FROST FORECASTING USING THE SERVIR WIRELESS SENSOR NETWORK FOR HUNTSVILLE ALABAMA

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I. Introduction

The SERVIR Africa Hub and RCMRD were approached in 2013 by various Kenyan authorities looking for a solution to a particularly difficult agricultural problem- frost. The Tea Research Foundation of Kenya (TRFK), the Kenyan Meteorological Service (KMS), and the insurance giant AON are all interested in how SERVIR Africa can enhance the ability to predict frost occurrences. Of particular sensitivity is the tea crop of Kenya, specifically in the Kericho area, where TRFK is located. For Kenya, tea makes up a large part of its agricultural exports, which account for a large percentage of its annual GDP. Particularly bad frosts have been difficult to forecast in the past in these highland areas, and have severely damaged the tea crops. If a tea plant is not damaged badly, it may recover but the delicate top shoots are lost and there will be a long delay in the production of the next good tea crop. However, if a tea plant is severely damaged, it may never recover. Therefore, the prediction of light, moderate, and severe frosts is of particular interest to Kenyan farmers, researchers, weather forecasters, and the crop insurance industry.

In mid-2013, SERVIR Africa began using MODIS satellite-retrieved Land Surface Temperature (LST) to gain estimates of the overnight surface temperatures for the East African domain that KMS uses in its forecasting methodologies. The MODIS LSTs at 1km resolution are mapped to the domain and show bands of colors for the estimation of frost likelihood. While these bands have proven useful, feedback from users of the maps has indicated that SERVIR's maps are picking up the more moderate frosts but missing the light frosts. This indicates that there is a "warm-bias" in the current estimation of frost conditions. In-situ observations are needed to "narrow" the temperature thresholds for the likelihood of frost events. Observations on the ground that could compare the MODIS LSTs to the observed temperatures could help improve this method of marking the frost potential, and also could be used for taking satellite data and ingesting it into numerical forecasting models. Additionally, frost requires additional surface variables to be observed to produce an accurate forecast, which in-situ measurements can provide.

SERVIR Africa and RCMRD have partnered with USRA to deploy the Wireless Sensor Network (WSN) to take such observations at a test site in the Tea Fields of Kericho. Although the WSN has many potential applications and has been used elsewhere before for other purposes, in Kericho it has sensors that measure temperature (°C), humidity (%), rainfall (mm), and wind speed (mph). These sensors are placed up to 1km apart in a network configuration on a hill in the middle of the tea crop. They feed back data for these variables every 15 minutes during the day and every 5 minutes overnight. This technology is repeated at RCMRD where a duplicate installation of the WSN is being used for training and regional capacity building. In

Huntsville, AL, where the WSN was developed and tested, these same sensors have been recording data intermittently since September 2013. WSN data for Huntsville is accessible at: http://3.0websitedesigns.com/wsnfrost/SensorGraph.aspx

The following is a methodology for the warning of frost likelihood of occurrence.

II. Assumptions and Caveats

a. Radiative Frosts

A frost forecast cannot be definitively made with certainty using temperature data alone, but the MODIS LST data is high-resolution and can be very valuable when combined with in-situ observations, such as those from the WSN. Particular variables must be observed by an automated network of sensors spread over the parcel of land to be forecasted for frost likelihood, including temperature, humidity, and wind speed.

It is also important to draw the distinction that there are two main classes of frosts; advective and radiative. Advective frosts occur more frequently in the mid-latitudes and in sub-tropical areas subject to the sudden influx of cold air (such as with the passage of a strong mid-latitude cold front). Advective frosts are typically characterized by cloudy, windy days into nights where the temperature drops steadily through the night and falls below freezing and may well stay below freezing. While these frosts can be just as damaging to crops as radiative frosts, they can be more easily predicted and also do not tend to occur in equatorial regions such as Kenya with much frequency. In equatorial regions and at high altitudes such as are found in the Kenyan and Ethiopian highlands, crops are occasionally vulnerable to radiative frosts. Radiative frosts are characterized by clear or nearly cloud-free nights with calm or nearly calm winds, and are typically preceded by warm sunny days and the temperature falls sharply and humidity rises in the few hours after sunset. For the purposes of this study, and given that no historical data for Kericho has yet been obtained and no observations from the WSN have yet been recorded for a frost night (as of Feb 14, 2014), we will assume that the main class of frost that Kericho experiences crop loss from are radiative frosts.

Huntsville, AL receives both radiative and advective frosts. The methodology and accompanying code and data for this study remove advective frosts and only attempt to study radiative frosts at the Huntsville, AL location for the WSN. It is important to note that the following algorithm and assumptions must be revisited, revalidated, and amended for other locations, such as Kericho, Kenya before they may be responsibly used. Calibration against a minimum of 20 historical frost events would be ideal, but also using the in-situ observations from the WSN for a captured frost event would be the optimal method of calibration. Only WSN data for Huntsville is used in this study, unless it is compared to US National Weather Service data for sky conditions for comparison.

b. Assumptions used for this code and its validation:

Assumption 1: WSN is accurately sensing wind speed, temperature, and humidity. Anytime observations are not within normal bounds or fail to quality check, they are rejected. Temperature values must be within the range of +40°C and -18°C. Humidity values must be within the range of 0% to 100%. Wind speeds must be greater than or equal to 0 mph and must be less than 70 mph.

Assumption 2: CASE STUDIES: Only radiative frost cases in Huntsville are used for the validation of this algorithm. Advective Frosts were observed by the WSN on Nov 13, Nov 24, possibly Nov 27 (no verification). Radiative frosts observed by the WSN occurred on Oct 26, Nov 8, Nov 14 (unverified, so not used), briefly on Nov 20, and Feb 14. Only those with verified observations are used in the calculation of the algorithm. The fact that only 4 cases of Radiative Frost were captured by the WSN to augment research findings in the literature review indicates that we must be cautious with the application of these results and that applying these methods to other regions would really, typically require historical data analysis but optimally also include a case study history from once the WSN is deployed to the area and successfully captures several radiative frosts.

Assumption 3: Only nodes that were properly reporting data at the time (quality checked) are used in the validation. There must be temperature, humidity, and wind speed data reporting or the calculation will not be made.

Assumption 4: Averaging temperature, humidity, and wind speed values over the current and past one time step can help ameliorate effects of temporary fluctuations in observations between sensors over time.

Assumption 5: Averaging the temperature and humidity from all observing sensors with quality-checked data will provide an accurate picture of the overall parcel of land within the observing network. However, this may tend to negate the impacts of terrain slope effects and cold air drainage can be a significant problem for frost forecasting. Areas within the WSN sensor array that are in low-lying areas prone to fog may frost before and worse than other nearby areas within the observations and would tend to make those frost-prone areas appear less severely impacted. If over several real case validations this is proven to be happening, then revisions to this algorithm and farming techniques for cold-air drainage mitigation should be considered.

Assumption 6: These calculations are valid for the Huntsville, AL pressure and elevation above sea level (approx. 650 ft.). Significant adjustment must be made for the elevation of Kericho, Kenya (7,165 ft.) if this technique is to be employed there. Barometric pressure may be estimated as a function of elevation, from which the saturation vapor pressure may be adjusted, as discussed below.

Assumption 7: Sunset times used are local. The ones in the code are for Huntsville, AL in the “frost season” from September 1 through March 31 is NON-leap years, such as 2013-2015. Daylight savings time is accounted for. Adjustments to these values MUST be made for other locations. A MATLAB code that reads in the .csv file produced by the WSN transforms the observational data’s timestamps into local time for use with this code. This is also accomplished in a separate tab of the Excel spreadsheet.

Assumption 8: In step with the current operations, this FORTRAN or MATLAB code in current form should be run between the hours of 2am and 9am locally, but preferably coincident with the receipt of MODIS LST data, around 3am. The Excel can be run anytime.

c. Assumptions used in the calculation of dewpoint temperature from WSN-obtained humidity measurement:

Dewpoint: The temperature to which an air parcel at initial temperature T and pressure P must be cooled isobarically to become saturated.

$$\frac{de_s}{dT} = \frac{L*e_s}{R_w*T^2}$$

T is in Kelvin,
Rw = 461.5 J/K/kg, this is the gas constant for water vapor
L=enthalpy of vaporization

L(at T=273.15)=2.501x10^6 J/kg
L(at T=373.15)=2.257x10^6 J/kg

So then we may express dewpoint as:

$$T_d = T\left[1 - \frac{T*\ln\left(\frac{RH}{100}\right)}{\frac{L}{R_w}}\right]^{-1} \qquad (1)$$

An alternate way to express the relationship between Td and RH that becomes nearly linear for values of RH>50%, and which is useful for our calculations (because frost formation needs nearly saturated or saturated air) is:

$$RH = 100 * exp\left[-\frac{L}{R_w*T*T_d}(T - T_d)\right] \qquad (2)$$

when exp satisfies the condition $\frac{L(T-T_{d)}}{R_w*T*T_d} \ll 1$

Through a Taylor expansion and disregarding the 2nd order and higher terms:

$$RH \cong 100 * \left[1 - \frac{L}{R_w*T*T_d}(T - T_d)\right] \qquad (3)$$

Now express this with the Dewpoint Depression in °C

$$RH \cong 100 - \beta_1(t - t_d) \qquad (4)$$

where $\beta_1 = \frac{100*L}{R_w*T*T_d}$

T and Td vary only about 10% in our temperature regime of (26°F - 80°F) or 270-300 Kelvin (for MODIS-retrieved values of temperature), so β1 is nearly constant, and so we have a nearly linear relationship between RH and (t-td).

If we assume Td≅T, which is an assumption of near saturation valid for when we have frost occurring, and we assume RH>50%, then $\beta_1 \approx 6.0$ for T≅300 K, and $\beta_1 \approx 7.4$ for T≅270 K which is just under the freezing temperature for water.

Our assumption of near saturation also allows us to assume $\frac{L*(T-T_d)}{R_w*T*T_d} \ll 1$

So for typical mid-range values of T=285 K for example, this assumption reduces to ≈0.07(T-Td)<<1, holding for T-Td ≤ 3 K, which is about 1/3 of the overall quasi-linear range. This extends up to a dewpoint depression of 10 K (10°C or 18°F). This means that as long as our dewpoint depression calculations are close to 10*C, then this relationship holds.

So using $$RH \cong 100 - \beta_1(t - t_d) \qquad (4)$$

$$where\ \beta_1 = \left.\frac{100*L}{R_w*T*T_d}\right\} \cong 7.4\ at\ freezing$$

Then solve for td: $$RH - 100 \cong 7.4t - 7.4t_d \qquad (5)$$

$$t_d = \frac{RH-100}{7.4} - t \qquad (6)$$

where t and t_d are in °C

III. Algorithm Methodology

Given the above assumptions, the algorithm contained in the accompanying Excel spreadsheet and documented in the FORTRAN-style program can be broken down into the following steps:

1- Read in the WSN .csv file and separate out the variables. In Excel, highlight in Dark Blue when Frost was observed by a human observer. In both, convert the UTC timestamp to local time. Then the algorithm calculates the Julian Day. Since the WSN reports down to seconds, and Excel has limitations for conversion on anything less than minutes, the time is converted to minutes and then the Julian Day is calculated.

2- Calculate the local Sunset Time for Huntsville, AL during frost season and account for Daylight Savings Time changes. In the Excel spreadsheet, this is done on a separate tab and then imported based on calculated Julian day from the date and time reported by the WSN. In the FORTRAN program, if the Julian day falls outside of the September 1 – March 31 range, then sunset time is returned as a missing data value, the program tells the user that it is not frost season, and the program ends. In Excel, the sunset time and the absolute value of the current time's distance from Sunset time is also calculated.

3- Check which nodes in the network (code currently based on 3 in Huntsville) are sending active data and quality check their values for Temperature, Humidity, and Wind Speed as stated above in assumptions. Reject any data failing the test.

4- Calculate the number of nodes with good data for Temperature and Humidity at the current time step for assignment to the denominator of the averaging function. Then average the values for Temperature and Humidity across those nodes reporting good data.

5- Average the values for Temperature, Humidity, and Wind Speed over two time steps to minimize the influence of sudden fluctuations in data.

6- Based on the Julian Day, sunset time was determined earlier. This section of the code searches back in the WSN data to find the Temperature at the sunset time and also the Temperature two hours after sunset. Again, this is location-dependent and is currently specified for Huntsville, AL local time. The code then calculates the change in Temperature for the two hours following sunset. If it is greater than a specified threshold, then frost formation is more likely and it warns the user.

7- Check that the wind speed is low enough to support radiative frost formation. This is calculated using a specified threshold. Specifies if winds are sufficient for “LOW,” “MEDIUM,” or “HIGH” risk of frost formation.

8- This section of the algorithm computes the dewpoint from the humidity given the assumptions previously stated for this conversion equation. At this time, MODIS LST (must convert from Kelvin to °Celsius to use this data) may also be inserted into the code for comparison with the WSN data.

9- The program is running under the stated assumption that it is early morning (approx. 3am local time). The Excel spreadsheet can be operated at any time, but will only calculate frost risk if the time is after midnight and before 8am. If that is true and all of the data has passed through the quality check to this point, then this section of the algorithm operates: 1) under the assumption that humidity values must be greater than or equal to 50% to approach frost formation and be sufficient overnight for frost, check to ensure the average value for humidity across the sensors is at least 50%. 2) to compute the dewpoint depression (air temperature minus dewpoint) and it is compared to critical thresholds (bands) for frost formation at certain temperatures. Frost formation likelihood is printed out on the screen and in the output file.

Condition Alpha:	If 1<=T<2, AND 1.5<DEP<=2
Condition Beta:	If 1<=T<2, AND 0.75<DEP<=1.5
Condition Gamma:	If 1<=T<2, AND 0<=DEP<=0.75
Condition Delta:	If 0<=T<1, AND 1.5<DEP<=2
Condition Epsilon:	If 0<=T<1, AND 0.75<DEP<=1.5
Condition Zeta:	If 0<=T<1, AND 0<=DEP<=0.75
Condition Eta:	If -2<=T<0, AND 1.5<DEP<=2
Condition Theta:	If -2<=T<0, AND 0.75<DEP<=1.5
Condition Iota:	If -2<=T<0, AND 0<=DEP<=0.75
Condition Kappa:	If -5<=T<-2, AND 1.5<DEP<=2
Condition Lambda:	If -5<=T<-2, AND 0.75<DEP<=1.5
Condition Mu:	If -5<=T<-2, AND 0<=DEP<=0.75
Condition Nu:	If T<-5, AND 1.5<DEP<=2

Condition Xi: If T<-5, AND 0.75<DEP<=1.5
Condition Omicron: If T<-5, AND 0<=DEP<=0.75

10- The frost formation potential has been stated and now the code reports the calculated variables into the output file. This is also when mapping of the frost likelihood would occur in a similar fashion to how it is being done now but using the "bands" for frost formation in Temperature (°C) to shade the map for the area of the WSN "point" observation. The difference between the WSN temperature from the MODIS LST at this granule location at nearby times could also be reported here for help verifying MODIS LST-based frost likelihood mapping.

Alpha indicates	Frost conditions may be likely soon
Beta indicates	Frost conditions should appear soon
Gamma indicates	Pockets of Frost or light frost likely
Delta indicates	Light Frost likely
Epsilon indicates	Light to Moderate Frost likely
Zeta indicates	Moderate Frost likely
Eta indicates	Light Frost likely
Theta indicates	Light to Moderate Frost likely
Iota indicates	Moderate to Heavy Frost Likely
Kappa indicates	Prolonged Light Frost
Lambda indicates	Prolonged Light-Moderate Frost Likely
Mu indicates	Prolonged Moderate Frost Likely
Nu indicates	Prolonged Mod-Heavy Frost Likely
Xi indicates	Prolonged Heavy Frost Likely
Omicron indicates	Severely Damaging Frost Likely

IV. Results from Testing

Case Study Summary:

Huntsville Radiative Frosts Captured by WSN				
Case Study	**10/26/13**	**11/8/13**	**11/20/13**	**2/14/14**
Julian Date	13299	13312	13324	14045
Local Sunset Time	10/26/13 17:59:00	11/08/13 16:46:00	11/20/13 16:39:00	02/14/14 17:29:00
Local Sunset Temp	14.0565865	No Values Near Sunset	9.35043035	6.313713222
Local Temp 2hrs AFTER Sunset	12.94866317	12.98391527	8.194664876	0.648196191
Temp change 2 hrs. After Sunset	1.10792333	#VALUE!	1.155765474	5.665517031
Temp Change Indicated Frost Likelihood	Temp change after sunset is not necessarily conducive to potential for radiative frost.	#DIV/0!	Temp change after sunset is not necessarily conducive to potential for radiative frost.	Temp change after sunset i very conducive to radiative frost conditions.

Condition	10/26/13	11/8/13	11/20/13	2/14/14
ALPHA	1	1	No Alpha Conditions Met	2
BETA	4	No Beta Conditions Met	No Beta Conditions Met	No Beta Conditions Met
GAMMA	No Gamma Conditions Met	No Gamma Conditions Met	No Gamma Conditions Met	No Gamma Conditions Me
DELTA	1	No Delta Conditions Met	1	No Delta Conditions Met
EPSILON	3	6	No Epsilon Conditions Met	2
ZETA	No Zeta Conditions Met	8	No Zeta Conditions Met	1
ETA	No Eta Conditions Met	No Eta Conditions Met	No Eta Conditions Met	No Eta Conditions Met
THETA	8	No Theta Conditions Met	No Theta Conditions Met	1
IOTA	No Iota Conditions Met	10	No Iota Conditions Met	13
KAPPA	No Kappa Conditions Met	No Kappa Conditions Met	No Kappa Conditions Met	No Kappa Conditions Met
LAMBDA	No Lambda Conditions Met	No Lambda Conditions Met	No Lambda Conditions Met	No Lambda Conditions Me
MU	No Mu Conditions Met	No Mu Conditions Met	No Mu Conditions Met	23
NU	No Nu Conditions Met	No Nu Conditions Met	No Nu Conditions Met	No Nu Conditions Met
XI	No Xi Conditions Met	No Xi Conditions Met	No Xi Conditions Met	No Xi Conditions Met
OMICRON	No Omicron Conditions Met	No Omicron Conditions Met	No Omicron Conditions Met	No Omicron Conditions Me
TOTAL FROST WARNINGS	17	25	1	42

IV. Results from Testing (continued)

- **FIRST FROST, MODERATE:** The Oct 26 case was a "first frost" meaning it was the season's first official frost, which is important for agricultural concerns. This was well forecasted by the algorithm's conditions, but as is evident from the conditions and the frost photos, it was also quite a significant first frost, the kind of event we would want to warn for. The only difficulty with this case was encountered in the fact that the temperature drop after sunset was not very big as would typically be found with moderate frost events. Secondly, there was a short period during which, at night, the winds changed direction to an East wind, which temporarily blew in drier air. During this time, while the temperature continued to fall steadily, the humidity dropped as well so the dewpoint depression (DEP) actually increased, negating the typical frost conditions. This may be why the frost was not even more moderate to heavy! When the dewpoint began to fall again and the winds changed direction, the indications for frost switched over to Delta and then to Epsilon, and so on. This is why no "Gamma" condition was reported.

- **MODERATE FROST:** On Nov 8 case, data from Nov 7 was not used because the WSN was inside Karthik's office recording values to be calibrated against test equipment, and then it was placed outside at 6pm, AFTER sunset occurred at 4:46pm CST. This meant that the Sunset conditions tested for could not be verified for this case, unfortunately.

- **BRIEF LIGHT FROST:** The Nov 20 case was a brief, light frost, observed from 4am-4:15 am and so the fact that the Delta condition catches it at all shows the algorithm's sensitivity to brief frosts.

- **HEAVY MID-WINTER FROST:** The Feb 14 case was the most clear-cut, but was also the only mid-winter frost caught by the WSN.

- Dewpoint Depression: Oct 26, when frost, DEW <=1.44. On Nov 8, when frost, DEW<=1.33. On Nov 20,

V. Camera Yet To Be Tested

During the field validation portion of our measuring frost with the WSN in Huntsville, it became necessary to physically go to the WSN observation location in person and validate the presence of frost. In the absence of a physical observer, one cannot just assume frost will be present at the WSN location, as patchy frost can occur in some places but not in others. This yields itself to the idea of using a camera to capture early morning evidence of frost instead. Pictures were taken of frosts observed in Huntsville, but it became evident that at certain angles and certain heights above the ground, light frost was difficult to photograph with a flash because of the large amount of water vapor present in the air between the camera lens and the ground. Close to the ground, at a very low angle, the ability to use flash photography to capture the frost presence was improved.

In recent days at the author's suggestion, a team member has acquired an IR and visible camera that may be useful for photography at remote WSN locations. This technology will be undergoing testing in Huntsville this winter and spring to further decide if this will be useful to the observations of frost in the tea fields of Kericho, where currently volunteer observers are required to confirm frost presence. The difficulties the team may face include a) keeping the camera lens clear of frost formation, b) observing distance of camera from tea plants and how much water vapor is in the space will reflect visible light back at the camera obscuring the picture, c) if IR methods are sufficient to prove the presence of frost. It is possible that the IR camera may just sense the surface temperature of the leaves or it may sense the ice crystals forming on them. It is hoped that the combination of this IR photography with the in-situ observations by the WSN will be sufficient evidence of frost presence.

VI. Variation of Vapor Pressure with Temperature for use in calculating dewpoint from humidity at other elevations

The derivation of the Clausius-Clapeyron Equation principle came about during the Industrial Revolution when two engineers worked to discover the thermodynamics of water vapor, and studied isothermal compression of pure water vapor in a cylinder to find the saturation vapor pressure at the point where condensation occurred. Using the Ideal Gas Law and various assumptions relating water vapor pressure to vapor density, etc., one arrives at the equation:

$$e_s = e_o * exp\left[\frac{L}{R_v} * \left(\frac{1}{T_o} - \frac{1}{T}\right)\right]$$

where e_o is a known vapor pressure at reference temperature T_o and R_v is the gas constant for water vapor. e_o =0.611 kPa and T_o =273 K are constant parameters, and R_v =461 J/K/kg. Absolute Temperature in Kelvins must be used for T in this equation. Over ice, the Latent heat of Deposition $L = L_d$ = 2.83x10^6 J/kg, which gives us L/R_v = 6139 K.

VII. A potential add-on or another code all together

One way that farmers have been trained in the US to know when to turn on their sprinklers in the fields and coat their crops with water to protect them and when not to on nights when radiative frost is likely to form is by using historical temperature records on clear sky, calm, frost nights. This aids their ability to calculate the regression coefficients for a model that they can then use to accurately predict what the minimum temperature at night will be during a particular time of year. The algorithm or model begins at two hours past sunset. The temperature at sunset and the temperature N hours after sunset are input into the model once it has those regional regression coefficients for that time of year and it will calculate the temperature trend overnight and given additional information about dewpoint two hours after sunset, it can also calculate the wet-bulb temperature between two hours after sunset and sunrise. See the FAO's handbook: "Frost protection: fundamentals, practice, and economics- Volume 1" Chapter 5 for more information and to request the Excel model.

It is also important for farmers to know what the minimum temperature to be expected overnight will be. The equations below are a good "rule-of-thumb" to use, and come (1) from Allen, C.,1957, *Mon. Wea. Rev.* 85:119-120 and (2) from "Kiwifruit Growing and Handling" by Janine K. Hasey, 1994. If there is fog, periodic or intermittent cloud cover, or variable winds then the model may predict temperatures lower than will be observed, but it holds well for clear, fog-less nights with light or calm winds, in the absence of cold air drainage issues. With a hand-held sling psychrometer, which are still available, this hygrometric approximation can use the dry and wet-bulb temperatures observed to calculate the minimum temperature. This form of equation can also be fitted to climatically similar locations to California by changing the slope and intercept constants. All formulas below are in degrees Fahrenheit:

i=the time in hours after sunset
Ti= the temperature at time "i" after sunset
Ts=the temperature at sunset
Tm=the forecasted minimum temperature
Tw=wet-bulb temperature at
Ta=dry-bulb (air) temperature at
h=time from sunset to sunrise in hours
C=coefficient

(1) $Tm=Tw - \frac{1}{4}(Ta + 16)$

(2) $Ti=Ts - C*SQRT(i)$
where $C=(Ts-Tm)/(SQRT(h))$

VIII. Case Study Photos of Frost in Huntsville

Fig. 1- Oct 26 Frost next to WSN, taken at 7am:

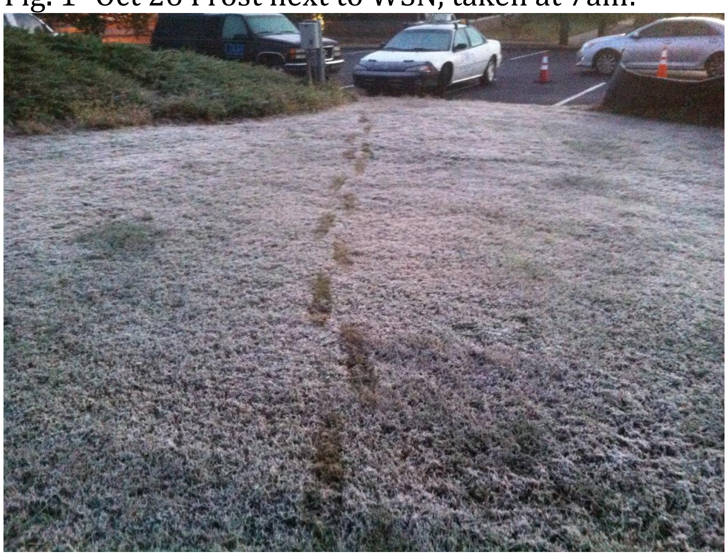

Fig. 2- November 8, 2013 WSN set-up and Frost next to WSN, taken at 5:37am

Nov 20, 2013- Cerese witnesses Frost from 4- 4:15am on various surfaces next to WSN (no photo available).
Feb 14, 2013- Cerese witnesses Frost on cars and on grass next to WSN where snow is no longer present, from 4 am up through 6am (no photo available).

IX. References

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