0.14	0.15	0.62
20030412	7:55	0.81	-0.06	0.25	-0.31	0.28	1.20
20031019	7:25	0.76	0.04	0.15	-0.01	0.18	0.76
20031102	7:35	0.76	0.09	0.36	-0.02	0.00	0.01
20031120	7:25	0.63	-0.06	0.27	0.18	0.08	0.34

Table 1. Results from estimated air temperature from MODIS LST and ETA model forecast compared to surface observed minimum temperatures at the twelve grid points and six COOP stations.

		Observed Temperature		**Estimated Temperature**		**ETA 24-hr forecast**	
DATE	**OVERPASS TIME (UTC)**	**MEAN (K)**	**SD (K)**	**MEAN (K)**	**SD (K)**	**MEAN (K)**	**SD (K)**
20030312	7:55	276.81	1.39	276.43	2.45	279.22	1.27
20030413	7:55	278.70	2.09	278.43	3.47	282.52	0.94
20031019	7:25	278.29	1.37	278.60	2.12	280.33	1.47
20031102	7:35	281.91	1.74	281.63	3.06	282.29	0.64
20031120	7:25	276.00	1.22	275.72	1.77	276.73	0.97

Table 2. Comparison of mean and standard deviation for surface observed minimum temperatures, estimated air temperature from MODIS LST, and ETA model at the twelve grid points and six COOP stations.

5. DISCUSSION

The estimation of air temperature from AQUA LST was closer to observed air temperatures than the 40 km ETA model. This implies that a forecast based on the 40 km ETA model would reveal little about the small scale temperature variations in northern Alabama under these conditions. The temperature estimation and results are presented as useful information to assist a forecaster but not as a forecast product. The method is highly dependent on the accuracy of MODIS LST and is limited to spatial temperature variations that are equal or greater than the resolution of the MODIS pixel. This methodology is only a first order approximation and works best for nights described as clear to partly cloudy, with little to no temperature advection and not for any night where the temperature changes considerably with respect to clouds and wind.

Since the evenly spaced grid points do not correspond to a surface observing location, validation of minimum air temperature at the grid point locations is subject to the accuracy of the contoured analysis of the minimum temperature observations. The validation of minimum air temperature at surface observation locations is more accurate than the contoured values at the grid points, yet both are considered to be ground truth minimum air temperatures. Spatial variations in soil moisture can influence the variation of land surface temperature whereas more moist soil has a higher heat capacity than drier soil.

6. FUTURE WORK

Improvements are needed for this work to be applied as a forecast tool on any given night when the sky is clear and winds are calm. It is necessary to consider all factors that affect the radiational cooling and account for them in the process. More input may be needed such as temperature and moisture profiles in the lower boundary layer, surface moisture, and forecasted minimum air temperatures at specific locations.

7. AKNOWLEDGEMENTS

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